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Hampered effluent accumulation process: Phosphorus management and societal structure

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Abstract

The changed type of phosphorus flux from pre-industrial to modern urbanized society is described. It is concluded that the urban phosphorus pollution problems cannot be solved at the point of effluence. End-of-pipe measures for phosphorus abatement lead to *h*ampered *e*ffluent *a*ccumulation *p*rocesses (HEAP) traps, where the former point source pollution is ultimately converted into non-point source pollution. It is also emphasized that this effect is not caused because of inefficiencies in the technical method for phosphorus extraction from the waste water, but by the disproportion between the areas of food production and sludge disposal. Preliminary studies indicate that the phosphorus accumulation ratio is in the range of 1:50–1:100 in the urban-suburban areas, including the agriculture where the sludge is deposited. This tendency is observed in several case studies where the sludge often is placed on an area less than 1/10 of the urban area. This implies a total deposition area of about 50,000 ha in Sweden and an average deposit in this area of about 210 kg phosphorus/ha * year. Since HEAP traps do not occur in self-organized ecological systems, societal structures, which are founded on observations of ecological structures, avoiding HEAP traps are proposed.

Keywords: Eutrophication; HEAP growth; Non-point source pollution; Phosphorus; Sludge; Societal structure; Steady state; Urbanization

1. Introduction

The demographic changes in society during industrialization have transformed the phosphorus management system from a circulating one to a mainly linear one (Günther, 1988; Günther, 1993; Günther, 1994b). An important effect of such linear flows is that elements which do not have gaseous phases in their normal cycles, e.g., phosphorus, tend to be lost from terrestrial systems to lakes and seas (see, for example, Vollenwieder and Kerekes, 1982). This is serious since the amount of phosphorus ore is in limited supply (Smil, 1990). Phosphorus is an important element in both animal and plant physiology. It is probably the element that is easiest to become limiting to living organisms. It is needed in fairly

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large amounts, in vertebrates as a structural material and in all organisms as a vital element in the genetic material and in the intracellular energy transport system. It is also considered an important pollutant in coastal and inland waters (Larsson et al., 1985).

In the modern urbanized society, a very large part of the population lives in a comparatively small part of the land. In Sweden, a sparsely populated country with a population of about 8.6 million, 7.1 million, 83%, live in densely populated areas, occupying about 1.2% of the land area (SCB, 1993). Therefore, the food is transported from a large area to a small area. This leads to a concentration of nutrients in the most populated areas. With modern communication, the food comes from almost the entire planet. This constitutes a linear transportation of phosphorus from mines via agriculture to cities, and from cities to deposition areas or directly into seas or lakes. The nutrients management is largely industrialized, from mining and manufacturing to agriculture, transport and trade, and therefore, the total chain is neither comprehensible nor in the hands of any specific person. Advanced wastewater treatment with phosphorus precipitation stops a large part of the phosphorus from being exported directly to nearby water systems (Balmér and Hultman, 1988; SCB, 1993). It has, however, been shown that efforts to hamper the point source effluents from the urban area will increase the accumulation of phosphorus in the total area where the element is deposited, i.e., in refuse dumps, suburban agriculture, golf links or other sub-urban storage (Forsberg and Rengefors, 1992).

1.1. Equifinal growth

The urban and suburban area are open systems, that is, energy and material can pass over their borders. Open systems have some features in common. One of these is *equifinality* (von Bertalanffy, 1968), that is, several initial states lead to the same end state. In the case of phosphorus transport to urban areas, this leads to unambiguous results.

Efforts to hamper point source leakage leads to a build up of non-volatile elements, phosphorus in the case of this study, but also of metals such as chromium (Anderberg et al., 1989) if there is a constant import into the area.

In areas with high concentrations of an element, there is a higher risk of leakage than in an area of low concentration, if not by other reasons, at least because of principles of diffusion chemistry. When the concentration increases, the probability of leakage will therefore also increase. With constant import into the area, the concentration with its corresponding leakage will rise to the point where export equals import (von Bertalanffy, 1968; Odum, 1983; Günther, 1988). This is the equifinal state pointed out by von Bertalanffy. It is attained regardless of the initial amount of phosphorus in the area. For the mathematics of this effect, see Appendix A.

Linear flows of non-volatile substances, hampered at the end-of-pipe by the wastewater treatment with phosphorus precipitation, will induce a 'leaking storage' of this equifinal type. For simplicity, I refer to this as a HEAP (*h*ampered *e*ffluent *a*ccumulation *p*rocess) growth (Fig. 4).

1.2. The history of the resource

Guano, semi-fossil excrement of seabirds accumulated on islands outside the coast of Peru, was the source of phosphorus that was used to substitute the deficits of nutrients that evolved in the agriculture supporting the population participating in the Industrial Revolution during the 19th century. These resources were exhausted in about 35 years (Gootenberg, 1993). Today, the source is mainly rock phosphorus. As with guano, these resources are also limited. The estimates differ regarding the supply of phosphate ores worth working (Table 1). The esti-

Table 1
Different estimates of the duration of the phosphorus resource

Author	Estimated resource (Tg)	Extraction rate (Tg/year)	Calculated duration (year)
Pierrou (1976), high estimate	9,000	12.6	714
Pierrou (1976), low estimate	3,140	12.6	249
Smil (1990)	2,600	20	130
Mew (1994)		21.6–16.5	120–154

[a] Calculated from the resource estimate of Smil (1990).

mates are however made on different times, and a normalization shows that they do not differ more than about 11%.

Mew (1994) points out that there has been a decline in world phosphate trade during the years 1990–1993. With the extraction rates of Mew (op. cit.) and the storage estimates of Smil (1990), the duration of the resource can be calculated to be between 120 and 154 years.

The resources used on any special occasion are naturally those most easily available, needing the least amount of energy to extract. Those left need more energy to extract, being less concentrated or deeper buried. This is a problem if energy tends to be more expensive to use (Cleveland, 1991).

The aim of this paper is to point out fallacies in the current type of phosphorus management which lead to a resource depletion in one end and to an ultimate pollution in the other end of the line. To be able to do so, I have studied the phosphorus flux in Sweden. I will start with a review of phosphorus abatement in urban areas of Sweden. In the following section, I discuss transports of phosphorus in six case studies and one estimated phosphorus budget of Sweden. The results are discussed in relation to the areas of primary use and deposition. At the end of the paper, suggestions are made for methods of redirecting the flows of phosphorus from linear to cyclical, in what I term ecomimetic structures.

1.3. Nutrient abatement in Sweden

With the linearization of the phosphorus fluxes, the endpoint nutrient accumulation became a pollution problem. This was early realized in Sweden (Selander, 1955), and different strategies were chosen to alleviate the problem. Below follows an outline of the different methods, common for many industrialized nations.

The water transportation systems for human faeces and urine became common in Sweden in the first half of the 20th century. By its high content of nutrients, the sewage wastewater caused eutrophication and was considered a pollutant. The solution to control this pollution was dilution. In the case of eutrophication of lakes in the urban areas, the dilution was achieved by building more far-reaching pipe systems. This, however, only converted the collected wastewater to new point source pollution, often with far-reaching consequences (Selander, op. cit.). After the widespread realization of this drawback, this method was abandoned in the early seventies.

1.3.1. Advanced wastewater treatment with phosphorus precipitation

A large rebuilding of the sewage plants was started after 1968 (Ulmgren, 1973) to eliminate effluents of phosphorus from sewage plants after the phosphorus was found hazardous to surface water quality (e.g., Rodhe, 1958). The method introduced was the 'third step', after the mechanical and biological purification of the sewage water.

The 'third step' is the precipitation of phosphorus as salts of calcium, iron or aluminium together with other insoluble substances in the sewage water. The resulting phosphorus reduction averages to more than 90%. The costs for the introduction of advanced wastewater treatment with phosphorus precipitation in Sweden was calculated to be around $25 * 10^9$ SEK (UN, 1987). However, since the goal for the process was set to eliminate phosphorus and biological oxygen demand (BOD) from the wastewater before it is released into the recipients, the future fate of the elements in the resulting sludge was not incorporated in the description of the problem, and therefore not solved by the process. The phosphorus was not let out into the waters, but moved to another place in the urban or suburban area.

1.3.2. The sludge disposal problem

After the introduction of the 'third step', the sludge problem became acute. Methods to get rid of it was to be found. Several methods were employed.

1.3.2.1. Landfills and waste deposits. In Sweden, 1990, 75% of the sludge is deposited on refuse dumps (SCB, 1993). The storage solution is preferably chosen when the sludge is contaminated by industrial effluents, as in the Tranås case (see below), where municipal sewage water is heavily contaminated by chromium. In the city of Gothenburg, the 'ultimate' storage is chosen, in artificial caves earlier used for storage of oil (Nilson, 1990). The use of sludge and ashes from waste incineration as filling-up in road-building is also proposed by some municipalities (Günther, 1991).

1.3.2.2. Deposition on agricultural land. Next to deposit on refuse dumps, deposit of the sludge on suburban agriculture is a common solution to the sludge problem, together with the use of sludge as planting compost. The sewage sludge was in the 1970s and 1980s largely used as manure in the agriculture surrounding the urban area. However, as it was realized that the sewage sludge contained not only P, but also heavy metals and organic pollutants of several types, the use of it as manure was boycotted by the LRF, the farmers organization in Sweden.

For some time, there was a problem of how to get rid of the sludge, and it was stored in unconventional places while the municipalities searched for new solutions to the problem. After that, increasing amounts of sewage sludge was put on refuse dumps. In the beginning of the 1990s, however, it is reported from Stockholm that there is no problem to find farmers ready to take sewage sludge (Brattberg, personal communication).

There are regulations restricting the use of sewage sludge on farmland to a maximum amount of 5,000 kg dry substance per hectare per five years, that is 150 kg P/ha (SNV, 1990). With an average content of 3% phosphorus in the dry weight, this means an average deposit of 30 kg P/ha*year. This deposition is about double the annual phosphorus fertilization recommended for wheat and potatoes by the Swedish authorities (15 kg) (Jordbruksverket, 1992) on a medium class soil, and more than double the average phosphorus fertilization on Swedish soils (12 kg) (Granstedt and Westberg, 1993). The applications on agricultural land in the Stockholm area was however found to be as much as 166 kg P/ha every fifth year (Forsberg and Rengefors, 1992).

1.3.2.3. Other solutions. One new solution to the problem is the deposit of sludge on golf links. Since many golf links were constructed in the vicinity of the cities during the late 1980s, this was a good opportunity to get rid of the sludge in times of restrictions from the farmer organisation (LRF). In 1992, however, half of the sludge from Malmö, the third largest city in Sweden, was reported to be placed on golf links, the remainder on farmland within 50 km from Malmö (Lundberg, personal communication). Problems associated with deposition on golf links are the possible future transformation of them to land for food production, and the large areas combined with heavy loads making them prone to leakage.

Sewage sludge is also proposed to be used as nutrient for cultivation of energy forests (Hasselgren, 1988).

None of the used or proposed solutions takes the disproportion between food production area and sludge deposit area into account. All the locations chosen for the disposal of the sludge are in the vicinity of the cities, the closer the cheaper. The farthest transportation range from Stockholm with a population close to one million is about 120 km, although the distance generally is shorter (Günther, 1994a). The food imported to the urban areas comes from a much wider range. In a study by Forsberg and Rengefors (1992) the calculated area for production was about 165 times larger than the deposition area. Thus, there is a *general tendency to concentrate nutrients in the urban and suburban areas.*

2. Estimating phosphorus flows in Sweden

Although phosphorus is easily analyzed and of great importance in a wide range of investigations, the knowledge of the amounts imported to, stored in and exported from different compartments of the societal system are unclear. One reason to this is that with few exceptions (Forsberg and Rengefors, 1992; Granstedt and Westberg, 1993; Petterson, 1992; Folkesdotter and Nilsson, 1992), most investigations focus on small parts of the system, and on detailed information rather than overall information of storage and flows.

To evaluate the general type of phosphorus transport in Sweden, I have collected the results from different investigations. These were found in reports (Sections 2.1 and 2.5), scientific papers (Sections 2.2, 2.6 and 2.7), planning papers from municipalities (Sections 2.3 and 2.4) or general statistics (7). Figures lacking in the different investigations were

Table 2
Data for phosphorus flux in some Swedish areas

Case study	Population	Food production area (ha)	From agriculture (kg P/ha)	Turnover (kg P/year)	Known leakage (kg P/year)	Deposited (kg P/year)	Deposition area (ha)	Deposition (kg/ha)	Concentration (area agr./ area dep.)	Concentration (kg agr./ kg dep.)
1. Stockholm	920,000	184,000	5.4	997,600	70,720	926,880	1,114	832	165	153
2. Lake Ringsjön watershed	9,000	7,000	12.7	244,000	8,100	146,900	7,000	21	1	1.7
2. People receiving food from (2)	127,142 [a]	7,000	12.7	89,000	7,120	81,880	104	8.9 [b]	9	8
3. Tranås	16,000	3,200	5.3	17,100	1,129	15,971	13	1,229	538	230
4. Nybro	14,500	2,900	4.6	13,300	300	13,000	26	500	111	109
5. Gävle	88,000	17,600	15.1	266,000	113,000	153,000	18	8,500	977	562
6. Swedish cities (est.)	7,258,400	4,145,000	4	10,756,000	572,000	10,184,000	48,400	210	86	53

[a] The annual turnover of phosphorus in one person is 0.7 kg. The annual turnover of 89,000 kg is divided with this figure to estimate the population.
[b] This figure is calculated from the Swedish average, 0.0067 ha/person.

completed by appropriate figures from other investigations to complete the information. Such amendments are specified in the discussions of the individual cases. A summary of the observations is given in Table 2.

2.1. *A phosphorus budget of Stockholm*

Forsberg and Rengefors (1992) studied the budget of phosphorus in the city of Stockholm, Sweden. An analysis of the study (Günther, 1994a; Günther, 1994b; Günther, 1994c) shows that the phosphorus imported to the urban area is deposited on a land area of about 1/165 of the calculated area for food production. This includes a heavy deposit on refuse dumps and a high farmland deposit, 832 kg/year average, deposited once per 5 years. In the current situation, 744 ton (82%) of the phosphorus entering the urban area is deposited on landfills with an area of 5 ha (148,800 kg/ha), and 183 ton are transported to 1,100 hectares of agriculture situated at the furthest 125 km from the city (Table 2).

The theoretical maximum circulation, that is, if all the areas used for phosphorus disposal also were used to produce food for the Stockholm population, is about 0.6%, and the concentration of phosphorus is 55 times higher than on a food producing agricultural area (Günther, op. cit.). The amount redistributed to agricultural areas is limited by economy, not by the available land (Öster, personal communication).

2.2. *Phosphorus flux in the Ringsjö area of southern Sweden*

In a study in the Ringsjö area in Skåne, southern Sweden, (Forsberg and Wallsten, 1986) the authors studied the flow of phosphorus in a watershed entering lake Ringsjön in the early 1980s. In the study, the authors remark that the circulation of phosphorus

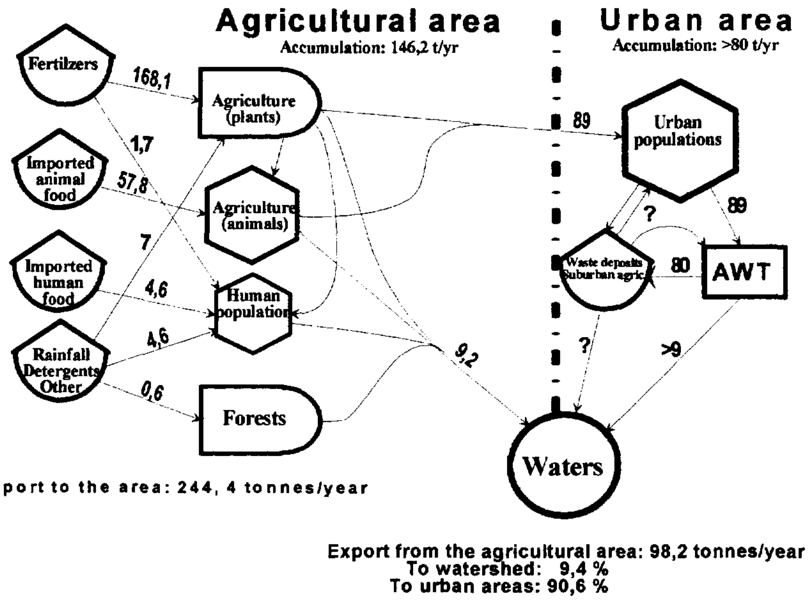

Fig. 1. In the Ringsjö area of southern Sweden, about 4% of the phosphorus imported to the agricultural area leaks out from this area. However, about 36% of the phosphorus is exported to urban areas. In these areas, there is about the same leakage (9 ton/year) from a normally functioning wastewater plant. The rest is accumulated in or subjected to diffuse leakage from the urban area. Also in the agricultural areas, there is a build-up of phosphorus of about 150 ton/year, which also may lead to future diffuse leakage. Figures in ton/year. (Modified after Forsberg and Wallsten, 1986.)

in the area represents a non-closed circuit because of the large leakage from the area to the nearby lake. However, the amount of phosphorus contained in the food from the agricultural area to urban areas is nearly an order of magnitude larger. This flow of phosphorus passes the inhabitants and is to a large extent impeded in the wastewater treatment plant and accumulated in refuse dumps or suburban agriculture. Thus, the amount of phosphorus that *bypasses* the wastewater treatment plant under normal conditions is of the same order of magnitude as the leakage from the agricultural area (Fig. 1 and Table 2). The leakage from the deposition areas adds to this estimate, but is not accounted for here.

In both the agricultural area and the urban area, there are accumulations. Of the phosphorus that is imported into the area, 60% is accumulated in the food production area, 36.5% is exported to urban areas, and 90% of this is accumulated in the deposition area. Of the total import to the Ringsjö area, 18 ton (9.2 + 9 ton) are *known* to leak from the total area of production and consumption. To this adds the leakage from sludge deposition areas.

2.3. A case study from Tranås in southern Sweden

Very few municipalities in Sweden investigate the phosphorus flows of their areas. However, in the ambitious survey of the general planning of Tranås, it is possible to calculate some of the flows of phosphorus from the estimations in the plan (Günther, 1991).

Also here, there is a general pattern of concentration in the central areas of the municipality (Fig. 2 and Table 2). Sewage water is handled in several places in local communities, but the resulting sludge is placed on a central refuse dump together with waste from households and local industries. The rest, at present about 1,100 kg phosphorus per year, follows the water to the lake system. The surface drainage water from the refuse dump is collected and transported to the wastewater treatment plant of

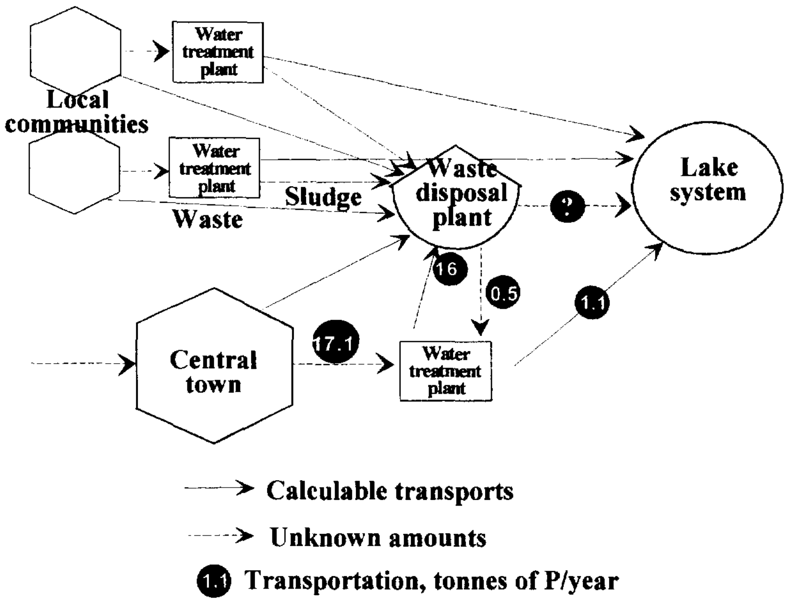

Fig. 2. The phosphorus transportation situation in Tranås, Sweden. Sludge and waste from the entire municipality are collected on a central waste disposal plant. The increasing amount of phosphorus in the seepage is circulated through the water treatment plant, leaking about 10% for each circulation.

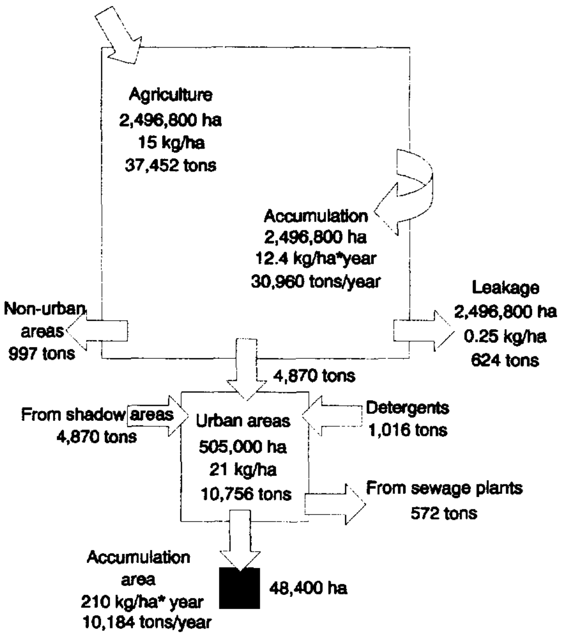

Fig. 3. An estimate of the phosphorus fluxes of Sweden.

Tranås. In 1995, this water contained 480 kg phosphorus. Ninety percent or more of the phosphorus in this seepage water is precipitated and transported back to the refuse dump, where an increasing amount of phosphorus is stored. Every time the phosphorus in the seepage passes the wastewater treatment plant, however, about 10% of it passes on to lakes and seas.

2.4. Nybro municipality

In an environmental survey of the Nybro municipality, population 14,500, south-east Sweden, the pattern appears to be very similar to that of Stockholm. A calculated amount of 36 ton of phosphorus is used as fertilizer on 45 km^2 of agricultural land. From this area 11 ton is imported to the Nybro municipality as food. After consumption this is mixed with other wastewater containing 2.3 ton of phosphorus, mainly from detergents. After purification, 13 ton is deposited on local agriculture (20%) and on local refuse dumps (80%) (Björn et al., 1994). The deposition area is 123 times smaller than the production area (Table 2).

2.5. Gävle

In a study of the Gävle municipality (Folkesdotter and Nilsson, 1992), 200 km north of Stockholm,

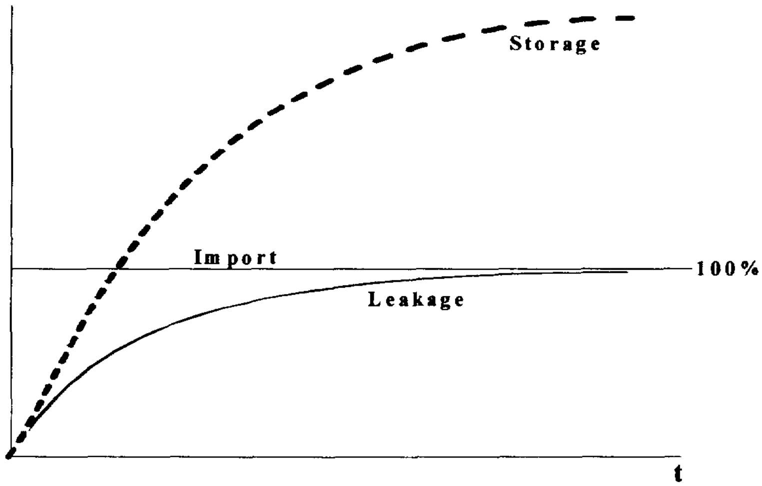

Fig. 4. Hampering the effluents will increase storage, not change the final state. The final state is independent of the initial state. It depends only on the import into the system. This is the HEAP growth pattern, where the increasing leakage successively approaches the input into the system.

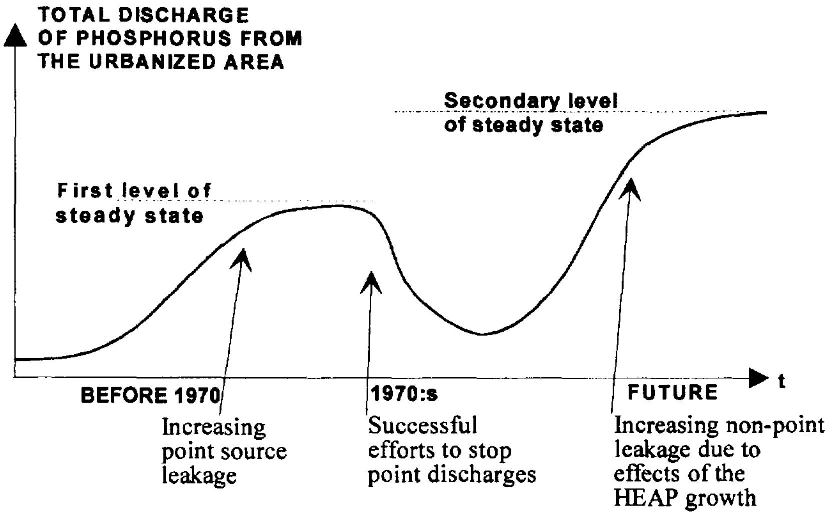

Fig. 5. A diminished pollution could be expected after the introduction of advanced wastewater treatment with phosphorus precipitation in urban areas. However, since import is not diminished, the diffuse export could be expected to increase until a new steady state is attained.

there was a total phosphorus import to the municipality of at least 266 ton per year (the import in the rivers *uncounted*). The export during the same time was 113 ton, but in this figure the export by the rivers is *counted*. This indicates an accumulation of phosphorus in the municipality of *at least* 153 ton of phosphorus per year, or about 1.7 kg per inhabitant.

The authors have made a calculation of the differences between the food production areas for the urban population and the deposition area of the phosphorus in the sludge. This area is about 1/980 of the food production area, and the annual deposition is about 8,500 kg phosphorus per hectare (Figs. 3 and 4).

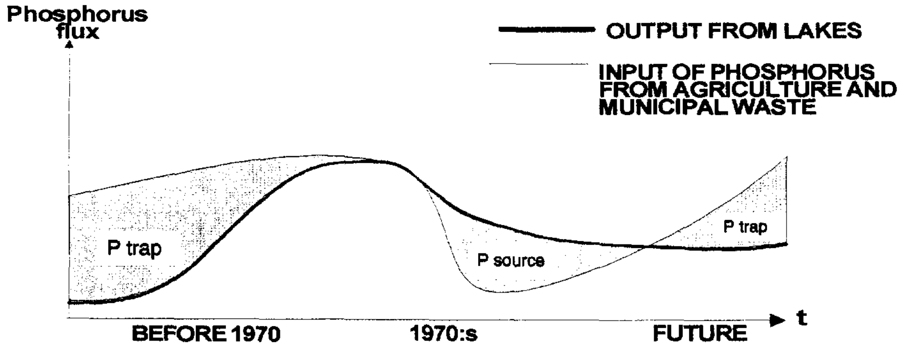

Fig. 6. The changing function of a lake in the vicinity of a terrestrial area with HEAP growth. When the amount of phosphorus in terrestrial areas is increasing or is in steady state, the lake functions as a phosphorus trap. This function is successively exhausted as the amount of phosphorus stored in the lake increases. When the input from terrestrial areas diminishes, the lake changes its function from a phosphorus trap to a phosphorus source. Ultimately, when terrestrial export increases because of HEAP saturation, however, the role of the lake could temporarily be expected to change to a phosphorus trap again. Fat line: discharge from lake; thin line: discharge from land.

2.6. Lake Roxen, an example of an intermediary lake

Lakes are often considered to be *sinks* for phosphorus. However, where the stored amounts are very large, as in eutrophicated lakes, and the import diminishes, as when point source pollution flows are diminished by advanced sewage treatment, the export from the lake could be expected to exceed the imports. The relative storage function of the eutrophicated lake will then change from a phosphorus sink in the earlier stages, to a phosphorus *source*. This is what is observed in a study of the lake Roxen, Östergötland, Sweden (Göransson et al., 1991). During a 9-year study, the lake was annually losing $132 \pm 8\%$ of the input. The behavior of the lake phosphorus pool counteracts the effect of the waste water treatment. Eventually, the lake may change into a phosphorus sink or a steady state pool again, after the suburban land has been saturated with continued input (Fig. 5), and a HEAP steady state is attained. In Fig. 6, this interaction between two dynamic pools is outlined.

2.7. Calculations of the Swedish fluxes of phosphorus from agriculture to urban areas

The Swedish total agricultural area is about 2.5 million hectares. Granstedt and Westberg (1993) estimate the export of phosphorus from agriculture to the Swedish population to about 1 kg/capita. An additional kg enters with import from foreign countries. The urban population is 83% of the total Swedish population (SCB, 1993). This is why its support area is assumed to be 83% of the agricultural area, 2,072,344 ha. From this area originates about 4,300 ton per year, or about half the phosphorus import in food to urban areas. Food of foreign origin is assumed to represent the same area of agricultural land. Thus, the urban area in Sweden (SCB, 1993) is dependent on a support area of about 4 million hectares of agricultural land for its food, about eight times larger (Table 2). Following the tendency observed in the studies described in Sections 2.1, 2.4 and 2.5, that the sludge often is placed on an area smaller than 1/10 of the urban area, this implies a deposition area of about 50,000 ha. The area concentration factor can then be calculated to 1:86, and the mean deposit in this area is about 210 kg/ha∗year (Fig. 3). If restrictions for phosphorus disposal on agricultural land are to be followed, more than 93% of this amount must be disposed of on landfills.

3. Discussion

As was shown in the above cases in Sections 2.1, 2.2, 2.3, 2.4 and 2.5 and Section 2.7, the constant import of food into the urbanized areas combined with efforts to hamper the point source leakage leads to a build-up of non-volatile elements. A conclusion from the cases studied is that in parts of Sweden there are imports of phosphorus that are much larger than the exports from these areas. Such accumulation areas were the refuse dumps and the agricultural areas in the vicinity of the cities where the sludge from the wastewater treatment plants was placed. Areas of this type are often chosen as close as possible to the wastewater treatment plants because of the transportation costs. Most of the sludge (over 93%) was placed on refuse dumps in the Stockholm study. In Tranås, all the sludge was placed on a central refuse dump because of pollution from chromium, even sludge that was not originated from the central municipality.

3.1. Urban areas

In urbanized areas in Sweden, it is possible that a first steady state was achieved already in the 1960s, leading to polluted lakes in the surrounding areas. With the introduction of advanced wastewater treatment with phosphorus precipitation, the storage capacity of the area increases and pollution is diminished. However, the storage of phosphorus imported in food increases, thereby increasing the risk for diffuse flows from the area. A possible scenario would be a state when the storage has increased to the extent that diffuse flow export plus point source exports equals the import to the area. The total export from urban areas could then be expected to follow the form outlined in Fig. 5. The first increase of point source output was effectively checked with the introduction of advanced wastewater treatment with phosphorus precipitation in most Swedish municipalities. This is reflected in the curve by a decreasing export from urban areas. As the import of phosphorus to the area is not diminished, increased storage and diffuse fluxes from terrestrial areas could be expected. The storage dependent leakage increases until export equals import, indicated by the rising curve. When a new steady state is attained, the storage becomes constant.

In urban areas, several subsystems of possible HEAP growth can be identified. Of these, the refuse dumps are probably the most important. From them, the most important export routes are the phosphorus dissolved in surface water and in water percolating into the ground water under the refuse dumps. Surface water from the refuse dump is regularly collected and transported to wastewater plants for cleaning before release. In a coupled refuse dump-sewage plant system of this type, as seen in the Tranås study, 90% of the phosphorus is retained and put back to the wastewater plant for every round. Conversely, of the phosphorus put into this system, a tenth will escape for every round. After ten rounds, less than half of the phosphorus is left. The amount of phosphorus in the refuse dump will increase during the process, so the amount coming back to the sewage plant will increase until a local HEAP is attained.

Another important subsystem of possible steady state storage in the urban area is the suburban agriculture, golf links and park soil, where a large amount of phosphorus from sludge is deposited. The dynamics of the leakage from such subsystems is to a large extent unknown. It is known, however, that cutting of fertilized lawns induces phosphorus leakage by drainage water (Sandberg, personal communication).

3.2. Agriculture

In agriculture, there is a large storage capacity for phosphorus in the soil. With yearly applications of phosphorus fertilizers exceeding the export with products, the storage capacity is exhausted, which is experienced as increased efficiency of fertilization. A change in Swedish agricultural fertilizing practices to replacement fertilizing has therefore recently been introduced. In the recommendations for fertilizer use from the Swedish agricultural authorities (Statens Jordbruksverk, 1992, p. 35), the recommendations have changed from storage fertilizing to replacement fertilizing in the higher classes of soil phosphorus content. Implicit is the notion that soils, due to saturation in the higher phosphorus classes no longer store a part of the phosphorus fertilizer applied. Thus phosphorus fertilizing is recommended to be restricted to the amount taken away with the product. This indicates that a steady state is already achieved in the Swedish agricultural soils where this policy is practiced.

Another example of the HEAP effect can be found in the local pollution by dense agricultural units. Today a large part of the pig meat production in Sweden is situated in south Sweden, in the drainage basins of the Laholm and Hanö bays, while the feed for those pigs is to a large extent grown in the surroundings of lake Mälaren, 600 km north, or imported as fish or soymeal protein. To grow a pig from piglet to a 100 kg pig requires food containing about 1.6 kg phosphorus. The pig itself, at time for slaughter, contains about 0,5 kg phosphorus (Simonsson, 1990). Regardless of the ambitions to spread the pig manure over large areas and if all pig carcasses leave the area, about 70% of the phosphorus in the pig feed is converted into pig manure, and will therefore, due to the net import of pig-feed in the area, induce a local HEAP-effect which already has caused leakage and environmental problems, both regarding phosphorus and nitrogen.

4. Biological systems and HEAP

In biological systems, both on the organism and the ecosystem level, steady state accumulation of nutrients are very rare. Where phosphorus or other nutrients are restraining the biological activity, such accumulation does not occur. Instead, the nutrient handling by the system tends to direct itself into circular flows. Such self-organizing circular flows of essential elements, *regenerative cycles*, (Günther, 1992; Günther, 1994b; Günther, 1994c) are prevalent in living systems, since systems organizing according to those principles appear to be the only type providing possibilities for the prolonged functioning of a biological system. The capacity of recycling essential elements increases parallel with the capacity of consuming exergy, a corollary of the laws of thermodynamics as pointed out by Schneider and Kay (1994).

In a regenerative cycle of an ecosystem, one can discern three essential functional components, the *reconstructors*, the *consumers* and the *recyclers*. The reconstructors (green plants) take up essential nutrients provided by the recyclers (mostly microorganisms and fungi). When taken up by the 'reconstructors', the nutrients have a low exergy content (mostly as inorganic ions), and are 'loaded' with exergy from solar radiation and thereby converted to compounds with higher exergy content (e.g., DNA, ATP, proteins, carbohydrates). The consumers, which can be green plants in dark conditions, or animals feeding on plants, use the exergy content of the 'loaded' molecules for their life processes. The exergy in the end products, as urine, faeces, or dead plants or animals, is used up by the recyclers, at the same time as they make the nutrient available for a renewed loading with exergy. Recycling nutrients is a necessary requirement of the thermodynamically based principle for the self-organizing of a living system (Schneider and Kay, 1994; Günther, 1994c).

If the system has a mode of operation that makes nutrients unavailable for reloading, the life processes will be retarded or terminated, thereby giving way for systems that have the potentiality for regenerative cycling. This is also true for human settlements in a long-term situation.

5. Societal structures and HEAP

It is possible to mimic the regenerative cycling of ecosystems in societal planning in order to avoid the HEAP trap. One prerequisite for such a system is that it has the functions of a balanced regenerative cycle, that is reconstructors, consumers and recyclers that cooperate in close connection to each other. The need for import of nutrients and other essential elements is minimized if a thorough cycling is established in that way, and thereby also the risk for accumulation leading to a steady state leakage.

The term *ecomimetic*, ecosystem mimetic, is proposed for human settlements that have a system structure similar to ecosystems, i.e., organized to accomplish a regenerative cycle. Such social systems avoid the HEAP trap, an example of how to develop human activities in synergy with ecosystem processes.

5.1. A prerequisite for regenerative cycling in human settlements: Integration of production and consumption

The concentrating, refining, packaging and transportation needed to provide for everyday products as food for the urban inhabitants require large energy inputs (as much as ten times the content of potential energy in the food (Hall et al., 1986)). Moreover, this also implies linear flows of nutrients and other elements. Trying to stop a linear flow at the end-of-pipe leads to a Bertalanffy steady state growth.

If one wants to implement the regenerative cycling structure of an ecosystem into societal planning, it is not possible to make a separation of the functions of living, agriculture and waste product handling in the way we are used to doing today. Instead, those functions need to be integrated with each other in moderate-size systems. If a human settlement is restricted in size to the production capacity of an ordinary agriculture, waste products from the settlement could be absorbed by the agriculture, thus avoiding the Bertalanffy trap and eliminating the need for import of fertilizers to the agriculture (Fig. 7).

The space proportions between an agriculture that produces the food for its animals and the settlement size possible to carry are calculated with figures from Granstedt and Westberg (1993). From this work, it can be concluded that 25% of the phosphorus circulated in a balanced agriculture is exported (3–4 kg/ha * year) as product and should, hence, later be returned to the agriculture. The annual turnover of phosphorus for a person is 0.6 kg. 5–8 persons per hectare of agriculture, and could then be supported in a sustainable way. A 20 ha agriculture could then

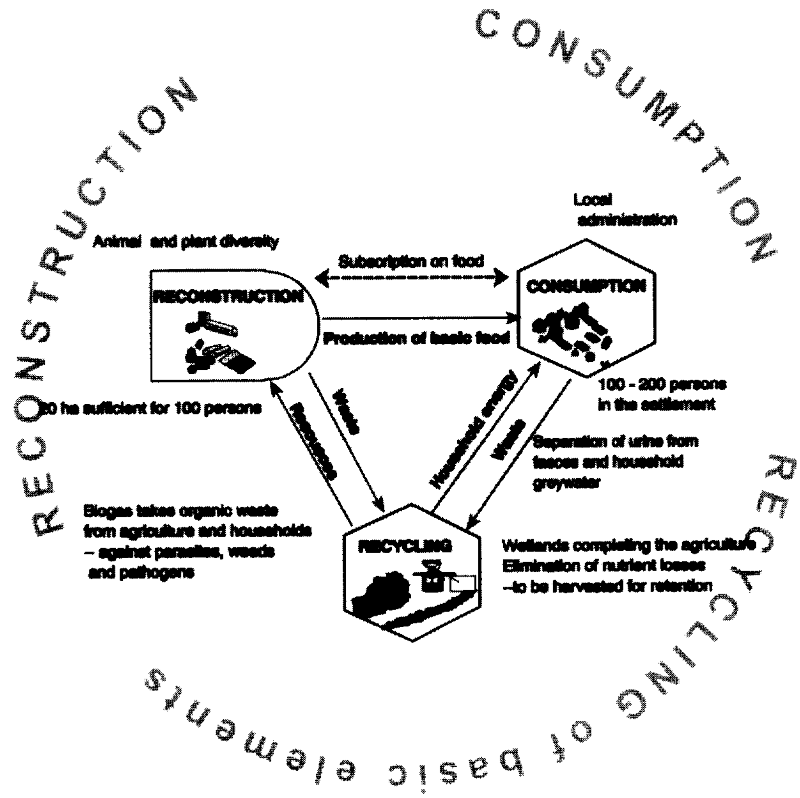

Fig. 7. A proposed societal module with ecomimetic structure.

produce food for and minister to the nutrients from 100–150 persons.

6. Conclusions

In this review, I have tried to point out that the fairly simple principle '*If you go on pouring something into a jar, it will ultimately pour over (at the same rate)*', also is valid for non-gaseous nutrients in large scale socio-geographic systems, in this case phosphorus.

The case studies show that there is a pronounced concentration of phosphorus close to the end-user regions. This concentration is between 100 and 900 times, regardless if the areas of agriculture/deposition are studied or if the concentration of phosphorus in these areas is regarded. This accumulation will induce a leakage, which after stabilization will correspond to the former point source effluent from the urban areas if the current practice is continued. The former point-source leakage of phosphorus from urban areas will by this mechanism be converted into non-point source leakage from the deposition area.

The problem is two-way. In one end it is a pollution problem, in the other end, it is a resource problem. Therefore, phosphorus is a good example of waste as a resource in the wrong place. If the linear transportation type of food and nutrients is maintained, diffuse leakage will increase until a steady state of phosphorus in the total urban region is attained. Because of the HEAP mechanism, the present policy to decrease phosphorus pollution by impeding it with chemical precipitation at the wastewater treatment plants, non-point source pollution will ultimately replace the point source pollution as the major origin of nutrient pollution and the investments will be in vain in the long run. The method buys time, the extent of which is still to be estimated, but it does not solve the problem. However, if the time bought is used to convert the current type of urban settlements to a settlement type with close integration between areas for production and consumption of food, the investments to stop leakage of phosphorus to the seas will not have been in vain in the long run.

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Appendix A. The mathematics of von Bertalanffy equifinal growth

Mathematically, the effect regarding a storage could be described with an equation integrating the inputs (J) and storage (Q) over the system. The output is determined by the storage and a constant (k) determining how large a part of the stored amount is that will escape in a given moment (Fig. 8). The stored amount will change from Q_0 in the start of the study to Q_t after the time t.

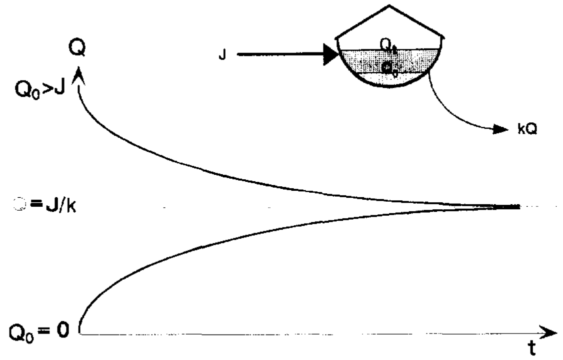

Fig. 8. Principles of equifinal growth. With a net import into the system, the stored amount will change into a steady state where J equals kQ (5). The input J will be stored as Q, and its corresponding outflow kQ is determined by the constant k. The stored amount will change from a low or high value, Q_0 to J/k at Q_t.

The momentary flow will then follow Eq. (A.1):

$$Q = J - kQ \tag{A.1}$$

After a time t, the stored amount will be:

$$Q = \int (J - kQ)\,\mathrm{d}t + Q_0 \tag{A.2}$$

or, fully integrated:

$$Q = \frac{J}{k}(t - \mathrm{e}^{-kt}) + Q_0\mathrm{e}^{-kt} \tag{A.3}$$

When the value of t increases,

$$\mathrm{e}^{-kt} \to 0 \tag{A.4}$$

The second term also reduces to 0, so, independently of the initial stored amount, the stored amount Q will after a long time reach a state where

$$Q = J/k \tag{A.5}$$

That is,

$$J = kQ \tag{A.6}$$

which means that input equals output. This steady state will be maintained as long as J is unchanged. Efforts to reduce kQ by increasing Q will only give results until the steady state reinstalls itself. The amount exported will ultimately depend on the amount imported into the system (Fig. 8).

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