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A cleaner production approach to urban water management: potential for application in Harare, Zimbabwe

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Abstract

Water quality is an urgent problem in the Lake Chivero catchment, Zimbabwe, whilst water scarcity will be a problem soon. This study focused on assessing the potential impacts of the application of cleaner production principles in urban water supply and sanitation in the context of sustainable management of water resources. The cleaner production principles are explained together with how they can be applied to urban water management. Data from City of Harare and previous studies were collected and analysed. The study focused mainly on water, nitrogen and phosphorus. About 304,000 m^3/d of wastewater, containing 30,000 kg/d TN and 3600 kg/d TP are currently produced and treated at five sewage treatment works in Harare. Water conservation, treatment and reuse strategies were developed for different land uses starting from water-saving devices, regulation, leak detection and repair, to wastewater treatment and reuse. This study showed that the application of the cleaner production principles would reduce total wastewater production from 487,000 m^3/d to 379,000 m^3/d (a 27% reduction) based on year 2015 projections. A very large investment in treatment infrastructure can be postponed for about 10 years. In terms of amounts treated and discharged at central level this translates to reductions of 47% on flows, 34% on TN, and 44% on TP. River discharges can be eliminated. It was concluded that a cleaner production approach could substantially reduce current water pollution and long-term scarcity problems in Harare.

Keywords: Cleaner production; Nutrients; Reuse; Sustainability; Urban water management; Wastewater

1. Introduction

The management of water in urban areas has quantitative and qualitative dimensions, both of which require careful planning if the concept of 'sustainable cities' is to be realised in future. Urban water management (UWM) involves the qualitative (hygienic) and quantitative aspects of all water in urban settings (Siebel and Gijzen, 2002). This includes abstraction, treatment, storage, transmission and distribution to consumers and the subsequent collection and processing of the generated wastewater. Water scarcity is a perennial problem in many countries as reported by Engelman and LeRoy (1993), but water quality seems to be a major problem in developing countries (Moyo, 1997; Gijzen, 2001). Conventional wastewater treatment is rarely geared to effluent reuse such as irrigation, fertilisation or aquaculture. Thus it does not generate income or employment, both high priorities in developing countries (Polprasert, 1996; Al Salem, 1996; Helmer and Hespanhol, 1997). Most urban sewerage projects also eat up funds in underground pipes and inevitably approach disposal from a short-term "least cost" point of view (Rybczynski et al., 1978). They promote tertiary treatment and river disposal instead of taking advantage of the long-term benefits of reuse. In most cases the desired treatment level is rarely achieved (King, 2000).

Harare, the capital city of Zimbabwe, is one of the towns that are facing water quality problems whilst water scarcity problems will be a major problem in the next five years (JICA, 1996; Moyo, 1997; Nhapi et al.,

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2002a). Harare has a population of about 1.8 million and obtains about 95% of its water needs from Lakes Chivero and Manyame. The lakes are located downstream of the city and they also supply water to the other neighbouring towns of Chitungwiza, Epworth, Norton and Ruwa via two water works. Lake Manyame has a dam capacity of 480,236,000 m^3 but the raw water abstraction point is located upstream and closer to the spillway of Lake Chivero (Fig. 1). This means the abstraction from Lake Manyame is limited at low water levels (drought years) and Lake Chivero, dam capacity 247,181,000 m^3, remains the major source of potable water in the area. Based on average flows, Lake Chivero can safely supply about 421,000 m^3/d to the Morton Jaffray Waterworks without drawing down the Lake (Nhapi et al., 2002a). Abstractions from Chivero are about 416,000 m^3/d although the city still has room for abstractions from Manyame. Harare has been failing to raise money for developing another source of water supply since some ten years ago. On the other hand, household water consumption is reported to be too high. Figures given by JICA (1996) are 625 l/cap.d for low-density residential areas, 315 l/cap.d for medium density, and 80 l/cap.d for high-density residential areas. The water quality in Lake Chivero is deteriorating due to regular inflows of poorly treated sewage effluents (Nhapi et al., 2004; Magadza, 1997). This paper, therefore, focuses on a cleaner production approach as a possible solution to urban water management. The paper looks at current approaches to urban water management, describes the cleaner production principles and how they can be applied to the urban water supply and sanitation sector. Harare is then used as a case study to assess potential impacts. The paper mainly focuses on water and nutrients (nitrogen and phosphorus).

2. Current urban water management systems

Three issues have contributed to current high water demand: virtually free water, no economic need or environmental incentive to limit water consumption, and the concept that water improves health. Rapid urbanisation and recurrent water borne diseases have raised concerns about water quality deterioration in towns. The engineering solution to this has been to construct better facilities for treatment and the development of 'cleaner' water resources (Gijzen, 2001). Often these solutions are supply-driven and end-of-pipe technologies based on the notion of 'unlimited water resources'. Very sophisticated and expensive water and wastewater treatment technologies have been developed over the years to cater for deteriorated water quality and many countries have enacted stricter effluent disposal regulations that are difficult to achieve. The abundance of potable water has resulted in it being used for non-potable purposes like cleaning and transporting waste out of cities.

Huge investments on supply driven water supply technologies have paid off in terms of successes in reducing health-related problems. However, the continued growth of cities mean that future water needs will have to be developed further away from the city. The eco-

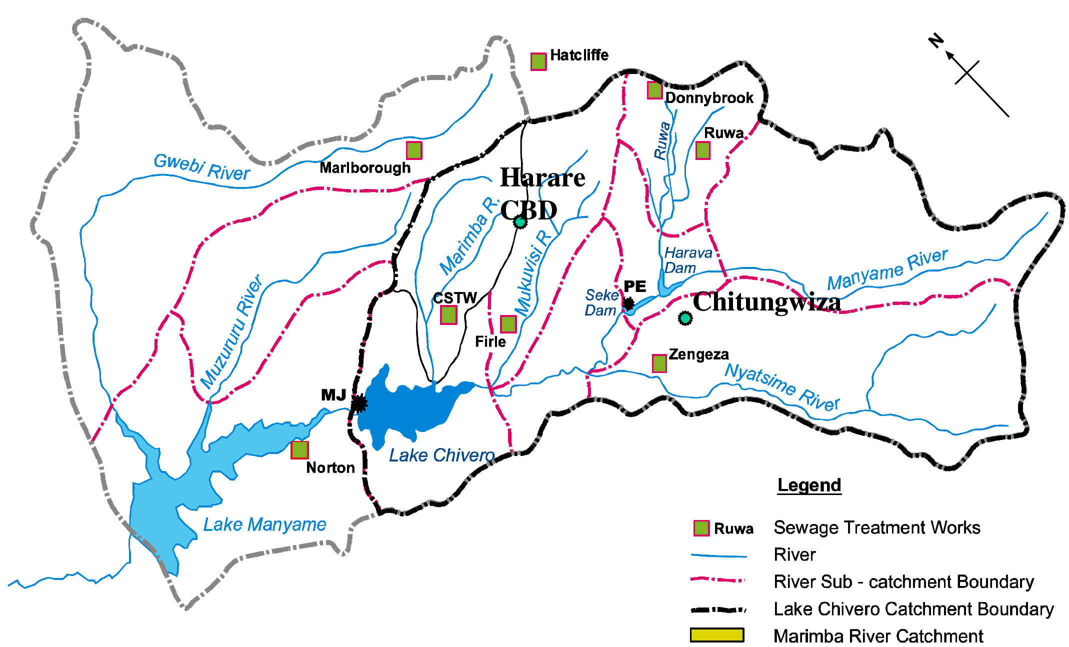

Fig. 1. Map of the study area showing the location of Harare relative to Lakes Chivero and Manyame, and the sewage treatment works (MJ = Morton Jaffray Waterworks; PE = Prince Edward Waterworks).

nomic considerations (investment and cleaning up the environment) and the realisation that water is a limited resource in terms of quality and flow, raise questions on the sustainability of the conventional approach to urban water management. In water management, sustainability amounts to maintaining the abundance and quality of water resources to sustain ecosystems and support future human needs while also meeting current household and commercial water requirements (Braden and van Ierland, 1999). Of particular concern are the quality needs for different ranges of water uses, and consumption levels in some cities (Otterpohl et al., 1997; Gijzen, 1998; Frijns and Jansen, 1996). The high water consumption promoted by the water supply sub-sector has serious implications on treatment technologies and investment costs for the sanitation sub-sector. One litre of water consumed potentially translates to 0.5–0.851 of wastewater, which, after some treatment, will potentially contaminate many litres of fresh water. The response to treatment requirements through the use of high-tech systems has resulted in many people failing to have access to reliable water and sanitation facilities As the size and cost of a wastewater treatment plant is related to volume of incoming wastewater, the solution to pollution now is concentration. This contrasts well with the water supply sub-sector, which promotes high water consumption and, therefore, more diluted wastewater (Fig. 2).

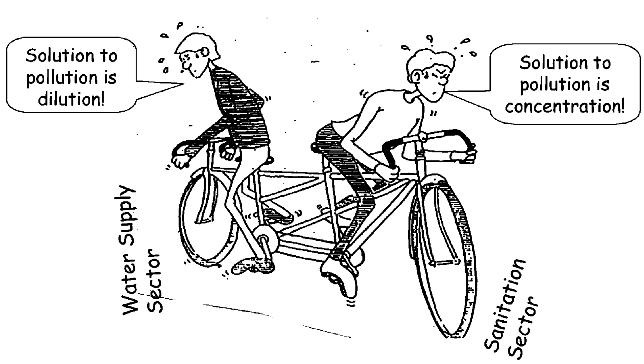

Fig. 2. An illustration of contradictions in management approaches between the water supply and the sanitation sub-sectors of urban water management.

An analysis of costs related to water and wastewater treatment reflects economies and diseconomies of scale, which tend to favour high water consumption but smaller wastewater volumes (Gunnerson and French, 1996) (Fig. 3). A number of issues are now being questioned based on the sustainability criteria (Box 1).

Box 1: Sustainability Issues in UWM

- Dilution of waste does not favour efficient biological treatment methods like anaerobic treatment
- The energy bound in organic mater is wasted through energy-intensive aeration
- Nutrients (proteins) in wastewater are removed whilst high cost and energy is wasted in industries in the production of fertilisers
- Highest effluent standards are adopted in many countries and this potentially reduces possible reuse options of the nutrient-rich effluents
- Same expensive solutions are offered for all regions without due regard to the local situation and economic capacity

It is expected that a vast majority of urban dwellers in developing countries will remain without access to appropriate services unless sustainable and feasible concepts are developed. The cost of inaction is even more serious, resulting in public health impacts, environmental and economic damage. The economic damage relates to losses of lives (e.g. cholera outbreaks), loss of economic uses of water (tourism/recreation, fish production), higher cost of drinking water, and costly restoration. As a way forward, this paper proposes the application of cleaner production (CP) concepts in urban water management.

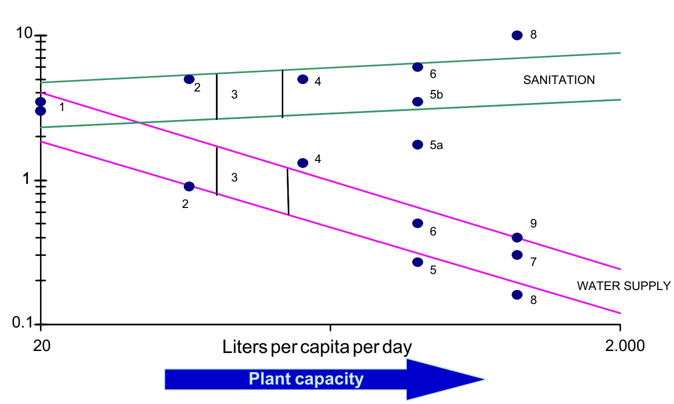

Fig. 3. An illustration of economies and diseconomies of scale for water supply and wastewater treatment plants (Source: Gijzen, 2001).

3. Cleaner production principles

Although many cities are already facing water quantity and quality problems, it is not possible that they will all benefit from new intervention measures because of the lead times involved. It is, however, necessary to initiate discussion on alterative approaches (sustainable) so that current and future generations would benefit. Most towns in developing countries have not yet heavily invested in physical infrastructure and may still benefit in the short-term. Other towns can still consider immediate measures to minimise cost and wastewater production based on cleaner production approaches. Cleaner production is the approach in which processes and activities are carried out in such a manner that the environmental impact therefore is as low as possible (Siebel and Gijzen, 2002). Cleaner production traditionally refers to improving industrial production process so as to reduce the flow of waste products (Pinkhan, 1999). In UWM the following essential elements of cleaner production remain valid: pollution prevention, proper choice of raw materials, process efficiency, reuse and recycling of materials, life cycle approach, and least impact treatment with resource recovery.

4. Application of CP concepts to water supply and sanitation sector

The implications of the application of CP concepts to UWM are summarised in Table 1 and the necessary actions required in UWM are explained below. Essentially, the CP approach emphasises on pollution prevention and resource recovery (water, energy and nutrients). This is achieved by avoiding mixing, dilution, and transport of waste and is best achieved through onsite or decentralised management of wastewater.

5. Action on principles

5.1. Resource consumption

The supply of 80–630 l/cap.d (Harare) of zero coliform water when only about 2–8 l/cap.d is needed for drinking should be discouraged and different quality ranges supplied for different water uses. Water consumption, especially for domestic and industrial purposes should be greatly curtailed to levels that are necessary to ensure comfort and decency. This can be achieved through the use of water conservation devices like low-flush toilets (3/6 l), water-saving shower heads (3–6 l/min) and faucets (2–4 l/min), recycling of greywater, and drip irrigation in urban agriculture. Non-technical measures that can be applied include punitive rising-block tariff structure for water consumption, water rationing, and awareness-raising campaigns for both industrial and domestic users.

5.2. Choice of resources

Domestic water uses include drinking (2–5%), cleaning (4–35%), flushing toilets (15–40%), outside use (20–60%) (Siebel and Gijzen, 2002). There is therefore a scope for reductions in the quantity of drinking water supplied to consumers. Alternatives that can be considered include bottled water, internal reuse, and dry sanitation. Rainwater harvesting can be considered to supplement surface waters. The rainwater may be used with or without any treatment or can be used to recharge underground aquifers.

5.3. Generation of industrial and domestic wastes

Industries can reduce production of wastes through process optimisation. Processes can be improved

Table 1
Cleaner production principles and implication for UWM (Pinkhan, 1999; Gijzen, 2001)

Cleaner production principle	Implications for urban water management
Principle 1	
Only use input material as necessary	Quality ranges for different uses, 2–8 l/capd potable only Pollution prevention first Conservation of resources avoid wastage as water losses waste water, energy, chemicals
Principle 2	
Do not use input of higher quality than necessary	The following non-potable uses of water should be stopped: toilet flushing, washing cars, fire fighting, clean floors, gardening, transporting waste
Principle 3	
Do not mix separate waste flows	Municipal sewage should be kept separated as urine, faeces, and greywater Industrial effluents (and stormwater) should be kept and treated separately
Principle 4	
Evaluate other economic function and uses of by-products before considering treatment and final disposal Do not mix, dilute, transport	Discharge of domestic sewage without treatment should be avoided Reuse and recycling of waste components should be encouraged as far as possible

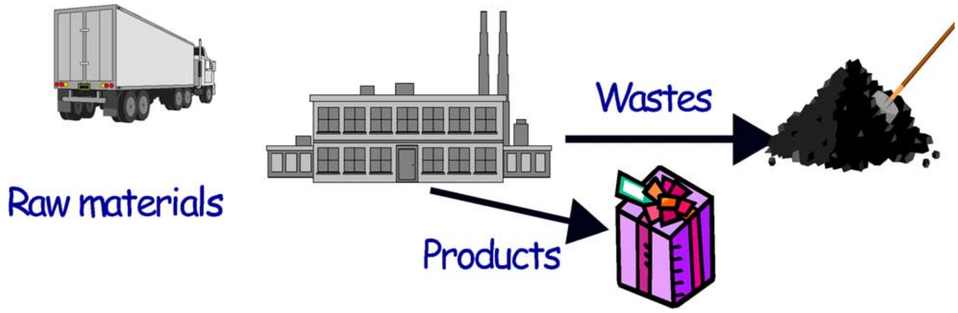

Fig. 4. Efficient industrial processes would result in reduced product to waste ratios.

through personnel training, motivation, procedural changes, recovery and reuse, recycling, and smarter treatment. High tariffs for industrial consumption may force industries to replace obsolete equipment, which result in high waste to product ratios (Fig. 4). Industries require water for production process and transporting waste, and potable water may or may not be needed. Industrial effluents should generally not be mixed with domestic wastewater as it can inhibit microbial degradation processes. Households can reduce waste production by using dry or low water sanitation systems in combination with continuous or batch collection of nutrients for recovery/reuse. For example, urine can be stored separately and collected at times of low sewer flow.

5.4. Quality of waste

The quality of waste can be maintained by avoiding the dilution of what is concentrated, and the pollution of what is produced separately. Regulations can also be used to restrict/prohibit the use of household/industrial products with negative side effects on waste quality (avoid cocktails). Examples of this which have already been implemented elsewhere include the banning of the use of phosphorus detergents and some pesticides like DDT.

5.5. Treatment

The treatment objectives should aim at maximising the re-utilisation of wastewater components (water, biogas, and nutrients). Anaerobic treatment can be used to recover energy, whilst animal/plant biomass (aquaculture, duckweeds) and irrigation is used to cover nutrients and water. Treatment should ideally be done close to the source of generation to reduce collection and energy costs. The use of large central plants often results in serious damage to the environment in cases of plant breakdowns.

The application of CP concepts discussed above could potentially result in Gijzen (1998):

- significant reduction in potable water consumption in households,
- use (reuse) of water with different quality ranges for different purposes,
- recovery and reuse of water components, and
- development of low-cost alternatives for smaller volumes of wastewater to be managed.

6. Application of cleaner production principles in Harare

6.1. Water management problems in Harare

Problems relating to water scarcity and quality in Harare have already been outlined. The water quality problems are related to rapid population growth caused mainly by rural-to-urban migration. This has resulted in overloading of wastewater collection and disposal infrastructure. Wastewater is treated by trickling filter, biological nutrient removal (BNR), and waste stabilisation pond (WSP) systems. Trickling filter effluent is mixed with primary and secondary sludge (after anaerobic digestion) and pumped to pasture irrigation farms. Waste stabilisation pond effluent is supposed to be pumped to farms for irrigation but this is rarely the case because of numerous plant breakdowns. Poor quality effluent is thus discharged into watercourses and this has resulted in the eutrophication of Lake Chivero (Kamudyariwa, 2000; Tirivarombo, 2001; Nhapi et al., 2004). The city also experiences frequent pumping problems resulting in some high elevation areas, like Mabvuku and Tafara townships, receiving erratic supplies of water. There is no comprehensive plan for monitoring distribution water losses although it is estimated that about 25% of the treated water is unaccounted for (JICA, 1996). Data for the two water treatment works of Morton Jaffray and Prince Edward show plant losses of $11 \pm 6\%$ and $7 \pm 3\%$ respectively (Nhapi et al., 2002a). These losses have been attributed to frequent backwashing necessitated by high concentrations of algae in raw water (Mckendrick, 1982).

6.2. Water consumption and wastewater generation

An assessment of sewage flows and nutrient discharges was done using unit pollution loads for nitrogen and phosphorus mainly from JICA (1996) and council reports (Harare and Bulawayo). Population and nutrient loads were determined for each sewage treatment plant in Harare based on data from Nhapi et al. (2002b). Table 2 shows that residential (domestic) areas play a major part in the pollution problems in Harare. High-density areas provide 31% of the total wastewater volume, and over 50% of both nitrogen and phosphorus contributions. The contribution from commercial areas remained second highest for the three parameters. The high contribution of commercial activities to nutrient loads is attributed to toilet discharges and the use of phosphorus detergents. However, the contribution of phosphorus detergents at household level has been shown to be small at about 6% (Gumbo and Savenije, 2001). The contributions from industries were much higher for phosphorus (15%) compared to 6% for nitrogen. This is also attributed to the use of phosphorus detergents for cleaning in industries. The data presented in Table 2 was checked against observed loads at the five sewage treatment works (Nhapi et al. (2002b). The estimated nutrient and flow data agreed with observed data within some margin of errors (1–15%).

Table 3 was developed from various sources and assumptions as given in the remarks column. The major water uses considered are body washing (bath or shower), toilet flushing, laundry, kitchen, gardening and other uses (car washing, house cleaning, etc.). Per capita household water consumptions in Harare are very high for medium and low density areas when compared to international figures (Metcalf and Eddy, 1991). The culture of water conservation in Harare is lacking

Table 2
Summary results on wastewater generation and nutrient load estimation in Harare for the year 2002

Landuse	Population	Unit flow (l/cap.d)	Total flow (m^3/d)	Unit TN production (g/cap.d)	Total TN production (kg/d)	Unit TP production (g/cap.d)	Total TP production (kg/d)
Residential areas							
Low density unsewered[a]	76,000	315	24,052	13	993	1.4	107
Low density sewered	137,000	315	43,155	13	1781	1.4	192
Medium density[b]	164,000	210	30,783	12	1968	1.3	213
High density[c]	1,485,000	63	93,555	11	16,335	1.2	1782
Commercial			61,629		6943		756
Industrial			50,594		1690		525
Total	1,862,000		303,768		29,710		3575

Source: Nhapi et al. (2002b). N.B. Population figures and medium density flows rounded off.
[a] Low density, stand size >2000 m^2, 13 people per stand.
[b] Medium density, stand size ±1000 m^2, 10 people per stand.
[c] High density, stand size ±300 m^2, 7 people per stand.

Table 3
Estimates of sources of domestic wastewater for Harare

Usage	Residential area category			Remarks
	High (l/cap.d)	Medium (l/cap.d)	Low (l/cap.d)	
Bath	25	90	90	High density residents use shower or bucket (20 l) Low and medium density residents use geysers, common size 90 l
WC	24	80	80	High density figure derived from Hoko (1999) For low and medium density a cistern capacity of 16 l and three urine and two faeces flushings per day
Laundry	5	16	26	60 litres per week per stand for high density 180 litres per week per stand low and medium density
Kitchen	5	11	17	Based on three washing routines at 60 l/d for high and 120 l/d for medium and low density
Other	4	13	102	Calculated as balance to achieve the total observed figure This figure comprises mainly water for gardening
Total	63	210	315	Harare figures from JICA (1996)

Reference has also been made to the Bulawayo City Water Conservation reports.

whilst large garden areas account for a substantial portion of water consumption. The rationale for large stands should therefore be questioned, not only from a water conservation point of view, but also in terms of wastage of valuable space, unit cost of infrastructure (pipes and roads), and sewage treatment options. Diluted sewage is expensive to treat, as large treatment structures are required to handle the high hydraulic load.

The current design of commercial stands that average about 200 m^2 and buildings taking up almost all the stand area makes it impossible to treat sewage from commercial areas onsite. Onsite systems would suit most industrial stands depending on specific activities and stand size and also low and some medium density residential areas. From Table 2, it follows that 155,000 m^3/d (51%) of wastewater, 23,300 kg/d (78%) of TN and 2500 kg/d (71%) of TP generated in Harare's high-density and commercial areas has to be handled at centralised treatment works.

6.3. Onsite treatment and reuse of wastewater

The prevalence of on-plot cultivation and large stand sizes offers an opportunity for onsite treatment and reuse of wastewater, especially for low density and industrial areas, and (to a limited extent) medium density areas. Both black/greywater and urine/faeces separation is feasible with the other option being combined treatment of all wastewater streams but aimed at reuse close to the source. Source separation is advantageous because it requires little or no water usage. It also enhances opportunities for localised direct reuse of waste components (urine, greywater) and a host of technologies are available for this (Lindstrom, 1998; Jeppson et al., 2002). Greywater comes from laundry, bath, and kitchen, and can be easily collected from waste downpipes before they discharge into a gully trap. In most cases it can be directly reused for gardening, or can undergo basic treatment and uses extended to toilet flushing and car washing. Waste from the toilet can be treated separately using anaerobic systems, drying beds, or co-composting with refuse (Strauss, 1991). The same methods can be used for faeces only. Composting toilets are already in use in peri-urban areas of Harare. After stabilisation, the sludge can be applied as manure in gardening. Another option is to treat greywater and toilet waste (blackwater) together using septic tanks as is currently happening in some low-density areas. Greywater can also be reused directly for gardening and cleaning purposes.

6.4. Potential impacts of CP in Harare

6.4.1. Greywater separation

An assessment of greywater reuse potential was only done for residential areas. There are no published figures on greywater quality in Zimbabwe. However, literature shows that greywater contains about 10% of TN and 50–70% of TP of the household wastewater (Larsen and Guyer, 1996; Hanæus et al., 1997). In Harare domestic sewage constitutes about 18,300 kg/d TN and 2200 kg/d TP. The results showed that greywater in Harare amounts to about 86,800 m^3/d (52%) of the domestic wastewater generated. For all landuse categories in Harare, greywater reuse would reduce the export of 29% of flow, 6% of TN, and 37% of TP from sources of generation.

6.4.2. Urine separation

There are also no local values on nutrient concentrations in human urine. In other countries urine is estimated to contribute about 80% to the nitrogen and 30–50% to the phosphorous found in ordinary household wastewater although it forms 1% of the volume (Jönsson et al., 1998; Larsen and Udert, 1999). These literature values were adopted for calculations although it is noted that the composition differs a lot depending on diets. The results revealed that urine potentially contributes 14,600 kg/d TN, and 1200 kg/d TP of the total domestic nutrient load. For all landuse categories in Harare, urine separation would reduce the export of 52% of TN, and 34% of TP. Urine separation is therefore more attractive compared to greywater.

6.4.3. Other onsite options

In Zimbabwe there are other treatment methods where expertise is still growing. These include composting toilets used in two peri-urban areas of Harare, constructed wetlands used for some small housing estates and large industrial complexes, and septic tanks in most low density residential areas. Upflow anaerobic sludge blanket (UASB) and small versions of activated sludge systems are also being used in industries. However, the quality data of these plants is rarely available to assess their performance. There is, however, new legislation that compels owners of such systems to periodically supply quality data to the local environmental monitoring agency. Regulations, like banning of phosphorus detergent, are also useful options.

6.4.4. Predictions to the future

The potentials of the resultant re-organisation of wastewater collection and treatment in Harare for the year 2015 are shown in Table 4. All low-density sewered dwellings have been replaced with onsite systems. In developing this table, water consumption has been reduced via water saving measures like low-flush toilets,

Table 4
Results of flow and nutrients projected to be received at offsite STWs in Harare for the year 2015 after several interventions (2015 population and developments data from JICA (1996))

	Projections to 2015 without interventions (business-as-usual scenario)			Projections to 2015 with CP-based interventions		
	Flow (m^3/d)	TN (kg/d)	TP (kg/d)	Flow (m^3/d)	TN (kg/d)	TP (kg/d)
Domestic	285,720	34,323	3739	199,977	6490	2123
Industrial	115,769	4056	1261	86,827	4056	757
Commercial	61,629	13,111	1429	46,222	13,111	857
Groundwater	28,450			28,450		
Total	491,568	51,490	6429	361,476	23,657	3737

low-water shower heads and faucets, and also greywater reuse and rainwater harvesting. From this, total wastewater production will be reduced from 492,000 m^3/d to 361,000 m^3/d (a 27% saving). A very large investment in treatment construction can be postponed for about 10 years. Table 4 was developed from population projections in JICA (1996).

7. Conclusions

The CP approach to managing urban water appear a viable option for many cities and Harare, in particular. It would potentially reduce water consumption and the volumes of wastewater to be generated (by 27% in year 2015). Nutrient loads will also be reduced and most of them handled within the property boundary. Thus the long-term water scarcity and the current water pollution problems in Harare can be solved by a CP approach. However, the issues of public health (pathogens), quality requirements for different use and reuse options, and cost implications need further consideration.

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