ECOLOGISING SOCIETAL METABOLISM: THE CASE OF PHOSPHORUS

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ABSTRACT

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 Bellagio principles underpin the basis for this new approach to environmental sanitation. There are two main concepts emanating from the Bellagio principles, which make the basis of this paper. Firstly, the 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. Recycling of Phosphorus (P) in urban or peri-urban ecological agriculture (without synthetic fertilisers) is used in this paper to assess the feasibility of these concepts. An inventory of annual P-fluxes based on characterisation of input goods, processes, transformation, output fluxes and storage was conducted for a high-density suburb in Harare, Zimbabwe where agriculture is already a major activity. Using systems thinking approach and material flow accounting two compartments or subsystems are defined to enable accounting and analysis of P-bearing materials. The "household" (consumption/use and excretion/waste) and "agriculture" (soil-plant interaction). Total diversion of P in sewage onto the land under agriculture translates to an application rate of about 65 kg/ha compared to a recommended fertiliser application rate in Zimbabwe of 42 kg/ha as P. Partial diversion of the waste flux from the "household" subsystem in the form of source separated human urine can sustain agricultural activities in terms of P thereby enabling the closing of the P-cycle at household and neighbourhood scale through ecological agriculture.

KEYWORDS

Ecological sanitation, material-flow-accounting, phosphorus, recycling, urban agriculture

INTRODUCTION

Implementation of the Household Centred Environmental Sanitation (HCES) and Circular System of Resource Management (CSRM) approaches for environmental sanitation as proposed in the Bellagio (Italy) principles requires integration between excreta disposal, wastewater disposal, solid waste disposal, and storm water drainage (SANDEC and WSSCC, 2000). Firstly, the HCES makes the household the focal point of environmental sanitation planning, reversing the customary order of centralised top-down planning. 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 (Schertenleib, 2001). Many water supply and sanitation problems would be resolved by a new paradigm, which places all aspects of water and waste within one integrated service delivery framework (Schertenleib, 2001; Niemcynowicz, 1997; Esrey et al, 1998, Schertenleib and Gujer, 2000; Larsen and Gujer, 1997).

The principal nutrients (Phosphorus and Nitrogen) flow in a circular, closed loop system in nature, but we perceive of nutrients in a linear, open-ended system. 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 P-cycles in the urban environment is closely related to closing of water cycles. New solutions in terms of environmental sanitation for sustainable cities (green or eco-cities) of the future are perceived to be source orientated, non-mixing, ecologically sound, local and small scale (Otterpohl et al, 1997; Esrey et al, 1998; Beck et al., 1994; Roelofs, 1996).

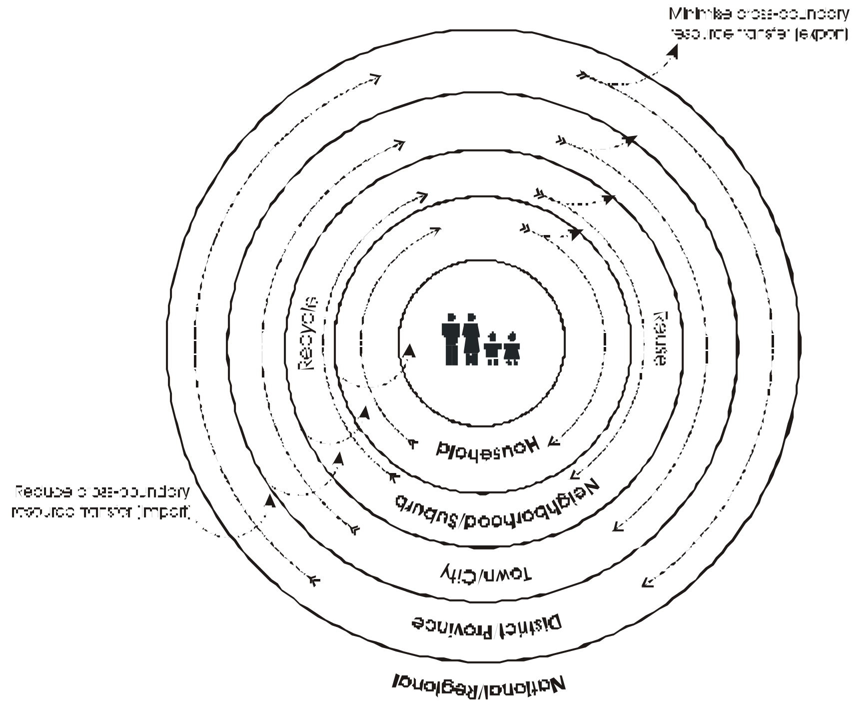

Figure 1 The household centred environmental sanitation and circular system of resource management concept (Bellagio Principles)

Flows of P into the city, in the form of food, fertilisers and detergents, are predominantly derived originally from mined sources; in passing through the city and into the urban drainage system they undergo a significant change of state, from particulate to soluble forms; they are thereby mobilised and thus "diverted", as it were, into the (terrestrial) aquatic environment. The net result is the all too familiar problem of eutrophication in freshwater systems (Beck et al, 1994; Herrmann and Klaus, 1997).

Systems analysis and material flow accounting present attractive tools in desegregating the complex web of cycles and flows. The tracking of the flow of materials and products through society and the environment is an activity of increasing prominence and consequence throughout the world. Material Flow Accounting (MFA) is the investigation of the physical flows of materials, typically on a geographic basis. MFA can help us 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 and Ayres 1998; Baccini and Brunner, 1991; Wackernagel and Rees, 1996).

Since cities need to close the open loop of limited resources such as P, urban agriculture seems to be an option in closing the open loop by reusing and transforming the by-products of human metabolism especially, which, usually are dumped as polluting waste into the bio-region (Smit and Nasr, 1992). The importance of the research and this paper is to reveal and demonstrate the links between, urban agriculture, closing nutrient and water cycles, urban food production, urban poverty, resource recovery and sustainable urban planning and development. The analysis of P-fluxes in urban systems provides an indication where technological interventions can be inserted in the new look urban water and waste infrastructure (Gumbo 2000a).

WHY RECYCLE P?

History of P

A secretive alchemist, the self styled Herr Doktor Brandt, made the initial discovery of Phosphorus (P) in Hamburg around 1669. One imagines that Brandt envisioned a golden future as he toiled over his vats of urine, following the "golden stream" (turning base metals into gold), in pursuit of the philosopher's stone (Emsley, 2000). Until 1750's phosphorus was rare and expensive and it's main use was medicinal. The ninetieth century saw a great increase in the manufacture of phosphorus, which, until a mineral source was discovered in the 1860s, was derived from bones with Albright and Wilson Plc, being the first large scale commercial venture using bones as a source of P (Emsley, 2000; Driver et al., 1999). The blessing in the discovery of P in terms of its vital role as an agronomic nutrient has been dented by its potential as a killer in the manufacture of phosphorus bombs and nerve gas with the former, ironically, used for the first time in Hamburg by the allied forces against Germany in the second world war.

Production and fate of P in the environment

Phosphorus belongs to the class of cycles called lithospheric cycles in which the principal and most important reservoir (*source*) is the lithosphere. Today, the annual global production of phosphate is around some 40 million tonnes of P_2O_5, derived from roughly 140 million tons of rock concentrate. Around 80% of phosphates produced by the world's industry today are used in fertilisers, with a further 5% being used to supplement animal feeds, 12% in synthetic detergent manufacture and about 3% of the total consumption is used in diverse applications such as metal surface treatment, corrosion inhibition, flame retardant, water treatment and ceramic production (Steen, 1998; CEEP, 1998; Harben and Kuzvart, 1996). The three major producing countries USA, China and Morocco, currently produce approximately two thirds of global phosphate production.

Zimbabwe is self-sufficient in terms of rock phosphate, with a current consumption of about 43 000 tonnes/a as triple super-phosphate, which drives its agro-based economy of 12 million inhabitants. The deposits occur within igneous rocks in carbonatite complexes of late Palaeozoic to Mesozoic age, and meta-carbonatites believed to be of Achaean age and in addition cave accumulations of bat guano. No phosphate deposits of sedimentary origin are known in Zimbabwe (Fernandes, 1989; Barber, 1989).

Between 1950 and 2000, about 800 million metric tonnes of fertilizer P were applied to the Earth's surface, primarily on croplands. During the same time period, roughly 300 million metric tons of P were removed from croplands in the form of harvested crops. Some of this produce was fed to livestock and a portion of the manure from these animals was reapplied to croplands, returning some of the harvested P (about 50 million metric tons) to the soil. Thus the net addition of P to cropland soils over this period was about 400 million metric tonnes. This excess P has either remained in soils or exported to surface waters by erosion or leaching. The majority of applied P remains on croplands, with only 10 to 20% leaving by export to surface waters. It is likely, therefore, that about 400 million metric tons of P has accumulated in the world's croplands. The standing stock of P in the upper 10 centimetres of soil in the world's croplands is roughly 1 300 million metric tons. That means that a net addition of 400 million metric tonnes between 1950 and 2000 would have increased the P content of agricultural soils by about 30% (Carpenter et al, 1998; Schlesinger, 1997). Figure 2 illustrates that close to a quarter of the mined P (250 Mt) since 1950 has found its way into the aquatic environment (oceans and fresh water lakes) or buried in sanitary landfills (*sinks*).

Despite the fact that forecasting the expected life of existing P deposits is an inexact science and depends on many factors, global P reserves are regarded as finite, with present recoverable reserves calculated to last for less than 150 years (Steen, 1998; Barber, 1989). There might appear therefore that there is no supply crisis of P at present, but the main issues of concern besides being a limited resource are basically threefold:

1. The mobilisation of P from particulate (stable form) to soluble forms (unstable) and subsequent diversion, as it were, from the terrestrial into the aquatic environment;
2. Excessive fertilisation of croplands and manure production with the net result, in macroscopic terms, being a transfer of P from concentrated point (land) *sources* to dispersed (land) *sinks* (Beck et al, 1994);
3. The steadily increasing level of impurities in phosphate rock, notably cadmium, uranium, nickel, chromium, copper and zinc (Steen, 1998). These metals are a threat to human health because of their tendency to bio-accumulate in plants and other high forms of life.

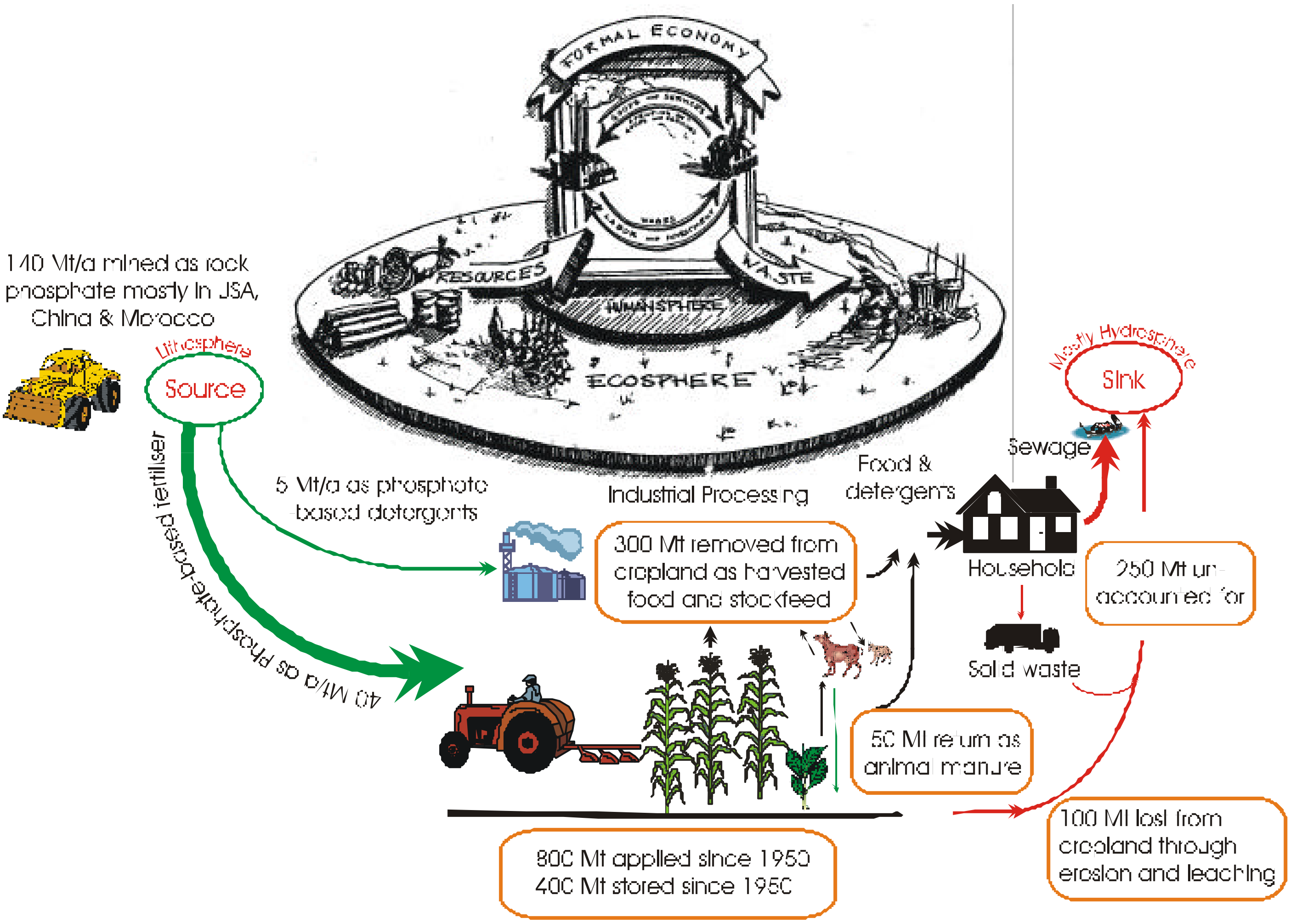

Figure 2 The source to sink of P with respect to the global economy and resource use since 1950 (Formal economy picture adapted from Wackernagel and Rees, 1998)

ANALYSIS AND DESCRIPTION OF STUDY AREA

An inventory of annual P-fluxes based on characterisation of input goods, processes, transformation, output fluxes and storage is presented for a high-density suburb in Harare, Zimbabwe where agriculture is already a major activity (Gumbo, 2000a). Using systems thinking approach and material flow accounting two compartments or subsystems are defined to enable accounting and analysis of P-bearing materials namely the “household” (consumption/use and excretion/waste) and “agriculture” (soil-plant interaction) (Figure 3).

Lake Chivero (Full Supply Capacity of 250 Mm^3) the main water supply source for Harare, whose basin contains the micro-study catchment described in this paper receives a pollution load of approximately 365 tonnes/a as P i.e. 1 tonne/day of which 40% is the contribution from point sewage discharges (Gumbo, 2000a; Nhapi et al, 2001). The remainder is from non-point sources emanating from flows within the catchment area extending over 1 150 $(km)^2$ which include urban storm runoff and runoff from commercial farming areas. This Lake Chivero case, downstream of the Harare metropolis is a demonstration that societies can no longer rely on sewage treatment plants, as kidneys and liver to separate and remove nutrients so that they do not enter the aquatic environment. At the same time it highlights the problems associated with the unidirectional flow of nutrients through a society.

In Harare like many major cities in Africa many urban dwellers grow their own vegetables and part of their cereal requirements within the confines of the city boundary (Mbiba, 1995; UNDP, 1995, ENDA, 1995). In Harare today more than 10 000 hectares of public space is under cultivation annually (36% of open space). The figure is considerably higher if on-plot cultivation is included. Due to high unemployment rate and economic difficulties in the recent years a significant number of households have resorted to both legal and illegal urban agriculture in order to improve the household food security (Matshalaga, 1997). Local recycling of nutrient derived from societal waste (metabolism) is therefore a possible and realistic option with multiple benefits i.e. social, economic and ecological.

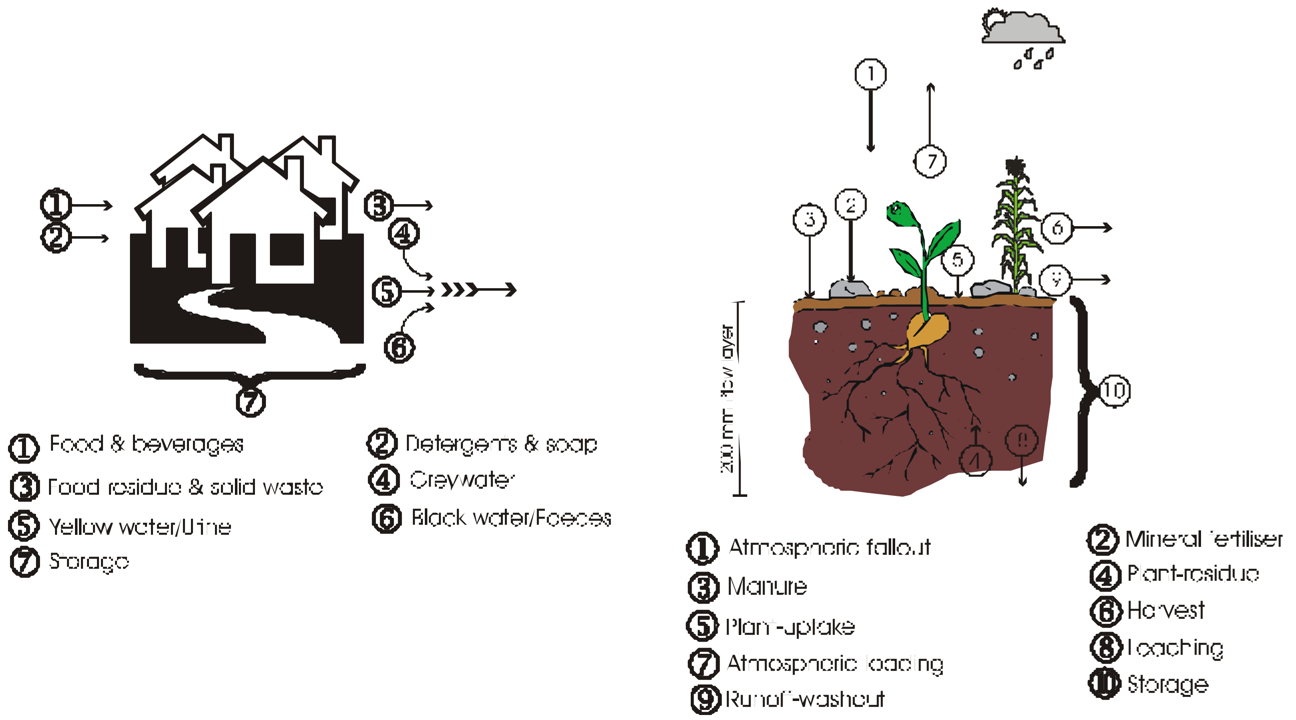

Figure 3 P-fluxes analysed in the household and agricultural subsystems

The micro study catchment falling within the Lake Chivero basin consists of Mufakose and Marimba Park suburbs, which lie within a distinct hydrological catchment area of 6.5 (km)^2. Mufakose and Marimba suburbs are situated in the western end of the city about 15 km from the city centre. The total population is about 100 000 (projected from 1992 census) which translates to a population density of about 7000 inhabitants/km^2. There are an estimated 9 400 residential stands including flats and about 100 non-residential stands. The average occupancy per stand is estimated to be 10.6 people. The age structure is as follows: 0-14 years, 43%; 15-64, 54% and 65 years and over, 3 %. Most of the residents in Mufakose are in the low-income band with an estimated income per household of about US $50 per month.

RESULTS

The household subsystem

P inflows into the "household" subsystem (mainly to do with the activities "to nourish and clean") amount to about 26 600 kg/a as food/beverages and 1 860 kg/a as detergents. Storage is taken as negligible by assuming that as soon as household P-bearing goods are purchased they are immediately consumed/used. The amount of P in food was established through mapping of weekly diet of the inhabitants based on a national nutrition survey and a local solid waste study (Table 1).

Table 1 Main components of the food flux: household subsystem

Food group	Kg/cap.a	P mg/100g	P g/a
Cereals	160	185	296
Meat and fish	17	155	26
Milk and eggs	16	93	15
Vegetables	88	85	75
Nuts	8	405	32
Starchy roots	7	46	3
Pulses	11	462	51

Beverages	11	13	1
Total	318	-	500

The most common food/beverage items consumed in considerably amounts and at least periodically were inventoried and the total P-content determined in the laboratory. Literature values were used to compliment and confirm laboratory results (Chitsiku, 1991; CSO, 1998; FAO, 1968; FAOSTAT, 2001). The most common food is sadza (thick mealie meal porridge with the consistency of mashed potatoes made from white maize meal) taken with a leafy vegetable called 'rape'. Mealie meal has a P-content of 2.0 g/kg whilst for the vegetable its 1.1 g/kg and it is estimated that a household (residential stand) consumes about 10 kg of mealie meal and 1.3 kg of leafy vegetables per week.

Using the P-content of the individual food and beverages the related P-influx per annum was calculated. From Table 1 it can be deducted that an average Zimbabwean urbanite consumes about 1.4 g/day as P. Similarly the type of soaps and detergents used were studied in a survey by observing weekly usage and chemical analysis of the most popular soaps was carried out. The quantities used per week multiplied by the average P-content of 1.5 g/kg in the soap and detergents produced the related P influx as soap/detergents.

Since the transport and transformation of P in a region is dependent on the water cycle, a water flux balance depicted in Figure 4 was also established for the study area (Gumbo, 2000c). The inputs being water supplied from the municipal mains (2.40 Mm^3/a) and rainfall (820 mm/a), and main outflux being evaporation (3.55 Mm^3/a), sewage (1.93 Mm^3/a) and storm water (1.62 Mm^3/a). Samples of sewage and storm water were collected for analysis and the average concentration of P as Ortho-P was 12.0 mg/l and 1.1 mg/l respectively. The average daily water consumption per stand for the past five years is 720 l/stand.day. The breakdown of water usage per stand was as follows: toilet flushing, 30%; bathing, 25%; laundry, 15%; kitchen, 10%; and garden, 20%.

Tests on fresh and stale urine indicate that the P-content varies between 0.3 to 0.5 g/cap.day whilst P-content of faeces was derived indirectly from wastewater characterisation and calculation. About 75% of P outflux is through sewage (combined black and greywater; 22 800 kg/a) and the remainder through the solid waste stream. P composition of sewage varies between 0.7 to 1.1 g/cap.day this includes the contribution by detergents and soaps. The solid waste generation rate and content varies significantly with the time of the year, from 0.2 kg/cap.day to about 0.5 kg/cap.day. Up to 65% of the waste is compostable organic material consisting of food scrap, agricultural residues and garden waste (Table 2). Using the average P-content of 1.3 g/kg, with suitable adjustment for the moisture content of waste, the solid waste flux accounts for about 4 800 kg/a as P. The annual P-flux for the household subsystem is shown in Figure 5.

Table 2 Solid waste characteristics as discarded

Solid waste	Composition (%)	Moisture Content (%)
Paper and cardboard	11	8
Organic and vegetable material	65	70
Plastics	8	2
Glass	5	2
Metals	3	1
Wood, leather and rubber	2	15
Textiles	4	10
Miscellaneous inert material	2	15

The agricultural subsystem

Urban agriculture extending over an area of about 3.5 $(km)^2$ (both on-plot and off-plot) accounts for the importation of about 4 410 kg/a of synthetic fertiliser as P (calculated from the average application rate of 10.5 kg/ha) (ENDA, 1995). A variety of crops are grown, but the major ones being maize, sweet potatoes and vegetables (rape, tomatoes and onions). The maize crop is used for calculations in this subsystem. The main outfluxes are runoff (1

750 kg/a) and the harvested portion of the crop (1 440 kg/a). The washout rates are estimated at about 4.5 kg/ha.a, which is high compared to commercial farming areas where the average rate is about 8 kg/ha.a considering that the latter apply five times as much fertiliser (FAO, 1986). This discrepancy is mainly due to poor soils with limited humic substances, which act as a soil conditioner for P retention, steep slopes and lack of conservation tillage knowledge, by the urban farmers. Average maize yield of 2 000 kg/ha.a was estimated, and this is comparably higher than the less than 1 000 kg/ha.a observed in communal areas of Zimbabwe (Grant, 1981; Bratton and Truscott, 1985).

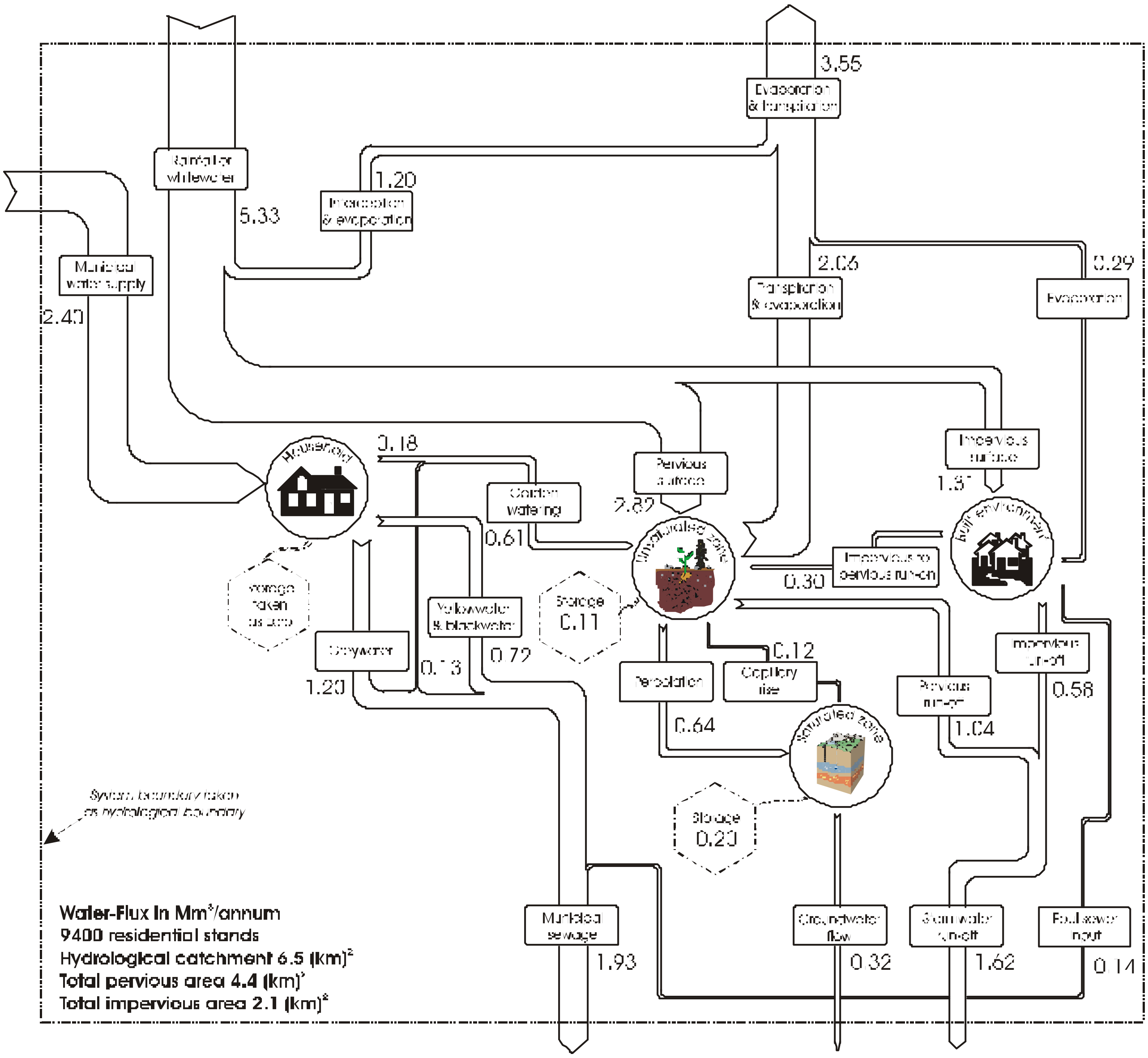

Figure 4 The annual water flux for the study area

A net storage of about 990 kg/a in the plow layer is realised. Soil fertility tests done after the harvesting period in year 2000 however, indicate a deficiency of available P in the plow layer for maize production (average value of 10 mg/kg was obtained using the resin extraction method). In Zimbabwe a soil is considered P deficient if the concentration is less than 30 mg/kg (Cooper and Fenner, 1981; Grant, 1981). This demonstrates that although there is a net accumulation of P in the soil, a large percentage is strongly absorbed in or precipitated by the soil and not immediately available to the crop (Table 3).

Table 3 Summary of soil fertility test results: agricultural subsystem

Parameter	Value	Desirable
pH	4.2	5.2-7.8
Total P mg/kg	230	-

Available P mg/kg	16	> 30
Potassium me/100g	0.25	> 0.3
Mineral nitrogen mg/kg	25	> 40
Organic carbon %	0.8	-

The optimum environment for phosphorus availability requires that the soil climate is just slightly acid to slightly alkaline. This requires the soil reaction to be between pH 6.3 to pH 7.0. The degree of aliveness of the soil also plays a major role in P availability. Maintaining or increasing the amount of active soil organic matter (humus) can best assist this function. For example, a land use system with a phosphorus-fixing soil, application of low dose of P-fertiliser may not result in a measurable yield increase at all because P added is quickly immobilised. Application of a higher dose is needed to saturate the immediate P fixing capacity of the soil and bring about the desired increase in production.

Soil deficiencies are a major constraint on African agriculture. Soil in the savanna are extremely weathered, the chemical status is poor due to deficiencies in phosphate and organic nitrogen, and the amounts of phosphorus and sulphur mineralised annually are often below requirements of high crop yields. At the same time highly acidic and weathered soils have high capacities for phosphorus fixation (Fernandes, 1989; Smaling, 1993; Rockstrom, 1997).

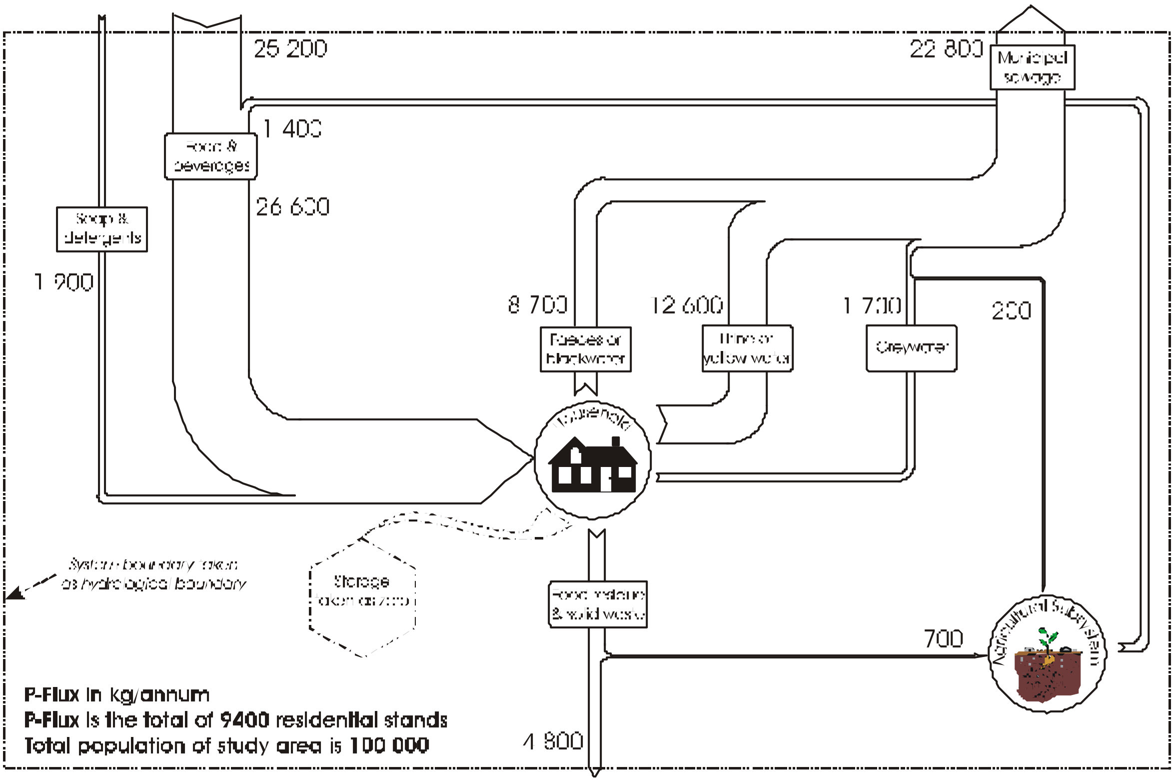

Figure 5 The annual P-flux for the household subsystem

In Zimbabwe the recommended mineral fertiliser application rate as P for commercial maize production is about 42 kg/ha. This is commonly administered as compound D fertiliser also called "maizefert" (8:14:7;N:P_2O_5:K_2O) which at current prices costs about US$0.50 per kg. The majority of the urban agriculturists in the micro-study area apply "maizefert" as basal fertliser once a year or season at application rates of about 20% (10 kg/ha as "maizefert") the recommended commercial farming value (ENDA, 1995). Ammonium nitrate is applied as "top-dressing" usually twice because of its susceptibility to leaching and washout. The annual P-flux of the agricultural subsystem is shown on Figure 6.

ECOLOGISING WASTE

The P stemming from human metabolism contained mainly in urine is of particular interest (Johansson et al, 2000; Larsen and Gujer, 1996; Jonsson et al, 1998). A total diversion of P in sewage (22 800 kg/a) onto the land under agriculture translates to an application rate of about 65 kg/ha.a. If urine is diverted and stored properly, an equivalent of 36 kg/ha.a can be achieved. In both cases fertilisation rates attained are comparable to the recommended commercial farming rates in Zimbabwe (42 kg/ha.a). Partial diversion of the waste flux from the "household subsystem" in the form of urine can sustain activities in the "agricultural subsystem" in terms of P thereby enabling the closing of the P-cycle in this human settlement through ecological agriculture. Also the staggering 660 tonnes/a as dry mass of the organic component of solid waste generated can be composted or co-composted with faeces to produce the much needed soil conditioner as humus (Obeng and Wright, 1987).

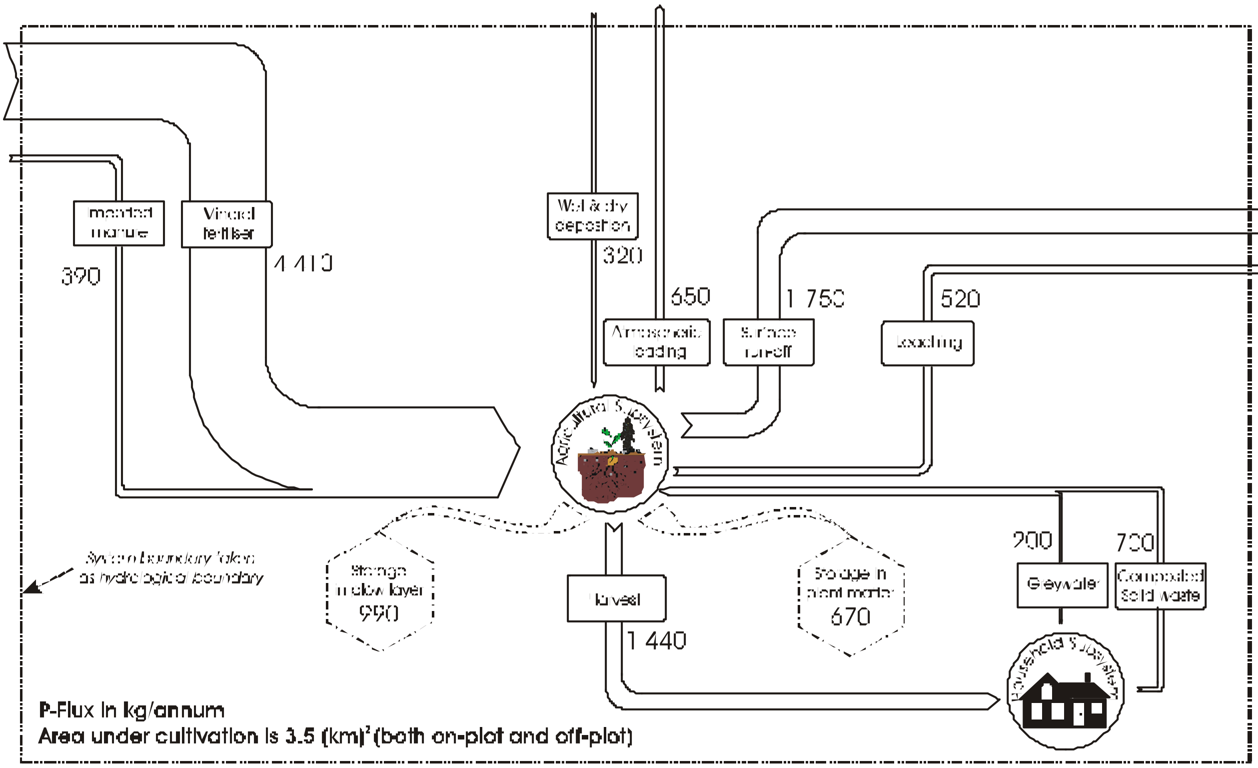

Figure 6 The annual P-flux for the agricultural subsystem

There are different possibilities to design sanitation systems, in accordance to 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, 2001; Morgan, 2000; Jenkins, 2000, Del Porto and Steinfeld, 2000). The focus on urine is because it contains the bulk of the plant nutrients in human excreta, 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 sterile usually and less objectionable to handle. Ways of recovering the resources in urine, which include – diversion, separation, absorption and combined processing with faeces – are currently under intensive investigation. The plant availability of the nutrients Nitrogen (N), Phosphorus (P) and Potassium (K) in source separated urine is high (Kirchmann and Pettersson, 1995, Lentner, 1981) and the concentrations of different heavy metals are low (Jonsson et al., 1997). Furthermore, after being stored for six month the hygienic quality of the source separated urine improves considerably (Hoglund et al., 1998; Hoglund, 2001).

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 re-direct 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 if low-cost and reliable waste recovery technologies and approaches can be demonstrated and proven feasible (Rose, 1999; Chan, 1996; Gardner, 1998, Smit and Nasr, 1992).

CONCLUSIONS

This paper illustrates the advantages of approaching the environmental sanitation concept from a systems analysis and material accounting angle. By creating such mass balances of macro-nutrients N, P and K, it becomes more convincing especially to urban planners and other technocrats to integrate activities which assimilate "waste" like urban agriculture within the urbanshed. The flux diagrams presented are essential for scenario building and as a means of comparing alternative ecological options. The ideal scenario would be to reduce the influx (resource import) and minimise the outflux (resource or "waste" export) shown in Figure 4, 5 and 6 through increased local recycling and reuse. Conceptually, ecologising societal metabolism and local recycling of P is feasible. However, a number of barriers need to be surmounted and these are mostly related to negative perceptions about city planning and design, public health, social acceptance and technological constraints.

ACKNOWLEDGEMENTS

This research is kindly funded by the Netherlands government and guided by Prof. H.H.G. Savenije and Dr. P. Kelderman at IHE-Delft.

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