# Regional planning and product recovery as tools for sustainable sludge management

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**Abstract** The article presents two aspects of sludge management: regional planning and product recovery. The introduction of these two elements can reduce the cost, close the ecocycle and make the management more sustainable. A spreadsheet program to optimize the regional location of different facilities is presented. The simple example shows the potential of the model. The brief comparison of formal problems concerning sludge disposal in Poland and Sweden is also discussed. Requirements of phosphorus recovery and recycling of phosphorus to the phosphate industry make sludge fractionation in combination with product recovery a new development in wastewater handling. Phosphorus recovery from sludges with chemical bound phosphorus requires complex and expensive process technology and may therefore lead to increased regional sludge management with a central sludge treatment plant.

**Keywords** Product recovery; regional modelling; sludge; sustainable development

## Introduction

Local communities often face environmentally, financially and socially overwhelming problems of sludge disposal. The common reluctance to accept the sludge from the different communities pushes the parties to solve the problems individually, without taking advantage of the economy of scale. The concept of sustainable development demands an analysis of the solutions from economic, technical/environmental and social points of view.

In spite of the progress in sludge management processes three methods of sludge disposal remain the basic ones: landfilling, land application, and incineration (Campbell, 2000). It is expected that in year 2005 about 45% of sludges produced at the wastewater treatment plants in the EU will be utilized in agriculture, while 38% will be used for energy recovery and only 17% of the sludge will be stored in the landfills. Such policy remains in agreement with the policy of the European Union Council, which prioritises sludge recycling as the best sludge handling method (Kurbiel and Zeglin, 2001). Meeting these goals of sludge disposal requires maintaining the high quality sludge standards. This can be obtained by following four basic rules of sludge management policy:

- limitation “at the source” of the amount of the harmful and toxic substances incoming to the plant and effecting the sludge content
- efficient sludge processing using technically, ecologically and economically feasible methods to reduce its quantity and improve its utilization properties
- energy and product recovery through advanced sludge processing methods
- safe and environmentally sound sludge utilization, preferably as an agricultural supplement

At present, Poland and Sweden have the same structure for sludge disposal (Table 1), but the Swedish experience can be used to underline the difficulties the Polish authorities are about to face in the near future, for instance possible requirements for phosphorus recovery. The Swedish authorities have encouraged the use of sludge on agricultural land if the sludge quality fulfills certain requirements concerning heavy metals and some key organic substances (Ministry of Foreign Affairs and SEPA, 1998). However, the Federation of Swedish Farmers (LRF) recommended its members not to use sludge after January 1, 1990. Later, a national consultation group was formed in Sweden between LRF, the Swedish Water and Waste Water Association (VAV) and the Swedish Environment Protection Agency (SEPA). This group has reached agreements concerning agricultural use of sludge. The future agricultural use of sludge is, however, uncertain and under debate. Landfill of sludge will be restricted in the future and will only be allowed for sludges containing a low fraction of organic material.

Recently, Swedish policy has required phosphorus to be recycled and, because agricultural sewage sludge re-use is increasingly limited, this is putting pressure on cities to develop phosphorus recovery systems. In a number of cases, authorization to construct sludge incinerators is being given on condition that phosphorus must be recovered. A national goal has been proposed to the Swedish government that at least 75% of phosphorus from wastewater and other biological wastes should be recovered at the latest by 2010 without risks for health and environment. The Swedish Environment Protection Agency (SEPA) has been given a task from the government to evaluate possibilities of implementing this goal and propose modifications (Wallgren, 2001). During the same period the West European phosphate industry has fixed an objective of using 25% recovered phosphates, as raw material (Fielding, 2000). The mounting difficulties call for more and more advanced strategies of sludge management.

## New strategies for sludge treatment

### Principles

In the past the main focus was on reaching certain effluent requirements (for instance for phosphorus) at as low a cost as possible, reached by efficient use of chemicals and energy. At present, more attention is given to product recovery with possible future requirements for phosphorus recovery, energy production from biogas and possible use of inorganic materials in the building industry.

### Technical solutions

*Separate treatment of sludges from wastewater treatment.* In a typical wastewater treatment plant with primary sedimentation and biological treatment followed by a post-precipitation step it may be advantageous to treat the sludges separately in order to reduce the sludge production and/or recover resources. Many possibilities are available for modified operation of wastewater treatment plants for389sludge reduction and production of organic acids, precipitation agents and phosphorus products as illustrated in Figure 1. In this modi-

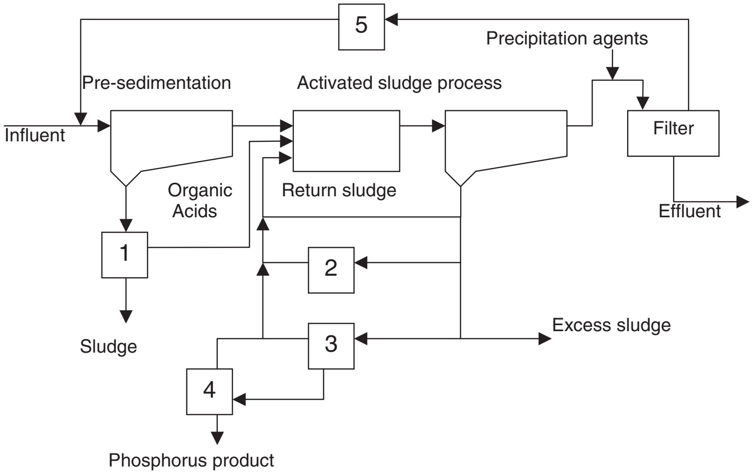
**Table 1** Sludge disposal in Sweden (VAV, 1991), in the European Union (Wilson and Jones, 1995) and in Poland (Kurbiel and Mucha, 1999)

| Disposal route | Poland (1999) % | Sweden (1988) % | European Union % |
|---|---|---|---|
| Agriculture | 35 | 35 | 32 |
| Incineration | 1 | 0 | 13 |
| Sea | | 0 | 5 |
| Landfill | 58 | | 48 |
| Deposition | | 40 | |
| Land restoration | | 15 | |
| Green belts | | 10 | |
| Others | 6 | | 2 |

fied operation the released sludge components may be separated into different products or to small flows of harmful substances such as heavy metals. The dissolution of components from sludges or ashes, increase of sludge biodegradability and recovery of products may be done at several places in the wastewater treatment plant, for sludges treated by anaerobic digestion, digested sludge and ashes.

Much attention has been given to treating primary sludges anaerobically in order to produce organic acids. These acids may be used for improvements of the biological phosphorus removal, denitrification or as a first step in anaerobic digestion. Two different types of treatment of return sludge have been used. The first type of treatment is related to biological phosphorus removal by use of the Pho-Strip method. In this case, a part of the return sludge is diverted to the anaerobic phosphorus stripper tank at a ratio of about 10–30% of the influent flow. This tank also plays the role of a thickener. Released soluble phosphate in the supernatant from the stripper tank is removed by use of chemical precipitation with for instance lime or by crystallisation. The second application of treatment of a fraction of the return sludge has the purpose of decreasing the amount of excess sludge produced. By physical (as heat), mechanical, chemical (as addition of acids, alkali or ozone) or biological (use of enzymes) treatment cell walls are destroyed and the sludge is more easily degraded, thus giving a lower sludge production (Low and Chase, 1999).

*Product recovery*. Wider application of product recovery would solve sludge handling and disposal problems in future. Sludge fractionation is normally used for hygienisation, heavy metals can be released from the sludge and handled separately, and toxic sludge-bound organic materials may be destoyed by incineration of the residue after the fractionation. During the sludge fractionation the sludge amount may be reduced significantly by dissolving inorganic materials for use as precipitation agents and the fraction of biodegradable substances can be increased. The sludge normally gets better dewatering properties. Different sludge products are obtained making it possible to obtain far-reaching goals for ecocycling of resources.



(1) Hydrolysis of primary sludge for production of organic acids
(2) Treatment of a fraction of return sludge for reduction of excess sludge production
(3) Anaerobic treatment of a fraction of the return sludge for phosphate release
(4) Precipitation of phosphate
(5) Dissolution of post-precipitated sludge

**Figure 1** Examples of modified operation of wastewater treatment plants for sludge reduction and production of organic acids, precipitation agents and phosphorus products

Sludge fractionation for product recovery has been studied at laboratory and technical scale for a long while. Technical problems may be related to process function, odour, safety and corrosion, while economy has been related to energy and/or chemical consumption and also for high costs and complexity of the installations. The difficulties of finding suitable sludge disposal options have, however, increased the interest in sludge fractionation for product recovery. In Sweden, KREPRO is the main technology studied, in which digested sludge is treated by heat, pressure and acids. The dissolved sludge components are recovered as different products (iron phosphate, precipitation agents and energy) and a small stream of toxic metals can be handled separately (Water Quality International, 1996b). Far-reaching plans exist to install KREPRO at the Sjölunda treatment plant in Malmö, Sweden (Winnfors, 1999). The Cambi system may also be developed for product recovery (Plaza *et al.*, 2000). In the Cambi process thermal hydrolysis is used before the digester (Gotthardsson, 1998). The Danish company, BioCon A/S, has recently developed a system with heat drying of dewatered sludge and incineration followed by product recovery. The recovery is based on dissolution of the formed ashes followed by product recovery of phosphorus acid, ferric iron, potassium hydrogen sulphate and heavy metals by use of a system with four ion exchangers. The system is planned to be built in the medium-sized city of Falun in Sweden (Widén, 2000).

## Regional planning as a part of advanced sludge management

### Cost minimization and role of plant size

Generally, the cost of sludge management is a sum of variable and fixed costs of disposal and the cost of sludge transportation from the WWTPs through the sludge treatment facilities to the landfill. Building larger facilities reduces the variable and fixed costs, but increases the need for sludge transportation. There is a need to find the balance among these trends. The presented model is one of many tools to assist in this decision process.

There are many different indicators of the economic performance. In this case, the presented mixed-integer facility location model minimises the total cost of waste transportation and processing, taking into account the cost of waste transportation between different facilities, processing costs at the facilities and fixed costs of the new facility construction. The fixed cost is included only if the new facility is selected to be built. The model accepts the reduction of volume of processed waste at different facilities. The model is based on the Gottinger model (Gottinger, 1991), but thanks to the flexible matrix form applied by the authors it is easily programmable and can be used in other applications. The model has been developed as an Excel spreadsheet, which makes it even more user friendly.

### A brief review of the existing models

Many models have been created over the last decades to assist in more efficient waste and sludge management. An extensive review of these models can be found in many works (MacDonald, 1996; Björklund, 1998; Stypka and Kulesza, 2000). Looking into applied solution methods, the models can be classified as linear programming (LP), mixed integer programming (MIP), heuristic or branch and bound algorithms, dynamic programming (DP), and multiobjective programming. To express uncertainty different models use probability, fuzzy, and grey systems theory. MIP models are mostly applied for economic optimisation. The effort has been made in some of these models to include the environmental impacts such as air pollution, leachate impacts, and traffic congestion. More mathematically advanced models such as grey fuzzy linear programming (GFLP) and the grey chance-constrained programming (GCCP) were also developed. Some models (dynamic) are able to incorporate changes in the system over time, while the other models are called static.

### Description of the model

The presented model is a network flow model. It assumes that the waste is generated in up to ten sources from which it is shipped through twenty transfer facilities to up to ten sinks. Source can represent the individual wastewater treatment plant where waste is generated or districts, cities or regions. At transfer facilities, which represent such facilities as incinerators, composting facilities or transfer stations, waste reduction can be obtained. Finally, the reduced volume of waste is transported to up to ten sinks – landfills. Each source can be linked with many transfer facilities and/or directly with the one or more sinks. Any transfer facility can be linked with sinks and/or all other transfer facilities. Theoretically, the sinks can also be linked with each other. The links represent the physical possibility of sludge shipment from one node to the other and are described by the unit annual cost of transportation between the nodes. The waste is being processed at the transfer facilities and at the sinks. One can consider such processes as composting, stabilisation, incineration, compaction, sorting, landfilling etc. The cost of the facility's operation is divided into two categories: the fixed cost and variable component. If the facility is at the design stage, the fixed cost covers not only the annual constant cost of the facility operation, but also its construction cost divided by the years of potential use. The variable cost is assumed to be linear to the inflow to the facility.

The total cost of waste disposal is a sum of costs of waste transportation, processing (fixed and variable cost) and the landfilling. The objective of the model is to design the system of waste treatment in such way that would make the total cost of waste disposal minimal. The mathematical form of this facility location model is presented in the equations:

$$\min z = \sum_{i\in S}\sum_{j\in I\cup L} f_{ij}t_{ij} + \sum_{k\in L}\sum_{j\in I} f_{jk}t_{jk} + \sum_{j\in I\cup L} p_j \sum_{i\in S} f_{ij} + \sum_{j\in I\cup L} F_j y_j \tag{1}$$

$$\sum_{j\in I\cup L} f_{ij} = G_i \quad \ldots \quad i\in S \tag{2}$$

$$\sum_{i\in S} f_{ij} - a_j \sum_{k\in L} f_{jk} = 0 \quad \ldots \quad j\in I \tag{3}$$

$$\sum_{i\in S\cup I} f_{ik} \le C_k y_k \quad \ldots \quad k\in L \tag{4}$$

$$\sum_{i\in S} f_{ij} \le C_j y_j \quad \ldots \quad j\in I \tag{5}$$

$$\sum_{j\in F} y_j \le 1 \tag{6}$$

$$fij \ge 0$$

Where: $f_{ij}$ = flow from i to j; S = set of sources; I = set of intermediate pseudofacilities still to be built and the intermediate facilities already in existence; L = set of pseudofacilities at landfill sites that may be "built" and the landfill facilities that already exist; F = location of potential facilities; $t_{ij}$ = transportation cost from i to j; $p_j$ = processing cost at (pseudo) facility j; $F_j$ = fixed cost at (pseudo) facility j; $G_i$ = quantity of waste generated at source i; $y_j$ = 1 if the facility j is already in existence = 0 or 1 if j is from F; $C_k$ = capacity of (pseudo) facility k

The first two terms of the objective function (1) give the total transportation costs. The third term covers the costs of processing at facilities and the fourth term gives the total fixed cost incurred. Eq. (2) implies that all the wastes generated at all sources should be shipped out. Eq. (3) is a balance equation between the input and output at intermediate facilities. Eq. (4) implies that at all facilities the amount of treated wastes is smaller or equal to their capacity. In the case of the facility that is planned to be built, there is a problem to assume its capacity, hence its fixed and variable costs. The best strategy would be to build a facility of capacity equal to the flow through the facility, when we are dealing with the static models. The problem is that the optimal flow is known after running the simulation and the costs, which can depend on the output, have to be known before the simulation is run. The difference in costs for the different sizes of the plant can be significant. To solve this problem, in the computer model one real facility is substituted by three facilities of different sizes and fixed and running costs, with the assumption that only one of them is going to be built. This is reflected in inequalities (5) and (6).

To make the presented model more universal, and to simplify programming, the model was written in the matrix form size (30 × 30). All equations and constrains are written assuming the possibility of flow between any two nodes. At the beginning, it is assumed that the cost of flow between all the nodes is infinitely large. Programming of the model, developed as an Excel spreadsheet, is limited to filling the cost matrix and entering the processing costs and capacity limits. After declaring the set of decision variables, the model is ready to be solved by the Solver procedure. Filling the cost matrix means entering the real costs of transportation only between the potential nodes and entering the capacity of the potential and existing facilities. Because there are binary variables the model is not a linear model and has to be solved as a non-linear model.

### Example calculations

To present the potential of the model the example calculations were carried out. There are four wastewater treatment plants producing different amounts of sludge a day. It is possible to transfer the sludge directly to the landfill or through the transfer station. There is also a possibility of building an incinerator that will reduce the volume of waste disposed at the landfill. The layout of the facilities and the assumed costs of operation are presented in Figure 2. The capacity constraints for the processing and disposal facilities were assumed so high not to be binding in the final solution. After entering the data into the spreadsheet and running the model the results presented in Figure 3 were obtained. The minimal total cost of transportation construction and processing is obtained with the solution that assumes the construction of the incinerator, but no transfer station. The sludge from plants 1 and 2 will be shipped directly to the landfill. Because not all the waste is incinerated before landfilling the total reduction of volume of sludge is only 41%. The total cost of disposal is to be 226 units per year.

The presented model is very simple. It minimises the sum of variable and fixed costs of transportation and disposal. The factor of time is neglected, as well as such elements as environmental and social impacts. Introduction of such indicators into the optimization procedure seems to be the next step in the model's development. Introduction of factors such as product recovery measured differently, then the sludge volume reduction should be a step in the right direction.

## Discussion

*Ecocycling*. The general environmental policy in Sweden and in many other countries is to promote ecocycling. If agricultural use for different reasons is not suitable many strategies can be used to find new cost-effective methods of ecocycling of resources from sludge such as: combined use of product recovery, short term sludge storage with possibilities to use natural processes to improve sludge properties and incineration. Ecocycling may be partly achieved if resources such as phosphorus are recovered before or after the incineration process. The ashes produced after processing may be used for instance in the building industry. In incineration, metals must be separated to a solid phase and preventive measures must be taken to avoid leakage of metals. Product recovery is facilitated by low concentra-

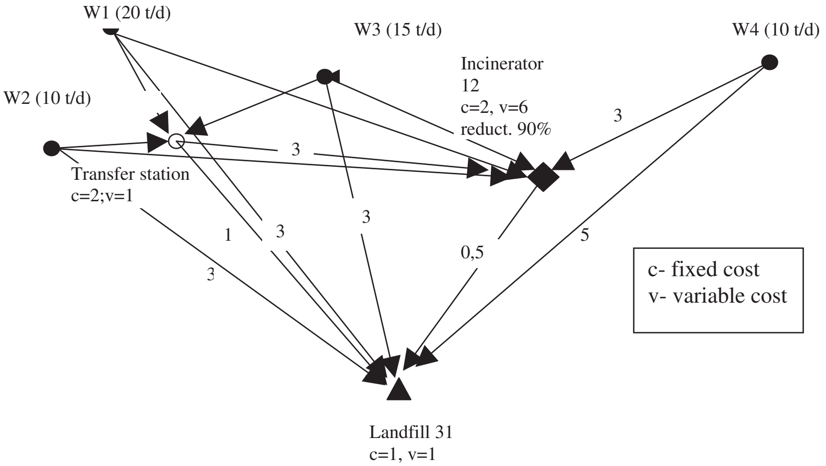
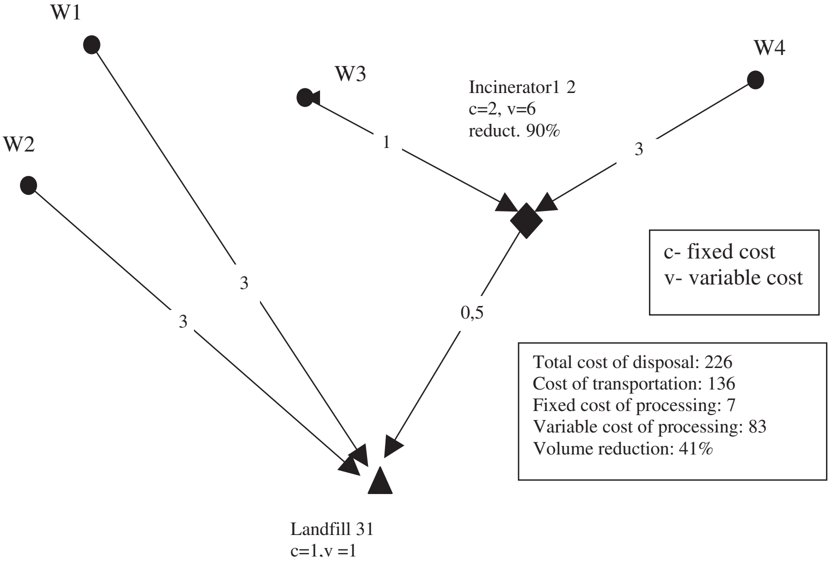


**Figure 2** The analyzed regional model of sludge treatment



Total cost of disposal: 226
Cost of transportation: 136
Fixed cost of processing: 7
Variable cost of processing: 83
Volume reduction: 41%

**Figure 3** The solution of the analyzed regional model of sludge treatment

tions of harmful substances in the sludge. A systematic approach to improve source control and certification of sludge handling should therefore be encouraged.

*Flexibility*. Flexibility is important in sludge handling. For a large municipality it may be argued that a short term sludge storage place should be a complement to the use of incineration for product recovery. The short-term storage place could be used for improvement of the sludge quality (increase of dry solids concentration and further degradation of organic pollutants) by use of mechanical or biological methods for soil production. The sludge with best quality could be used directly for agriculture, green belts, while sludges with lower quality could be used after increase of the dry solids concentration for incineration.

*Regional planning*. The economic and environmental performance of the sludge management can be improved by application of the regional planning. Many available models are seldom used due to the NIMBY syndrome that forces the communities to deal with their own waste. Applied total cost of disposal is well understood but neglects, among others, the time factor. Introduction of the time, environmental and social indicators into the optimisation procedure will make the model more complex but significantly better. Multicriteria analysis seems to be the next step in the model's development.

## Conclusions

The economic and environmental performance of sludge management can be improved by application of the regional planning and product recovery. At present, there are tools and technologies to apply these two methods. In wastewater treatment systems with chemical precipitation for phosphorus removal the systems for phosphorus recovery (KREPRO, BioCon) are rather complicated and regional handling of sludge may be advantageous. Application of even simple linear programming models, such as the one presented here, can bring significant savings.

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