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The relationship between ecosystem services and purchased input in Swedish wastewater treatment systems — a case study☆

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Abstract

There is an increasing awareness of ecosystem services and use of ecological engineering in today's search for more sustainable wastewater treatment systems, but there is still great uncertainty about how to compare and evaluate the ecological sustainability of different systems. The aim of this study was to analyze the use of resources in three different wastewater treatment systems: (i) conventional three-step treatment (WWTP), (ii) conventional mechanical and chemical treatment complemented with a constructed wetland (TP + CW), and (iii) treatment in a natural wetland (NW), and to investigate to what extent increased space, time, and dependence of ecosystem services could substitute for purchased input in wastewater treatment. In order to compare resources of different quality we used emergy analysis, assessing the amount of solar energy required, directly and indirectly, for a certain production. Emergy use due to purchased inputs and to local renewable inputs differed substantially between the three treatment system studies, with emergy ratios of purchased to local renewable inputs of 9:1, 141:1, and 3056:1 for NW, TP + CW, and WWTP, respectively. Total use of emergy per person equivalent (p.e.) and kg phosphorus was similar in all three systems, strengthening our hypothesis of unchanged total emergy use in systems of different purchased input and land use. However, in the present study, purchased input was not fully substituted, while the natural wetland, apart from requiring a large land area, also needed a lot of purchased resources to fulfil the strict rules for wastewater treatment prescribed by society. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Wastewater treatment; Resource use; Emergy analysis; Ecosystem services; Area demand; Wetlands

1. Introduction

During the past four decades, alternative systems for wastewater treatment have been continually developed. A major focus is on reduction of the use of non-renewable resources and to what extent environmental inputs that are renewable

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[1] Calculation based on emergy in rain.

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and free can substitute for non-renewable resources. One common characteristic of these strategies is the acknowledgement of ecosystem services by the use of ecological engineering (Wittgren and Hasselgren, 1993; Mitsch, 1998).

Ecosystem services could be defined as 'the benefits human populations derive, directly or indirectly, from ecosystem functions' (Costanza et al., 1997). Examples of ecosystem services are regulation of local and global climate, pollination, soil formation, biotic regulation, bacterial denitrification, photosynthesis and support of biodiversity.

The differences between wastewater treatment strategies often constitute the degree of management. Using ecosystem services (see Table 1), we rely on time and on space of interaction for different purposes, be they biological, e.g. nitrification and denitrification; chemical, e.g. adsorption and fixation; or physical, e.g. sedimentation and evaporation. Increased energy input for forced aeration, increasing nitrification of ammonium, in a wastewater treatment plant (WWTP), can substitute for the requirement of time and space for the same process in a wetland (Knight, 1995; Ødegaard, 1995). A process that takes days in a wetland is accomplished within hours in a WWTP.

A large amount of experience and knowledge has been gained in the design and function of alternative wastewater treatment strategies (Crites, 1984; Reed et al., 1988; Cooper and Findlater, 1990; Wittgren and Hasselgren, 1993; Wittgren, 1994; Knight, 1995; Kadlec and Knight, 1996), but there is still great uncertainty about how to compare and evaluate the resource use of different systems. This is especially true when one wishes to include comparisons of such disparate matters as the use of ecosystem service, space, and time.

Table 1
Ecosystem services used in wastewater treatment

Biological	Chemical processes	Physical
Denitrification	Ammonification	Sedimentation
Nitrification	Adsorption	Evaporation
Fermentation	Fixation	Transpiration
Plant uptake		
Oxidization of organic matter		

Life cycle assessment, environmental impact analysis, energy analysis, exergy analysis and mass flow analysis have been applied in evaluating resource use in Swedish wastewater treatment systems (Nilsson and Bergström, 1995; Ødegaard, 1995; Dalemo, 1996; Tillman et al., 1996; Bengtsson et al., 1997; Hellström, 1997; Lundin et al., 1999).

Finnveden and Östlund (1997) propose the use of exergy in life-cycle analysis as a measure of resource use or resource depletion to overcome the problem with comparison of resources of different quality.

The aim of this study was to analyze the resource use and illustrate the relationship between the demand for space, time and purchased input in different wastewater treatment systems. We wished to investigate the extent to which increased space and dependence on ecosystem services can substitute for purchased input. Since it is possible to measure these resources on a common basis in emergy analysis, this method was chosen. An emergy analysis considers environmental work (e.g. ecosystem services) as well as direct and indirect resource use to sustain human inputs. Moreover, the method of analysis is built on an ecosystem perspective, acknowledging ecosystem structure and functions, which is appropriate when working with wastewater treatment partly in wetlands.

It would have been inappropriate to use energy analysis, since it does not consider resource use other than auxiliary energy (e.g. the energy used for exploitation or construction), nor any quality differences between different kinds of energies or include free environmental work. Furthermore, it does not properly account for the environmental work supporting human society. Nor is the problem of accounting, for environmental work supporting human society solved in exergy analysis. Another drawback of exergy analysis is that quality differences in different kinds of resources only are considered in respect of their ability to be converted to geobiochemical energy or mechani-

Table 2
Comparison of aspects relevant to this study of some environmental assessment methods

	Cost benefit analysis	Life cycle assessment	Emergy analysis	Exergy analysis
Goal	Service optimization	Assess resource use and environmental impact	Assess direct and indirect resource use	Assess resource use and production efficiency
Theoretical foundation	Neoclassical economics	Engineering sciences	Systems ecology	Thermodynamics
Ability to handle pollutants	Cost of treatment versus no treatment	Yes	In an 'end-use' emergy analysis	Chemical pollutants
Ability to handle difference in energy quality	Market decides the value	Subjective weighing factors used	Transformities are used as weighing factors	Gibbs free energy
Ability to handle other resources	Market interpretation	Subjective weighing factors used	Transformation ratios are used as weighing factors	To the extent that they can be converted to available energy
Perspective	Anthropocentric	Anthropocentric	Ecocentric	Not relevant
Ability to handle ecosystem services	If internalized	Yes-partly	Yes, conceptually but needs to be developed	No
Scale in focus	Process scale	Large to small	Large to small	Process scale

cal work (Szargut, 1998). Nor would it be appropriate to use LCA as it does not provide any conversion between different effect categories, e.g. employment of land, time and ecosystem service versus purchased inputs. Cost benefit analysis is too blunt while dealing with ecosystems and involves human preferences, e.g. willingness to pay, which was considered inappropriate in the present study. To further clarify the reasons of our choice of method, differences in scope and perspective of the considered environmental assessment methods are aggregated in Table 2.

The present analysis was limited to resource use. Three wastewater treatment systems (two case studies and one theoretical example); conventional three-step treatment (WWTP-wastewater treatment plant), conventional mechanical and chemical treatment complemented with biological N treatment in a constructed wetland (TP + CW-treatment plant + constructed wetland) and treatment in a natural wetland (NW-natural wetland) were analyzed to exemplify and discuss ecosystem service use and the use of time, space and energy. The hypothesis was that the amount of total emergy use would not differ between treatment systems, but only in the partitioning between the use of free environmental emergy and purchased emergy. It implies that there are fixed relationships between the substitutions which form the physical, biological and technological boundaries of all human activities. In order to compare natural and technological systems and test our hypothesis we must assume that our man-made treatment systems, as well as the natural ecosystems, are efficient in what they are designed for, namely the treatment of wastewater. Otherwise the substitutability will fail in terms of emergy use in the different systems.

To test our hypothesis we also analyzed the relationship between the use of free renewable to purchased non-renewable resources of the different treatments and the extent to which there was a trade-off in the use of purchased goods and ecosystems service. The latter is also the reason we chose the example with treatment of raw wastewater in a natural wetland — to compare two extremes with respect to purchased input use and time and land use.

The emergy analysis has previously been used in analysis of wastewater treatment in wetlands (Odum et al., 1987; Flanagan and Mitsch, 1997) and to our knowledge in one evaluation of a conventional treatment system (Nelson, 1998). The method is founded on principles for organization and optimization of self-organizing systems, developed from theories in ecosystem ecology (Odum, 1994). An advantage with the emergy analysis is the possibility to compare resources

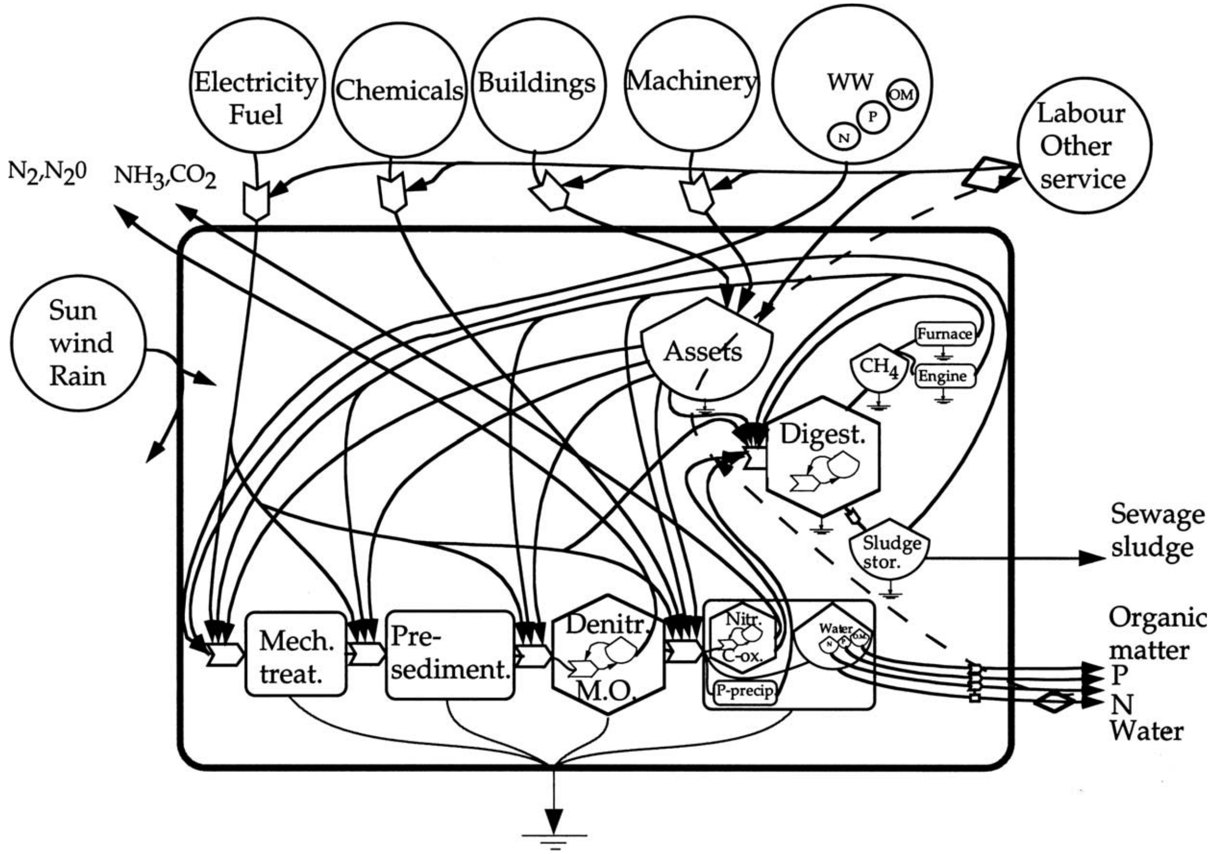

Fig. 1. Systems diagram of wastewater (ww) treatment in a conventional three-step treatment plant (WWTP). C-ox. – carbon oxidation; Dentr. – denitrification; Mech. Treat. – mechanical treatment; M.O. – microorganisms; N – nitrogen; Nitr. — nitrification; OM – organic matter; P – phosphorus; P′precip. – precipitated-phosphorus; Pre-sediment. – Pre-sedimentation; Sludge stor. – sludge storage; WW – wastewater.

and services of completely different qualities (e.g. land, fossil fuel, human labor, and biodiversity). This is especially important when one wishes to compare the use of present ecosystem services with purchased inputs originating from the use of resources and ecosystem services from other places or time periods, such as fossil fuel. All resources, free and purchased, are measured on a common basis, which takes into account differences in their time and territorial demand. Qualities generated in both the ecological and the economic system are considered. In emergy analysis the value of an ecosystem service is based on the amount of free environmental energy (sun, wind, rain) required to sustain the ecosystem that produces the service (Odum, 1996).

2. Materials and methods

The three wastewater treatment systems analyzed are described below.

2.1. Conventional three-step treatment

The WWTP with approximately 9700 person equivalents (p.e.) connected and located in the municipality of Surahammar, about 150 km west of Stockholm, has been thoroughly described by Björklund et al. (2001); see Fig. 1. The treatment is carried out mechanically and with simultaneous biological nitrification, stabilization of organic matter and chemical phosphorus (P) precipitation

Table 3
Retention values of BOD_7, P and N, wastewater inflow, wastewater turnover time and land area use in Surahammar conventional three-step treatment plant (WWTP), Oxelösund treatment plant and constructed wetland (TP+CW) and in a natural wetland (NW)

	WWTP mean values based on 1994–1995 data	TP+CW mean values based on 1996–1997 data	NW estimated values based on CW and literature data
BOD_7, yearly reduction			
% year^{-1}	96	95	95
kg year^{-1}	144 860	134 898	12 633
P, yearly reduction			
% year^{-1}	95	99	95
kg year^{-1}	7060	7558	220–550[a]
N, yearly reduction			
% year^{-1}	50	50	60
kg year^{-1}	24 150	23 792	2165
Yearly inflow, m^3 year^{-1}	2 100 000	2 330 000	156 420
No of p.e.	9714	9947	759
Turnover time, days	0.5	9	180
Land area, m^2 year^{-1}	8700	220 000	220 000

[a] Value depending on estimated retention capacity, further discussed under section Section 2.3

with $FeSO_4$. The raw sludge that settles during the wastewater treatment is digested anaerobically and the biogas is used to produce electricity for internal use at the treatment plant. After treatment, the water is discharged into the River Kolbäcksån, in the Lake Mälaren catchment area. Inflow and retention values for N, P and organic matter, i.e. biological oxygen demand for 7 days (BOD_7), as well as the turnover time for the wastewater are given in Table 3.

2.2. Treatment plant and constructed wetland

The TP + CW with approximately 10 000 p.e. connected is located in the town of Oxelösund on the Baltic coast about 120 km south of Stockholm; see Fig. 2. In the TP, the wastewater is treated mechanically in a grid and in an aerated sandfilter. The chemical treatment occurs in a pre-aeration pond, directly after the mechanical step, when the precipitation chemical $AlSO_4$ is added.

As a consequence of the international agreements between the countries around the Baltic Sea, Oxelösund was forced to decrease the N load to the recipient water by 50% by 1996 (Hägermark et al., 1998). Since the TP in Oxelösund lacked a biological step, conventional N treatment would have been very costly. Instead, a wetland of 22 ha for biological N treatment was created in 1993, about 2 km northeast of the TP, at the peninsula of Brannäs. The wetland consists of two parallel systems, each of two shallow ponds, intermittently loaded, and a final common pond. At the inlet, a sedimentation pond has been created where some of the precipitated P and organic matter from the chemical treatment, can settle. Common reed (*Phragmites australis* (cav.) Trin. ex Steudel), cattail (*Typha latifolia* L.), narrowleaf cattail (*Typha angustifolia* L.), reedgrass (*Glyceria maxima* (Hartm.) Holmb.), common club-rush (*Schoenoplectus lacustris* L.) and sedge (*Carex riparia* Curtis) were among the species established in the ponds during the first years (Ridderstolpe, 1995). The vegetation is not harvested regularly since nitrification–denitrification is the mechanism to be promoted in the wetland (Hägermark et al., 1998). Inflow and retention values for N, P and BOD_7 as well as the turnover time for the wastewater are given in Table 3.

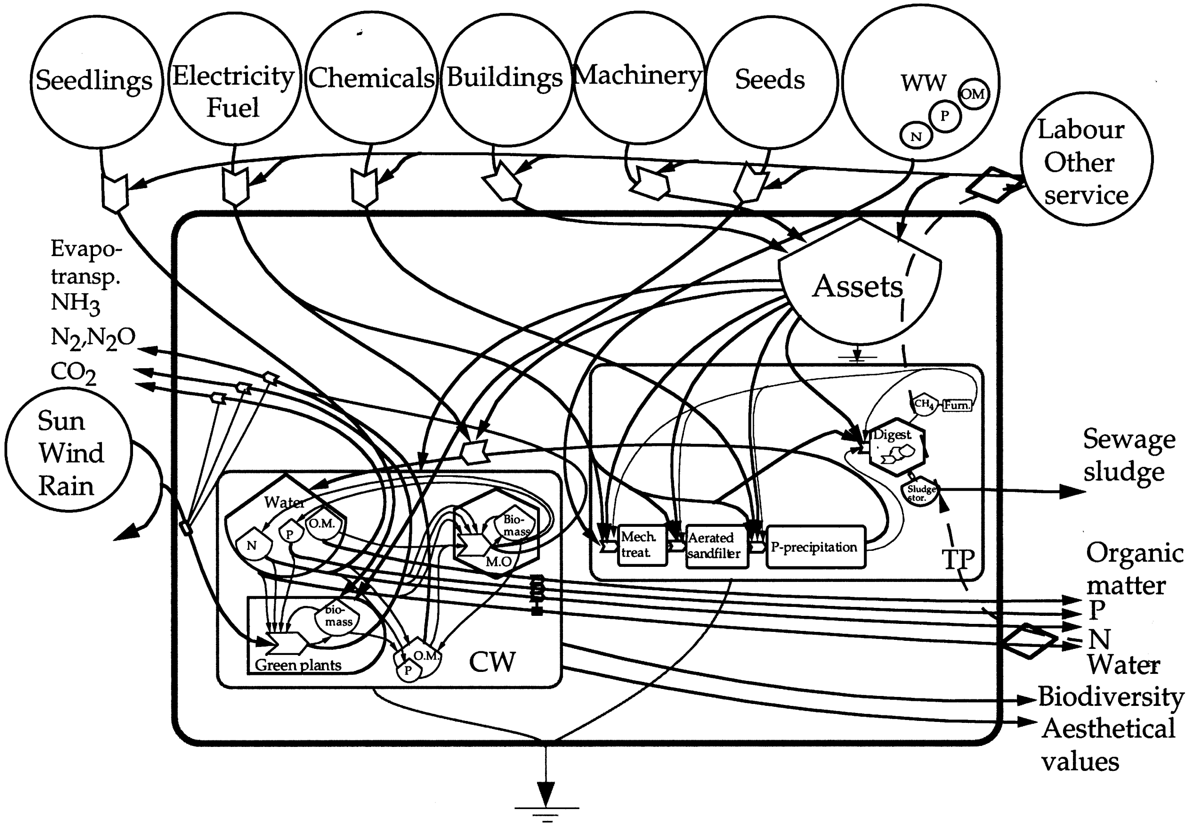

Fig. 2. Systems diagram of wastewater (ww) treatment in a conventional mechanical and chemical treatment plant with a constructed wetland (TP + CW). (i) Aggregation of processes explicitly drawn in Fig. 3. CW — constructed wetland; Digest. — digester; Furn. — furnace; Mech. treat. — Mechanical treatment; M.O. — microorganisms; N — nitrogen; OM — organic matter; P — phosphorus; Sludge stor. — sludge storage; WW — wastewater.

2.3. Natural wetland

The use of natural wetlands for wastewater treatment is controversial, especially under temperate climatic conditions, and the wastewater requires extensive pretreatment if wetland treatment efficiency is to be sufficient (Wittgren, 1994; Knight, 1995). When using a natural wetland as an example of wastewater treatment we have focused on long-term retention functions, i.e. peat accumulation and adsorption of P to soil aluminium (Al) (Richardson, 1985). N and BOD_7 can be effectively treated in wetlands since they have a significant atmospheric flux (i.e. nitrification–denitrification and oxidation) (Johnston, 1991; White et al., 2000) while P treatment will depend on long-term retention in sediments and in organic and inorganic inactive pools. In surface flow wetland treatment without chemical P pretreatment, retention of P will be the most critical process (Kadlec and Knight, 1996). No major subsurface flow was assumed to occur but some P will become adsorbed to soil Al and to some extent to iron (Fe) due to the movement of wastewater and due to the sediment fauna in the upper soil layer.

To make a good quality comparison of the different treatment systems we chose to use the CW in Oxelösund, mentioned above, as a model to calculate the load of raw wastewater treated in a hypothetical NW of the same size (22 ha). The P adsorption capacity of a wetland is correlated

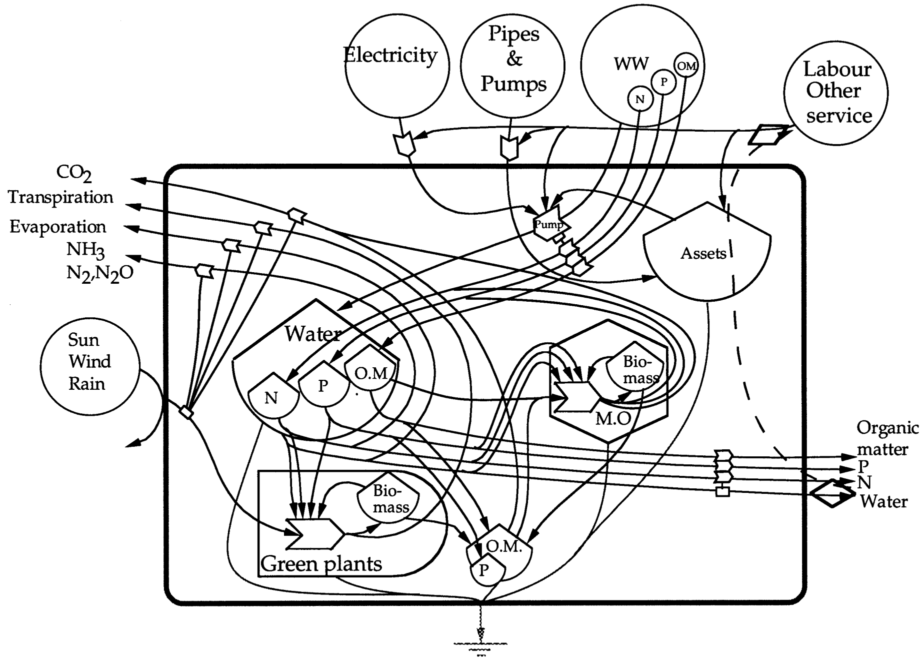

Fig. 3. Systems diagram of wastewater (ww) treatment in a natural wetland (NW). N — nitrogen; P — phosphorus; OM — organic matter; MO — microorganisms

to its content of extractable amorphous Al (Richardson, 1985). In terrestrial soils the risk of P leaching has been correlated to the concentration of Fe and Al suggesting that the risk of P leaching increases when the P concentration to Fe and Al concentration exceeds 30% (Lookman et al., 1995). There is, however, a problem with using Fe for P retention capacity in wetlands due to increased solubility of P adsorbed to Fe hydrous oxides when redox potential fluctuates. We assumed that the P concentration (mmol kg^{-1} soil) to (a) Al concentration (mmol kg^{-1} soil) in the upper 10 cm soil profile or to (b) the mean concentration of both Fe and Al could reach 30% without risk of leaching (Lookman et al., 1995). Data on extractable amorphous Fe and Al content in a Swedish clay soil under similar climatic conditions to Oxelösund was used (Öborn, 1994). We also set the restriction that only 50% of the upper 10 cm soil would actually come in contact with the wastewater. This resulted in a P retention capacity of the wetland between 1.5 ([Al] only) and 2.5 g P m^{-2} $year^{-1}$ ($0.5 \times [Fe + Al]$) with a life length of 20 years. We assumed that Fe would actually retain some P even in a long-term perspective and estimated the retention capacity, due to mineral adsorption, to 2.0 g P m^{-2} $year^{-1}$. To this was added 0.5 g m^{-2} $year^{-1}$ retained in peat accumulation (Richardson and Craft, 1993). With a total retention capacity of 2.5 g m^{-2} $year^{-1}$, 759 p.e. could be connected. The amount is in accordance with P retention capacities on a wide range of surface flow wetlands (Richardson, 1985; Kadlec and Knight, 1996). In order to test the sensitivity of the analysis to the estimated P retention capacity, an analysis was conducted for a retention capacity of 1.0 g P m^{-2} $year^{-1}$ with 302 p.e. connected. The driving forces and functions of the NW are seen in Fig. 3.

The wastewater was pumped intermittently to the parallel pond systems after pre-sedimentation, for further transport to the common final denitrification pond. Inflow and estimated retention values for N, P and BOD_7 as well as the turnover time for the wastewater are given in Table 3.

2.4. System boundaries and sources of data

The analysis of the treatment systems comprised the wastewater from its entry into the WWTP and TP + CW to the return of the treated water and likely residues (e.g. sludge) to surrounding ecosystems; see Figs. 1 and 2. The system boundary of the NW comprised the entry into a sewer system leading to the NW to the return of the treated water and likely residues (e.g. sludge) to surrounding ecosystems; see Fig. 3. System boundaries are based on the treatment function of the three systems.

The results of the WWTP emergy analysis by Björklund et al., (2001) and the analysis of the TP + CW and NW from this study were used to calculate resource use indices for the three treatment systems. The TP treatment data were mainly based on environmental and economic accountings from 1995, and on personal communications with staff at the wastewater treatment plants, see Appendix B. Treatment efficiency for the CW system was based on mean figures of 1996–1997 control programs of the Oxelösund CW since the efficiency of the wetland increased after its establishment in 1994.

Lifetimes of buildings were estimated to 50 years and of machinery and wetlands to 20 years.

The WWTP and TP + CW treatment systems were adjusted to the same level of nitrogen reduction (50%). Critical to the comparison of the resource use for treatment in the different systems would otherwise be that the first kilogram of reduction requires less resource use than the last. Kilogram reduction of BOD_7 and P differed slightly (Table 3).

Purchased input data in the NW example were partly taken from the CW case. Construction costs, i.e. cleaning, digging, leveling and planting, were omitted in the NW example. For maintenance, operational costs and planning administration, costs were added according to the amount of P treated in the NW, see Appendix C.

2.5. The emergy analysis

Emergy analysis is a quantitative analysis technique that determines the amount of direct and indirect energy of one kind that has been used to generate resources, services and products of different quality. Solar emergy is measured in units of solar emjoules (sej) and is the product of the solar transformity (from now on only referred to as emergy and transformity) and the available energy in the resource. The transformity is the solar energy used to make one joule of a resource (Odum, 1996). The method has been comprehensively described by several authors (Odum, 1994; Brown and Herendeen, 1996; Brown and McClanahan, 1996; Odum, 1996).

Transformities from other studies have mainly been used, but when no appropriate data were available, new values were calculated (Björklund et al., 2001). The context in which transformities from other analyses were calculated may have differed from that of which they were used in our study. In a few cases it was impossible to avoid double counting with regard to service in the transformity. As far as we are able to predict, this does not affect the conclusions of the study.

Corrections were made to avoid double counting of emergy when different flows originated from the same source. As regards sun, wind and rain all originating from the annual emergy input to earth, only rain, which gives the greatest emergy contribution, has been included in the total (Footnote 3, Appendices A, B and C).

To account for emergy in purchased goods, both the emergy input from the environment to generate the raw material and the emergy in human service to make the raw material useful in the economic system were calculated. Emergy in service was calculated from the average emergy flow per unit money flow for Sweden (Lagerberg et al., 1999).

2.6. Emergy use expressed as indirect and direct land area

It is possible to convert resource use evaluated in the currency of emergy to an area demand. To do so we used the annual emergy input originat-

Table 4
Comparative indices of resource use, expressed as solar emergy joules (sej), for Surahammar conventional three-step treatment plant (WWTP), Oxelbsund treatment plant and constructed wetland (TP+CW) and a natural wetland (NW)

Index	WWTP 10^{12} sej	TP+CW 10^{12} sej	NW 10^{12} sej
Total emergy use p.e.$^{-1}$	154	181	170
Total emergy use kg^{-1} N reduced	62	76	60
Total emergy use kg^{-1} P reduced	212	238	235
Total emergy use kg^{-1} BOD reduced	10	13	10
Total emergy use m^{-2}, empower density	162.8	8.2	0.6
Locally renewable emergy p.e.$^{-1}$	0.05	1.27	16.43
Local renewable emergy kg^{-1} N reduction	0.02	0.53	5.76
Local renewable emergy kg^{-1} P reduction	0.07	1.67	22.67
Local renewable emergy BOD^{-1} reduction	0.00	0.09	0.99
Purchased input p.e^{-1}.	154	180	154
Purchased inputs kg^{-1} N reduction	62	75	54
Purchased inputs kg^{-1} P reduction	212	236	212
Purchased inputs kg^{-1} BOD reduction	10	13	9
Purchased/free environmental inputs	3056	141	9

ing from local, renewable resources for the area in which our systems are situated. The emergy content in all purchased inputs were divided by the local renewable emergy input to this area (approximately 5.70×10^{10} sej m^{-2} year^{-1}), which was the contribution from rain. In this way an indirect area demand was calculated for all purchased inputs. This allows comparison of the direct and indirect area demand for the different systems. Direct area demand represents the actual use of land, which for the WWTP only consists of the area where the treatment plant is situated. Indirect area demand represents the emergy in purchased input.

2.7. Empower density

Empower density is the emergy inflow per unit time and area. A system organizes its structure and functions in relation to the amount and kind of inflowing emergy. The comparison between the emergy density in a certain area relative to the surrounding ecosystems may indicate the level of human activity in that area. It can also give information about the emergy needed to maintain the structure and functions in a certain area. Large changes in the emergy density, i.e. the emergy inflow to the area, abruptly alter the structure and organization of the system (Odum, 1994).

3. Results

3.1. Emergy use

The total emergy use per p.e. was about the same size in the WWTP, TP + CW and in the NW, with 1.5×10^{14}, 1.8×10^{14} and 1.7×10^{14} sej p.e.$^{-1}$, respectively, see Table 4. This was also true for the total emergy use per kg N reduced, while the WWTP system had a slightly lower total emergy use per kg P reduced than the two other systems. The ratio of emergy in purchased inputs to free environmental inputs for the wastewater treatment systems were 3056 in the WWTP system, 141 in the TP + CW, and 9 in the NW system. In spite of the large difference between treatment systems of this ratio, the analysis showed that the NW system did not have a lower use of emergy in purchased input compared with the WWTP system. Hence, a greater use of locally renewable inputs in the NW system did not result in a smaller use of purchased inputs. The TP + CW had a slightly higher use of purchased input than the WWTP and NW systems.

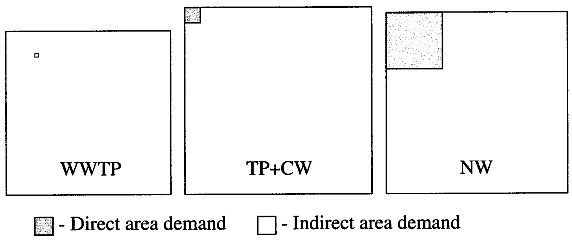

Fig. 4. Direct free emergy use (direct area demand) and purchased emergy use (indirect area demand), expressed as area per p.e. in the WWTP, TP + CW and NW systems for wastewater treatment.

3.2. Relationship between input and space

Obviously the direct area demand per p.e. was much larger in the NW than in the TP + CW and in the WWTP. The total area demand was similar in all three treatment systems; see Fig. 4. In this sense the present study supports our hypothesis that the total emergy use differs only slightly between different treatment systems. There was, however, no clear relationship between the use of locally renewable resource to purchased input for the wastewater treatment systems. Although the direct land use per p.e. was two orders of magnitude larger in the NW than in the WWTP, the indirect use of land per p.e. was similar in the two treatment systems.

3.3. Relationship between empower density and time

The empower density was almost 300 times larger in the WWTP system than in the NW system; see Table 4. The empower density had a strong correlation to the turnover time for treatment and total amount of P reduction in the systems, Fig. 5a–b, with a short turnover time for treatment and a large amount of P reduced in the high density WWTP system. The low empower density in the NW system corroborated with a long turnover time and low amount of P reduced. The TP + CW system which was a mixture of two systems with high (TP) and low (CW) empower density had a turnover time of treatment and P reduction similar to the WWTP system.

4. Discussion

4.1. Emergy in purchased input

The differences in total emergy use per p.e. between the WWTP and TP + CW were mainly due to the larger use of electricity and larger operational costs in the TP + CW compared to the WWTP. Even if the number of connected p.e. is similar in the WWTP and the TP + CW today, the TP + CW was constructed to treat wastewater from 19 000 p.e. and the WWTP to treat 12 000

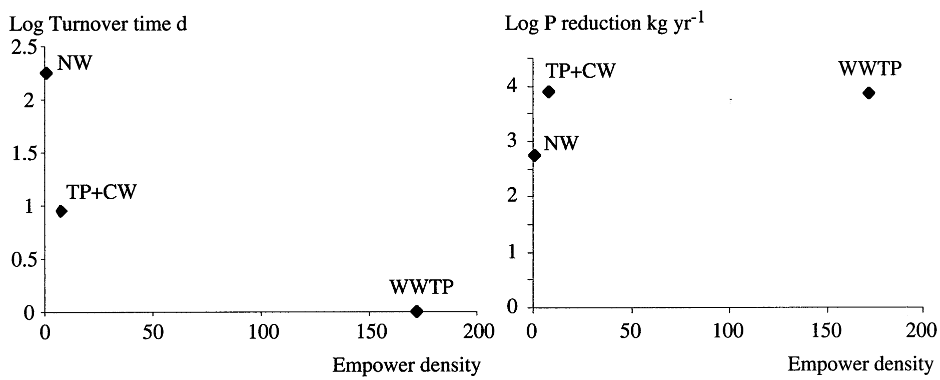

Fig. 5. (a) Log turnover time of treatment, days, and (b) log reduction of P, kg year^{-1}, in treatment systems of different empower density; a natural wetland (NW); a treatment plant complemented with a constructed wetland (TP + CW) and; a conventional treatment plant (WWTP).

p.e. The difference in electricity use may be a result of this over dimensioning of pumping capacity in the TP + CW. It is still surprising that the WWTP with both mechanical, chemical and biological treatment had lower electricity consumption than the mechanical and chemical treatment of the CW, the constructed wetland excluded. The operational costs in the TP + CW were more than twice as large as in the WWTP. To test the sensitivity of the analysis, we set the operational costs in the TP + CW equal to the costs in the WWTP. This resulted in an emergy use in the TP + CW of purchased input (p.e.$^{-1}$; N^{-1}; P^{-1}; BOD_7^{-1}) equal to or slightly smaller than in the WWTP and NW. This confirms the conclusion that there were only small differences between the systems in the emergy use of total and purchased input. However, it also shows a need for caution so as not to confuse site-specific differences with differences between treatment systems.

The emergy in service is calculated from the average emergy flow per unit money flow, in this case for Sweden (Lagerberg et al., 1999). In the analysis presented in this paper, the relatively large amounts of service in the WWTP and in the TP + CW will have a large impact on the results. Fluctuation in prices and regional differences in emergy flow per unit money flow will change the outcome of the analysis.

4.2. Design and dimensioning of the NW

It is always problematic to compare analysis of real systems with analysis of hypothetical systems as in the NW. Since we relied on a hypothetical example of the NW system, there is a possibility that the P treatment capacity of the wetland was not correctly estimated. N and BOD_7 treatment rely mainly on more easily estimated microbiological processes, while P reduction relies largely on chemical and physical processes, which are more difficult to estimate. The design and dimensioning of nutrient load will have a great impact on the results of the analysis. To test the sensitivity, we conducted an analysis with the assumption that the P retention capacity was only 1.0 g m^{-2} $year^{-1}$ (data not presented). Decreased P retention capacity did not have a large impact on the amount of purchased input, but the increase in total emergy input per p.e. in comparison to the other systems was substantial (44%). With a P retention capacity of 1.0 g m^{-2} $year^{-1}$ the direct area demand would increase 2.5 times. The need for reliable data is evident.

The model for the NW system, the Oxelösund wetland, was originally designed and constructed to reduce N in the wastewater. If P reduction had been the main goal it would probably have been designed differently, with some kind of infiltration system. Consequently we have assumed P reduction to be the most limiting process in the NW system. It is possible to argue that an infiltration wetland should have been used for the NW example to increase the treatment capacity and thereby decrease emergy use per kg reduced nutrient (e.g. P). We did, on the other hand, have the aim of reproducing the retention processes of a natural wetland and this was one of the reasons why we chose an example of a surface flow wetland (Kadlec and Knight, 1996).

4.3. Differences in output

It is important to be aware that the systems generate different outcomes. In the case of the WWTP, and to some extent the TP + CW, the output is treated water and sludge. At present, the sludge may only be applied on agricultural land which is not used for the production of human food or animal feed, due to high contents of hazardous components (Naturvårdsverket, 1996). The quality of the sludge depends to a large extent on the type of sewer system used, i.e. if storm water is connected to the wastewater plant or if there is other contamination. In the TP + CW and in the NW, heavy metals and persistent organic substances from the wastewater will accumulate in the wetland. Due to the restricted sewer system with few sources of contamination and the small load, the accumulation of toxic substances in the NW will probably be slow. This is, however, partly an effect of scale rather than of treatment system. After 20 years the NW will build up a capital of nutrients and organic matter which could be used for biomass production.

In the TP + CW and the NW, increased biodiversity is essential as the biodiversity is a basis for many ecosystem services in the wetland and the surrounding landscape (e.g. biotic regulation, hunting, aesthetic values, pollination, etc.). The main contribution of biodiversity from the CW is the increase in habitat biodiversity in the total landscape. In the Brannäs peninsula in Oxelösund, with agricultural and forest areas as the former land use, very distinct environments were created by the establishment of the CW. The peninsula as a whole has been enriched by the CW biotope. Changes in biodiversity are hard to predict in the NW receiving untreated wastewater. On one hand, systems that receive large energy and nutrient inputs are commonly considered as becoming low in biodiversity (Janssens et al., 1998). On the other hand, this is of course critical to the initial energy and nutrient level of the system, as an increase in the amount of energy and nutrient available can support new niches for new organisms (MacArthur and Wilson, 1967; Odum, 1994; Qian, 1998). Furthermore, wetlands positively and negatively affect the atmospheric content of greenhouse gases as they sequestrate CO_2 but emit methane (Laine et al., 1996; Milich, 1999).

4.4. Area demand

The direct and indirect land use based on emergy is similar to the concept of ‘ecological footprint’ developed by Rees and Wackernagel (Rees and Wackernagel, 1994; Fricker, 1998; Wackernagel et al., 1999) in that it relates resource use to an area. The difference is that when the land use is based on emergy, resources that are not directly tied to an area demand can be included and consistently converted to the amount of solar energy needed to generate them. This means that an area demand based on emergy use will give a more far-reaching comparison of the actual area needed for different activities.

Although we have chosen treatment systems, which are the opposite of each other in terms of land versus purchased input use, there was no large difference in purchased input use per p.e. between the WWTP and the NW; see Table 4. In the NW system we increase the land area and rely on ecosystem services and renewable emergy input for wastewater treatment. A secure and highly reliable wastewater treatment system including health aspects still require a high degree of isolation of the wastewater from the population. Therefore, the emergy in purchased inputs for transportation of the wastewater will be maintained at a high level. As a result of this, the substitutability between purchased inputs and ecosystem services is lost. If substitution of purchased inputs for renewable inputs are to be obtained, there might be no room for expenditures such as electricity use in pumping or for pipe and pump materials when treatment is based on processes occurring in natural wetlands. Purchased inputs could be exchanged for ecosystem services only if these services also guaranteed the transport of our waste.

In natural ecosystems, recycling of waste is carried out with small emergy costs but over long periods of time, with low and uneven concentrations of nutrient and less extreme non-equilibrium states. In human systems we demand high and non-fluctuating efficiency in treatment. Under those circumstances wastewater treatment in NW systems would only be possible in decentralized systems with very low population densities.

4.5. Empower density and time demand

The empower density in the WWTP is extremely high (Fig. 5). Compared with the empower density of for example Taiwan (60 sej m^{-2} $year^{-1}$ (Huang, 1998)) the WWTP empower density is nearly 30 times larger. This is what could be expected in a highly technological system. The empower density in the NW, al contrary, is commensurate with an average empower density of the Swedish agricultural landscape (Johansson et al., 2000). Still the NW empower density is about 10 times larger than the average empower density in the surrounding ecosystem which we estimated to about 0.6[1]sej m^{-2} $year^{-1}$. If ecological engineered systems are to be ecologically sustainable and self-maintaining they should be mainly driven by local renewable resources with a low degree of human control (Mitsch, 1998), resulting in an

[1] Calculation based on emergy in rain.

empower density commensurate with surrounding ecosystems.

The relations between turnover time and reduction capacity in wastewater treatment and empower density of the systems show important differences between the systems. In the WWTP with high empower density the incoming wastewater, concentrated from a large number of p.e. is treated in a small area in a short time. The degree of human control is high. In the NW system with a low empower density and a small number of p.e. connected, the time and area demands are many times larger than in the WWTP.

4.6. The choice of method

A major advantage with emergy analysis is the possibility to measure resource use of ecosystems. It has to be acknowledged, however, that the complexity of ecosystems, will always make calculations of transformities difficult and uncertain. This will affect the reliability of conclusions at high levels of detail.

The emergy analysis is developed out of theories in ecosystem ecology (Odum, 1994). Some of these theories are hypothesis that are new and controversial, e.g. the maximum empower principle. Only extensive research involving emergy analysis and system principles will verify the solidity of this approach. The circumstance that emergy analysis relies on a scientific basis which is not fully developed and which in some parts are not consistent with the present dominating scientific paradigm, complicates the communication of results of the analysis.

In the future, it would be useful to continue the present study by assessing the environmental impact of the resource use at different scales. That might be considered by complementing the emergy analysis with an LCA or including an emergy end-use assessment proposed by Ulgiati et al. (1995).

Eventually this study may, to further illuminate differences in output, be complemented with an assessment of the exergy in the different treatment systems. The ratio of exergy to emergy in each system would relate the level of organization to the resource use in respective system. A high ratio indicates a high efficiency of the system. Bastianoni and Marchettini (1997) have done such calculations for different kinds of ponds receiving wastewater. Their results indicate efficiency and aspects of quality in outputs of the different ponds. Ayres (1998) also argues that chemical exergy may predict some aspect of potential harm to the environment of a substance, while Genoni (1997), Genoni and Montague (1995) have proposed that transformities and emergy analysis may do the same. However, we argue that this was not an issue of this study.

5. Conclusions

The total use of emergy per p.e. and kg P was similar in all three treatment systems studied, strengthening our hypothesis of unchanged total emergy use in treatment systems of different energy to land use. On the other hand, we did not find any trade-off in emergy between the use of locally renewable resources to purchased inputs. An increased use of locally renewable resources did not result in a decrease in purchased input in terms of emergy per p.e.

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Appendix A. Emergy analysis of conventional Swedish wastewater treatment complemented with advanced tertiary treatment to reduce nitrogen discharge (50%) (WWTP) ^

Note	Item	Raw unit year^{-1}	Solar trans-formity sej unit^{-1}	Solar emergy sej year^{-1}, 10^{15}
	Free environmental inputs			
1	Sun	1.81 E+10 J	1.00 E+00	0.0
2	Wind	4.47 E+10 J	1.50 E+03	0.1
3	Rain	2.69 E+10 J	1.82 E+04	0.5
	Total emergy in free environmental resources			0.5
	Raw material in purchased inputs			
4	Electricity[i)]	2.51 E+12 J	1.19 E+05	298.3
5	Oil	1.02 E+11 J	6.60 E+04	67.6
6	Buildings; sheet-iron, beams, reinf.	1.45 E+07 g	2.65 E+09	38.5
7	Insulating material	3.25 E+05 g	1.84 E+09	0.6
8	Concrete[i)]	8.40 E+07 g	7.34 E+08	61.6
9	Bricks	1.67 E+06 g	2.52 E+09	4.2
10	Pipes; concrete	7.63 E+06 g	7.34 E+08	5.6
12	Iron	4.38 E+05 g	2.65 E+09	1.2
13	Copper cables	1.25 E+05 g	6.80 E+10	8.5
14	Hard made surface	1.38 E+07 g	4.74 E+08	6.5
15	Plastic in scrapers	2.00 E+04 g	5.87 E+09	0.1
16	Machinery[i)]	1.14 E+06 g	4.10 E+09	4.7
17	Chemicals	2.40 E+07 g	2.65 E+09	63.6
18	Maintenance iron/sheet-iron	5.92 E+06 g	2.65 E+09	15.7
20	Asphalt	2.07 E+07 g	4.74 E+08	9.8
23	Service in depreciation of buildings[i)]	9.57 E+05 SEK	2.15 E+11	205.8
24	Service in maintenance[i)]	2.38 E+05 SEK	2.15 E+11	51.2
26	Operation costs[i)]	1.47 E+06 SEK	2.15 E+11	316.1
27	Interests[i)]	1.34 E+06 SEK	2.15 E+11	289.0
	Total emergy in puchased goods and service			1498.9
	Total emergy use for WW treatment			1500.0

^ Pipesystem has been excluded from original analysis.
[i)]Complementation with advanced tertiary treatment.

A	Additional electricity for pumping	3.38 E+09 J	1.19 E+05	0.4
B	Iron in additional concrete, N treatment	1.13 E+07 g	2.65+09	29.9
C	Additional concrete for N treatment	1.64 E+07 g	7.34 E+08	12.0
D	Service in additional electricity use	4.70 E+02 SEK	2.15 E+11	0.1

Appendix B. Emergy analysis of conventional mechanical and chemical wastewater treatment and biological treatment in a constructed wetland (TP + CW)

Note	Item	Raw unit year^{-1}	Solar transformity sej unit^{-1}	References[i)]	Solar emergy sej year^{-1},10^{15}
Free environmental resources					
1	Sun	4.60 E+14 J	1.00 E+00	Odum (1996)	0.5
2	Wind	3.00 E+12 J	1.50 E+03	Odum (1996)	4.5
3	Water	6.85 E+11 J	1.82 E+04	Odum (1996)	12.5
4	Collected seedlings	1.34 E+09 J	2.11 E+03	[ii)]	0.0
5	Collected seed	6.09 E+07 J	1.06 E+04	[iii)]	0.0
6	Loss of top soil	1.70 E+09 J	7.40 E+04	Odum (1996)	0.1
	Total emergy in free environmental resources				12.6
Purchased goods and services					
7	Electricty	3.96 E+12 J	1.19 E+05	Björklund et al., (2001)	471.2
8	Oil in transport of sludge	4.78 E+10 J	6.60 E+04	Odum (1996)	3.2
9	Concrete	1.18 E+08 g	7.34 E+08	Björklund et al. (2001)	86.6
10	Iron	1.81 E+05 g	2.65 E+09	Buranakarn (1998)	0.5
11	Bricks	1.78 E+06 g	2.52 E+09	Björklund et al. (2001)	4.5
12	Hard made surface	5.80 E+06 g	4.74 E+08	Björklund et al. (2001)	2.7
13	Insulation	7.13 E+04 g	1.84 E+09	Björklund et al. (2001)	0.1
14	Copper	1.25 E+04 g	6.80 E+10	Buranakarn (1998)	0.9
15	Plastic in pipes	1.47 E+05 g	5.87 E+09	Odum (1996)	0.9
16	Machinery	4.00 E+04 g	4.10 E+09	Brown et al. (1995)	0.3
17	Chemical precipitate; bauxite	1.29 E+08 g	1.50 E+07	Odum, (1996)	1.9
	Electricity	6.03 E+10 g	1.19 E+05	Björklund et al. (2001)	7.2
18	Polymer; electricity	1.57 E+10 J	1.19 E+05	Björklund et al. (2001)	1.9
	Gas	1.70 E+10 J	4.80 E+04	Odum (1996)	0.8
	Oil	4.09 E+09 J	6.60 E+04	Odum, (1996)	0.3
19	Service in depr. of buildings	4.07 E+05 SEK	2.15 E+11	Lagerberg et al. (1999)	87.5
20	Service in maintenance	5.67 E+05 SEK	2.15E+11	Lagerberg et al. (1999)	121.9
21	Price of land	3.00 E+04 SEK	2.15 E+11	Lagerberg et al. (1999)	6.5
22	Operation costs	4.06 E+06 SEK	2.15 E+11	Lagerberg et al. (1999)	872.9
23	Interests	5.30 E+05 SEK	2.15 E+11	Lagerberg et al. (1999)	114.0
Total emergy in purchased goods and services					1785.5
Total emergy input					1798.1

[i)]References to transformities.
[ii)]Transformity see footnote 4.
[iii)]Transformity see footnote 5.

Footnotes to Appendix B

1. Sunlight	Mean daily global radiation (Eriksson, 1981) (insolation corrected for sun hours or amount of clouds) in Stockholm, measured values. The CW is divided into vegetated and non-vegetated area. 40% of the final common pond is vegetated and 65% of other ponds are vegetated (I. Hägermark, WRS personal communication, 1998) resulting in 130 000 m^2 vegetated and 90 000 m^2 non-vegetated area. Albedo is set to 0.12 in vegetated areas and to 0.20 in open water areas, according to Eriksson (1981). (74 499) (4.1868 J cal^{-1}) (1 E+4 cm^2 m^{-2}) (130 000 m^2)+(67 726) (4.1868 J cal^{-1}) (1 E+4 cm^2 m^{-2}) (90 000 m^2)) = 4.60 E+14 J $year^{-1}$
2. Wind energy	Mean monthly wind values from Stockholm and Norrköping. For division in vegetated and open water areas, see note 1. Equations used for calculations of energy in wind as in Björklund et al. (2001) (Oke, 1978). (1.05 E+07 J m^{-2})(130 000 m^2)+(1.83 E+07 J m^2)(90 000 m^2) = 3.0 E+12 J year
3. Chemical potential energy in water used in the system	Water used in the system defined as evapotranspired water. A mix of Nyköping maximum evapotranspiration values and values from overall national Swedish evapotranspiration was used, adding up to 630 mm (Eriksson, 1981). Chemical potential energy in used water: (annual evapotranspiration) (CW area) (water density) (Gibbs free energy in rain water (Odum, 1996). (0.63 m) (220 000 m^2) (1 E+6 g m^{-3}) (4.94 J g^{-1}) = 6.85E+11 J $year^{-1}$
4. Collected seedlings	Seedlings, 860 specimen. Estimated weight of seedlings: (860 specimen) (0.250 kg $specimen^{-1}$) = 215 kg. Estimated weight of root felt: (10 m^3)(0.1 Mg m^3) (Leyshon, 1991) = 1000 kg. Total amount of organic matter:1215 kg. Heat content of grass: 4.7 KWh kg^{-1} dm (Axenbom et al., 1992). Energy in collected seeds: (1215 kg) (4.7 kWh^{-1} kg^{-1}) (3.6 E+6 J kWh^{-1}) = 2.06E+10 J. Energy $year^{-1}$: (2.06E+10 J)/(20 year life length of CW) = 1.03E+09 J. Transformity for emergy in seedlings: Net primary production above ground in wetlands: 1.6 kg m^{-2} (Andersson, 1976; Kvet and Husak, 1978). Emergy inflow m^{-2}; 5.70 E+10 sej (contribution from rain). (Emergy inflow m^{-2})/((NPP m^{-2}) (Heat content of grass) (J $kcal^{-1}$)). (5.70 E+10 sej)/((1.6 kg m^{-2}) (4.7 kWh kg^{-1}) (3.6E+6 J kWh^{-1})) = 2.11 E+03 sej J^{-1}
5. Collected seed	Amount of seed collected: 72 kg (including panicles and ears). Heat content of grass: 4.7 kWh kg^{-1} dm (Axenbom et al., 1992). Energy in collected seeds: (72 kg) (4.7 kWh kg^{-1}) (3.6 E+6 J kWh^{-1}) = 1.22 E+09 J. Energy $year^{-1}$: (1.22 E+09 J)/(20 year life length of CW) = 6.09 E+07 J. Transformity for emergy in collected seed; Net primary production above ground in wetlands; 1.6 kg m^{-2} (Andersson, 1976; Kvet and Husak, 1978). Straw and root to seed ratio; 80:20 (Cook and Evans, 1983; Evans, 1993). Emergy inflow m^{-2}; 5.70 E+10 sej (contribution from rain). (Emergy inflow m^{-2})/((NPP m^{-2}) (0.20) (Heat content of grass) (J $kcal^{-1}$)). (5.70 E+10 sej)/((1.6 kg m^{-2}) (0.2)(4.7 kWh kg^{-1}) (3.6 E+6 J kWh^{-1})) = 1.06E+04 sej J^{-1}

6. Loss of topsoil	Loss of old sea bottom (considered as organic matter) in neighboring area caused by extraction of soil with sedge (*Carex riparia* Curtis) vegetation. Amount = 65 m^3, bulk density (well decomposed organic soil (Brady, 1974) = 0.25 Mg m^{-3}. Total amount of soil organic matter (SOM): (65 m^3) (0.25 Mg m^{-3}) (1E+06 g Mg^{-1}) = 1.62+07 g. (amount of SOM) (kcal g^{-1} dry SOM (Brady, 1974)) (J $kcal^{-1}$)/(estimated generation time). (1.62+07 g)(5 kcal g^{-1}) (4186 J $kcal^{-1}$)/(200 year) = 1.70+09 J
7. Electricity	The electricity use in TP is 900 MWh $year^{-1}$ and 200 MWh to pump the wastewater to the CW (which is equivalent to the electricity use used to pump the ww from the plant to the recipient) (Hägermark et al., 1998). Oxelösund TP: 900 MWh × 3.6E+9 J MWh^{-1} = 3.24 E+12 J. Pumping to CW 200 MWh × 3.6 E+9 $JMWh^{-1}$ = 7.20 E+11 J. Total electricity use: (3.24 E+12 J) + (7.20 E+11 J) = 3.96 E+12 J
8. Oil in transport of sludge	Amount of transported sludge: 308 ton of 24% dm (1283 m^3). The sludge is transported to the landfill of Björshult for incineration, 7 km away from the TP. Mean distance return is approx. 14 km, maximum load is 10 m^3. Number of trips: 1283 m^3/10 m^3 = 129 trips. Km: 129 trips × 14 km = 1806 km. Fuel consumption: light work, tractor < 100 hk, 45% of max. pulling capacity (Grant, 1989): 7l h^{-1}. Mean speed: 10 km h^{-1}. Total fuel consumption: (1806 km/(10 km h^{-1}) × 7lh^{-1} = 1264 l diesel. Density of diesel: 37.8 MJ dm^{-3} (Mörtstedt and Hellsten, 1994) = 3.78 E+07 × 1264 = 4.78 E+10 J
9. Concrete (mechanical + chemical treatment)	(m^3 concrete at TP)(density) (estimated life length). (1.04 E+03 m^3) (2.26 E+06 gm^{-3})/(50 year) = 4.70 E+07 g. Maintenance: 3% of (total amount of concrete). 3%(1.04 E+03 m^3) (2.26 E+06 g m^{-3}) = 7.05 E+07 g. Total amount of concrete in buildings and pipes (yearly amount of concrete) + (maintenance). (4.70 E+07 g) + (7.05 E+07 g) = 1.18 E+08 g
10. Iron sheet in buildings	((total wall area) (iron density) + (total roof area) (iron density))/50 year ((4.30 E+02 m^2) (6.10 E+03 g m^{-2}) + (6.65 E+02 m^2) (9.70 E+03 g m^{-2}))/50 year = 1.81 E+05 g
11. Bricks in buildings	(wall area) (wall thickness) (brick density)/(estimated life length). (5.87 E+02 m^2) (0.12 m) (1.26 E+06 g m^{-3})/(50 year) = 1.78 E+06 g
12. Hard made	Asphalt approximately: 2900 m^2. (paved area) (weight m^{-2})/(estimated life length). (2900 m^2) (1.00 E+05 g m^{-2})/(50 year) = 5.80 E+06 g
13. Insulation in buildings	(wall area) (thickness) (density)/(estimated life length). (2.91 E+02 m^2) (3.5 E−01 m) (3.5 E+04 g m^{-3})/(50 year) = 7.13 E+04 g
14. Copper sheet in digester roof 70 m^2	(total roof area) (sheet thickness) (copper density)/(estimated life length). (70 m^2) (1.00 E−03 m) (8.96 E+06 g m^{-3})/(50 year) = 1.25 E+04 g
15. Plastic in pipes	A plastic pipe (Wittgren et al., 1994) transports the treated wastewater to the CW. (length of pipe system to CW) (weight of plastic pipe line)/(life length). (2100 m)(3.5 E+03 g m^{-1})/(50 year) = 1.47 E+05 g
16. Machinery	6 pumps at the treatment plant á 100 kg. 1 pump from plant to CW á 200 kg. ((6) (100 kg) + (200 kg) (1000 g kg^{-1}))/(20 year) = 4.00 E+04 g

17. Chemical precipitation	Used amount: 429 650 kg (H. Wallin, WRS, personal communication, 1998). Electricity use in the process of mixing Bauxite and H_25O_4 is 39 kWh ton^{-1} ALG (L. Wingren, Kemira AB, personal communication, 1999). For each ton of $AlSO_4$ produced, 300 kg of bauxite is converted (P. Andersson, Kemira AB, personal communication, 1999). Electricity: (429.6 ton)(39 kWh ton^{-1})(3.6 MJ kW h^{-1}) = 6.03 E+10 J. Bauxite: (429.6 E+08)/(1 E+06)(3.00 E+05 g) = 1.29 E+08 g
18. Polymer	Used amount: 1994 kg, (H. Wallin, WRS, personal communication, 1998). Energy use per kg polymer: (Bengtsson et al., 1997). Electricity: (2.19 kWh)(3.6 E+06 J kW h^{-1})1994 kg = 1.57 E+10 J year^{-1}. Gas: (2.37 kWh)(3.6 E+06 J kWh^{-1})1994 kg = 1.70 E+10 J year^{-1}. Oil: (0.57 kWh) (3.6 E+06 J kWh^{-1})1994 kg = 4.09 E+9 J year^{-1}
19. Service in depreciation of buildings	(H. Wallin, WRS, personal communication, 1998) CW: 8.53 E+04 SEK. TP: 3.22 E+05 SEK = 4.07 E+05 SEK
20. Service in maintenance	(H. Wallin, WRS, personal communication, 1998): 5.41 E+04 SEK CW: TP: 5.13 E+05 SEK = 5.67 E+05 SEK
21. Price of land	Land rent CW: 3.00 E+04 SEK
22. Operation costs	(H. Wallin, WRS, personal communication, 1998) CW: 2.15 E+05 SEK. TP: 3.85 E+06 SEK = 4.06 E+06 SEK
23. Interest	Interest TP: (rate) (rest value of TP). (10% interest rate) (2.8 E+06 SEK) = 2.8 E+05 SEK. Real interest CW: (interest rate) (construction cost/2) only half of the construction cost is included as a mean value over time of the CW. (10%) (5.0 E+06/2) = 2.5 E+05 SEK. Total interest: (2.8 E+05 SEK) + (2.5 E+05 SEK) = 5.3 E+05 SEK

Appendix C. Emergy analysis of wastewater treatment in a natural wetland (NW)

Notes	Item	Raw unit year^{-1}	Solar transformity sej unit^{-1}	References[i]	Solar emergy sej year^{-1}, 10^{15}
Free environmental resources					
1	Sun	4.60 E+141	1.00 E+00	Odum (1996)	0.5
2	Wind	3.00 E+121	1.50 E+03	Odum (1996)	4.5
3	Rain	6.85 E+11 J	1.82 E+04	Odum (1996)	12.5
	Total emergy in free	Environmental resources			12.5
Purchased goods and services					
4	Electricty	1.68 E+11 J	1.19 E+05	Björklund et al. (2001)	20.0
5	Plastic	1.70 E+05 g	5.87 E+08	Odum (1996)	1.0
6	Pumps	5.25 E+03 g	4.10 E+09	Buranakarn (1998)	0.0
7	Service in depr. buildings	3.66 E+04 SEK	2.15 E+11	Lagerberg et al. (1999)	7.9
8	Service in maintenance	5.07 E+04 SEK	2.15 E+11	Lagerberg et al. (1999)	10.9
9	Price of land	3.00 E+04 SEK	2.15 E+11	Lagerberg et al. (1999)	6.5
10	Operation costs	2.02 E+05 SEK	2.15 E+11	Lagerberg et al. (1999)	43.4
11	Interest	1.26 E+05 SEK	2.15 E+11	Lagerberg et al. (1999)	27.1
Total emergy in purchased goods and services					116.8
Total emergy input					129.2

[i] References to transformities

Footnotes to Appendix C.

1. Sunlight	Mean daily global radiation (insolation corrected for sun hours or amount of clouds) in Stockholm, measured values (Eriksson, 1981). Vegetated and open water areas in NW based on vegetation cover in CW, Appendix B, note 1. The NW has 130 000 m^2 vegetated and 90 000 m^2 non-vegetated area. Albedo is set to 0.12 in vegetated areas and to 0.20 in open water areas (Eriksson, 1981): (74 499 cal) (4.1868 J cal^{-1}) (1 E+4 cm^2 m^{-2}) (130 000 m^2)+(67 726 cal) (4.1868 J cal^{-1}) (1 E+4 cm^2 m^{-2}) (90 000 m^2) = 4.60 E+14 J $year^{-1}$
2. Wind energy	Mean monthly values from Stockholm and Norrköping (Eriksson, 1977). For vegetated and open water areas of NW, see Appendix B, note 1. Equations used for calculations of energy in wind as in Björklund et al. (2001). (Oke, 1978). (1.05 E+07 J m^{-2}) (130 000 m^2)+(1.83 E+07 J m^{-2}) (90 000 m^2) = 3.0 E+12 J $year^{-1}$
3. Chemical potential energy in water used in the system	Water used in the system defined as evapotranspired water. Values in NW is based on estimated evapotranspiration in CW, see Appendix B, note 3, 630 mm. Chemical potential energy in used water: (annual evapotranspiration) (wetland area) (water density) (Gibbs free energy in rain water) (Odum, 1996) (0.63 m) (220 000 m^2) (1 E+6 g m^{-3}) (4.94 J g^{-1}) (Gibbs free energy in rain water) = 6.85 E+11 J $year^{-1}$
4. Electricity for pumping	(A. Morin, ITT Flygt, personal communication, 1999). Pipe length: 2500 m (dimension 125 mm), (height increase approx 5 m) loss of pressure 18 m, capacity 6.9 1 s^{-1} (7.4 kW (MF3127). (156 420 m^3)/(24.84 m^3 h^{-1}) = 6297 h (6297 h)(7.4 kW) = 46 598 kWh. (46.6 MWh)(3.6 E+9 J MWh^{-1}) = 1.68 E+11 J
5. Plastic in pipes and pump stations	A plastic pipe (2500 m, 125 mm) transport the raw wastewater to the NW. (length of pipe system to NW) (weight of plastic pipe line) (density = 67.3 kg m^{-3})/(life length). (2500 m) (3.4 E+03 g m^{-1})(50 year) = 1.70 E+05 g
6. Machinery (pumps)	One pump with 24.84 m^3 h^{-1} capacity (1801 pe^{-1})(max factor of 2*2) = 6.3 1 s^{-1}. (Weight of pump, 105 kg (A. Morin, ITT Flygt, personal communication, 1999)/(life length of pump). (1.05 E+05 g)/(20 year life length) = 5.25 E+03 g
7. Service in depreciation of buildings	Based on expenditures for pipes in CW (Wittgren et al., 1994). Pipes: (1 400 000 SEK)/(2000 m)(2500) m = 1 750 000 SEK. Pump+automatics (A. Morin, ITT Flygt, personal communication, 1999): 32 250 SEK. (Expenditures for pipes)/(estimated life length)+(Expenditures for pump)/(estimated life length). (1 750 000 SEK)/(50 year)+(32 250 SEK)/(20 year) = 3.66E+04 SEK
8. Service in maintenance	Based on service in maintenance per kg P treated in CW (H. Wallin, WRS, personal communication, 1999; I. Hägermark, WRS, personal communication, 1998): (Cost per kg P in CW)(kg P treated in NW): (5.41 E+04 SEK)/(586 kg P)(550 kg P) = 5.07 E+04 SEK
9. Price of land	Based on land rent for CW: 30 000 SEK (Wittgren et al., 1994) = 3.0 E+04 SEK
10. Operation costs	Based on operation cost per kg treated P in CW (H. Wallin, WRS, personal communication, 1998): (Operation cost in CW kg^{-1} P treated in CW)(kg P treated in NW). (2.15 E+05 SEK)/(586 kg P)(550 kg P) = 2.02 E+05 SEK
11. Interest	Interest NW: ((interest rate) (construction cost/2) only half of the construction cost is included as a mean value over time of the NW. Construction costs based on capital cost for pipes and pump in CW (Wittgren et al., 1994). (10%) (Cost for larger pipes system and smaller pump in NW)+((Project administration costs per kg treated P in CW) (kg P treated in NW))/2). 10% (1.78 E+06 SEK)+(8.00 E+05 SEK)/(586

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