An Investigation of Components in Wastewater Nutrients Management:
NATURAL SLUDGE DEWATERING AND STORAGE OF URINE

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AN INVESTIGATION OF COMPONENTS IN WASTEWATER NUTRIENTS MANAGEMENT: NATURAL SLUDGE DEWATERING AND STORAGE OF URINE

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Licentiate Thesis
Luleå, May 1996
Abstract

One important factor in developing a more sustainable sewerage system is the possibility of utilizing nutrients from human urine and faeces in agriculture. By using sewage sludge from wastewater treatment plants in agriculture, a greater proportion of phosphorus from wastewater can be recycled. However, the quality of the sludge cannot be fully trusted because of the uncontrolled mixing of different compounds in the sewer system. Thus, substances such as heavy metals will be found in the sludge. It is also noteworthy that sludge from smaller plants has a lower content of hazardous compounds compared with sludge from larger ones. Thus, it should be desirable to keep those sludges separated.

Urine, faeces and "greywater" contain different amounts of nutrients. Most of the nutrients are found in the urine. However, a significant part of the phosphorus is found in other fractions. Thus, different kinds of systems based on separation of the different fractions have been proposed. The choice of system is not obvious. The demand for a potential for efficient recycling of nutrients should be satisfied, as well as other basic criteria such as health protection and public acceptance. The choice is also influenced by the design of the existing system and the local conditions. There is also little experience of how different systems based on separation techniques work. Thus, it is necessary to improve our knowledge of the components in such systems. However, to develop a more sustainable system it is also important that the demands for resources in existing systems should be limited and that the potential for recycling of phosphorus should be improved within existing systems.

A concept based on natural sludge dewatering by a combined freezing/thawing and drying process was tested at a full-scale pilot plant. By using this process it became possible to avoid unnecessary transports of sludge. Dewatering sludge at a smaller treatment plant also meant that mixing of sludge of different quality is avoided and hence the recycling of phosphorus could be improved. The pilot plant included three types of outdoor ditches, a freezing ditch for the winter months, a drying ditch for the early summer months, and a combined drying-freezing-thawing-drying ditch (DFTD ditch) for sludge production in late summer and early autumn. The sludge was successfully dewatered in all ditches, in spite of unusually warm weather during one of the winters. The study shows that complete freezing increases the dewaterability of the sludge and that sludge that had been frozen had a porous and humus-like structure. However, the result measured as solid content is satisfactory even if all the sludge is not well frozen. The study also shows that the thawing rate in the studied ditches could be described by a simple equation based on the number of positive degree-days.

The composition of fresh urine, the nitrogen losses, and changes of pH and NH$_3$-N concentration during different storage conditions were studied. The study of the composition of the fresh urine confirmed values normally found in the literature. In laboratory studies of undiluted urine, it was shown that factors such as storage pH and temperature are important for changes in urine quality. In undiluted urine, the conversion of organic nitrogen into NH$_3$-N is a slow process. The conversion is favoured by high temperatures and inhibited by the addition of acid. In stored urine from a system with separation toilets about 85% of the nitrogen occurred as NH$_3$-N with a pH near 9. Thus, the problem of nitrogen losses from stored human urine needs to be further investigated.
Preface

The main part of the work on this thesis was carried out at the Division of Sanitary Engineering, Luleå University of Technology.

The project concerning natural sludge dewatering, presented in Papers I and II in this thesis, was supported by the Research Foundation of the Swedish Water and Wastewater Works Association (VA-FORSK) and the Municipality of Skellefteå, which are gratefully acknowledged. The study of fresh and stored urine, presented in Paper III in this thesis, was supported by the Swedish Council for Building Research, which is gratefully acknowledged.

The field work for studying the natural sludge dewatering was carried out at Lövånger, about 50 km south of Skellefteå. Without the contribution of the technical staff at the Municipality of Skellefteå the project presented in Papers I and II would not have been possible. Thus I am grateful to all the technical staff who took part in that project, and I would specially like to thank Bernt Johansson, Tore Johansson and Björn Eriksson for all their assistance during the field work. I am also grateful to PhD student Elisabeth Kvarnström at the Div. of Sanitary Engineering, Luleå University, for all her assistance and support during the project concerning natural sludge dewatering.

The study of fresh and stored urine was a result of a project conducted with PhD student Erik Kärrman at the Department of Sanitary Engineering, Chalmers University of Technology. I am grateful to Erik for his enthusiasm and support during the project concerning storage of urine.

An important person at the Div. of Sanitary Engineering is the laboratory assistant, Kerstin Nordqvist. Thus, special thanks are due to Kerstin, who continued to perform analyses even in quite unfavourable odour conditions.

I would also like to thank Mr Paul McMillen, Luleå University, who helped me by reviewing the language.

Finally, I would like to thank my supervisor, Professor Jörgen Hanæus, Head of the Div. of Sanitary Engineering, for his encouragement and support throughout this work.

Luleå in May 1996

Daniel Hellström
This thesis consists of the following parts

**Efforts to improve the sustainability of sewerage systems**

Paper I  
Natural sludge dewatering - freezing-thawing and drying combined in a full-scale pilot plant.  
*Journal of Cold Regions Engineering (subm.)*

Paper II  
The thawing-drying process in full-scale sludge freezing ditches  
*Journal of Cold Regions Engineering (subm.)*

Paper III  
Nitrogen and phosphorus in fresh and stored urine.  
*presented at the 2nd International Conference on Ecological Engineering for Wastewater Treatment*, 18-22 Sept. '95.
**Efforts to improve the sustainability of sewerage systems**

**Nutrient management in sewerage systems**

Existing sewerage systems have been designed to guarantee public health and to protect the recipients. The technical solution to this is normally a system that consists of a sewer system that collects the wastewater and transports it to a treatment plant. The collection and transport of wastewater also include the collection and transport of nutrients, because the wastewater contains substantial amounts of nutrients that originate from human consumption of food. This means that most of the nutrients that are leaving agriculture as vegetables and animal products will pass through the sewerage system. For example, about 70-80% of the nitrogen from vegetables and animal products is passing through the sewerage system (Petterson, 1992). Nutrients have been considered to be a problem because of their effects in accelerating eutrophication of lakes and promoting aquatic growth (Metcalf & Eddy, 1991). Thus, nutrient control has become an important part of wastewater treatment and treatment plants have been designed to remove the nutrients from the water. Different techniques to remove nutrients from wastewater are used (Metcalf & Eddy, 1991). In Sweden the most common solution has been to remove phosphorus by using chemical precipitants, because phosphorus has been identified as a factor limiting growth. However, increased concern about the environment in coastal areas has resulted in an upgrading of treatment plants located near the coast, to also include biological nitrogen removal (SNV¹, 1993).

The nutrients, however, may also be regarded as potential fertilizers that can be made available for agriculture. But as has been described above, the design of the sewerage system has focused on removing the nutrients, not on collecting them to use them in agriculture in an uncontaminated and manageable form.

The primary reasons for recycling nutrients are not the same for different nutrients. However, the overall objectives for recirculating nutrients are the same. Those objectives are the principles for a sustainable society, as presented by Holmberg (1995), for instance. One of the principles says, “Substances extracted from the lithosphere must not systematically accumulate in the ecosphere”, which means that the use of fossil fuels and mining must be radically decreased. Another principle says that “the use of resources must be efficient and just with respect to meeting human needs”, which practically means that an increased technical and organizational efficiency is needed. The differences in primary reasons and the common demand for sustainability are illustrated by the situation for phosphorus and nitrogen. The source of phosphorus as a fertilizer is mineral phosphorus (Günther, 1992). The amount of concentrated phosphorus in minerals is limited (Smil, 1990). Another problem with fossil phosphorus is that it is contaminated with cadmium (SNV, 1993). Thus, mining of phosphorus means a net input of cadmium into the biosphere and a risk of accumulation of cadmium. Concerning nitrogen, one could not say that the nitrogen itself is a limited resource. However, significant quantities of energy are needed to produce nitrogen fertilizer (Bockman et al., 1980). In addition, it should also be remembered that to achieve removal of nitrogen from wastewater by biological

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¹ Swedish National Environment Protection Board
methods, an extra input of energy and other physical resources are needed. The upgrading of treatment plants to achieve biological nitrogen removal also means a significant economic investment. It should also be remembered that discharge of nitrogen into the sea is considered a problem, whereas nitrogen used in agriculture can be considered as a resource.

The use of chemical precipitants at wastewater treatment plants means that most of the phosphorus entering a treatment plant will be precipitated and bound to a sludge. However, only limited amounts of other nutrients such as nitrogen and potassium are bound to the sludge (Metcalf & Eddy, 1991). Thus, if the treated wastewater is not used for irrigation, the nutrients will be lost for further utilization on farmland. The addition of a biological treatment step for nitrogen removal does not change this situation, because this method is based on nitrification and denitrification and thus the nitrogen is only transformed to nitrogen gas.

Phosphorus bound to the sludge makes the sludge interesting as a phosphorus fertilizer. Unfortunately, not only phosphorus is bound to the sludge, but also toxic compounds such as heavy metals and organic compounds that derive from the wastewater. It should be mentioned that levels of toxic compounds in Sweden have decreased during the last decades, primarily due to reduced discharges from industries into the public sewerage system (SNV, 1989). It could also be mentioned that the Swedish limits for contaminants allowed in sludge are low in an international perspective (SNV, 1993). In spite of this, the quality of the sludge is not fully trusted among agriculturalists and food producers. One uncertainty is the difficulty of guaranteeing the quality of all sludge and the risk of the presence of not analyzed, but hazardous compounds in the sludge. These uncertainties may to some extent be explained by the magnitude of the system. There is a risk that a large system might become anonymous, and that the common users might feel little responsibility for what they put into the system.

It is also noteworthy that sludge from smaller plants was found to have a lower content of hazardous compounds compared with sludge from larger ones (SNV, 1993). This is probably because larger plants normally collect wastewater from more densely populated areas and areas with more traffic and industrial activity. Thus, it should be desirable to keep the sludges separated. This means that transport of sludge from smaller treatment plants to larger treatment plants for mechanical dewatering should be avoided.

To summarize, existing systems have a large potential to collect and transport phosphorus to agriculture, but further efforts are needed before the overall quality of the sludge will be fully trusted by the agricultural and food industries.
Proposals to improve nutrient management in sewerage systems

As has been pointed out above, the recycling of nutrients is not the overall objective - but an important part of a development towards a sustainable system. This means also that the resources used to recycle nutrients are not allowed to exceed the resources saved by the recycling operation. The resources needed to recycle will be highly dependent on the design of the existing systems. For example, it could be assumed that upgrading of existing systems to collect and recirculate other nutrients than phosphorus will require large investments of physical resources and money. Hence, it is most likely that existing systems and systems developed for a more complete utilization of nutrients in wastewater will work in parallel for several years. Thus, to develop a sustainable system it is also important that the demand for resources in prevailing systems should be limited and that the potential for recycling of phosphorus should be improved within these systems.

A concept showing how the potential for recycling of phosphorus may be improved and how the demand for unrenewable resources is reduced is presented in Papers I and II of this thesis. The concept is based on natural sludge dewatering by a combined freezing-thawing and drying process. By the use of this process it becomes possible to avoid transports of the sludge from the smaller plants to a central plant to be dewatered by mechanical equipment such as centrifuges. In addition, the amount of transports of dewatered sludge to a suitable farmland is probably reduced because there are often more agricultural areas available near small plants. Dewatering sludge at smaller treatment plants also often means that mixing of sludges of different quality is avoided.

Systems designed to separate different wastes such as faeces, urine and greywater\(^2\) have been suggested. The reason for this is the distribution of nutrients in the different fractions and the concern about nutrient recycling. As seen in Table 1, most of the nutrients are found in the urine (SNV, 1995). However, a significant part of the phosphorus is also found in the faeces and there is also some phosphorus in the greywater, mainly due to detergents containing phosphorus. It is also interesting that the data presented in Table 1 concerning the amount of nutrients is close to the result of the investigation presented in Paper III of this thesis.

<table>
<thead>
<tr>
<th></th>
<th>Urine g/p.d</th>
<th>%</th>
<th>Faeces g/p.d</th>
<th>%</th>
<th>Greywater g/p.d</th>
<th>%</th>
<th>Total g/p.d</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nitrogen</td>
<td>11 (81)</td>
<td>1.5 (11)</td>
<td>1.0 (7)</td>
<td>13.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Phosphorus</td>
<td>1.0 (48)</td>
<td>0.5 (24)</td>
<td>0.6 (29)</td>
<td>2.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Potassium</td>
<td>2.5 (63)</td>
<td>1 (25)</td>
<td>0.5 (12)</td>
<td>4.0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

There are several suggestions about the separation of the wastes and the management of the separated fractions. However, a categorization is performed based on the way faeces are treated:

- Only urine is sorted out at the toilet. Faeces and greywater are collected and transported by a sewer system to a treatment plant. This means that a large part of

\(^2\) wastewater from dishes, laundries, baths and showers
the nutrients could be collected and stored as relatively concentrated urine (Malmqvist et al., 1995).

- Urine and faeces are separated. Urine is led to storage tanks and faeces could be conditioned by composting (Wolgast, 1993).
- Urine and faeces could also be treated together without being mixed with greywater. This mix of urine and faeces could then be stabilized by anaerobic or aerobic methods (Jenssen and Skjelhaugen, 1994).

The composition of the remaining wastewater will be strongly affected by the choice of system. Thus, the demand for treatment of the wastewater will be different for each system.

The design and maintenance of sewerage systems include many aspects besides the demand for efficient recycling of nutrients. The chosen system must also meet basic criteria such as minimizing the risk of infections and guaranteeing acceptable sanitary conditions. To the basic criteria could also be added that the impact on the recipient should be minimized. There are also sociological and economical aspects to consider.

The demand for a potential for efficient recycling of nutrients means that the system should handle the wastes in such a way that losses of nutrients are minimized. Thus, for a system based on urine separation the risk of nitrogen losses during storage should be studied. One question is how different storage conditions affect the transformation of nitrogen. The results from such a study are presented in Paper III. However, a high degree of nutrient recycling cannot be achieved only by the separation of urine (see Table 1). This means that the faeces either have to be collected or treated in a way that allows recycling.

Efficient recycling of nutrients also means that the resources needed to achieve nutrient recycling should be minimized. Thus, studies to reduce the resources needed for nutrient recycling are needed.

How a sewerage system should be designed and operated to achieve an efficient nutrient management is a complicated question. One problem is that many criteria should be considered as well as the local situation. Another problem is our limited experience of different components that could be used to improve the recycling of nutrients in sewerage systems. Thus, to increase our knowledge and experience of different components, different kinds of experimental work are necessary.

Thus the aim of this thesis is to present results from different experiments dealing with components that may be useful to make the management of sewerage systems more sustainable.
References


PAPER I
NATURAL SLUDGE DEWATERING - FREEZING-THAWING AND DRYING COMBINED IN A FULL-SCALE PILOT PLANT.

Daniel Hellström and Elisabeth Kvarnström

Abstract: A Swedish full-scale pilot plant employing all-year-round natural sewage sludge dewatering is presented in this paper. The treatment includes three different types of outdoor ditches, a freezing ditch for the winter months, a drying ditch for the early summer months, and a combined drying-freezing-thawing-drying ditch (DFTD ditch) for sludge production in late summer and early autumn. The test period included two consecutive winters. Complete freezing of the sludge was achieved in the first winter in contrast to the second when incomplete freezing of the sludge occurred due to an unusually warm winter. The dry matter content for the freezing ditch was, at the harvest in August, 30-70% for the first test year. The second test year yielded a sludge with a dry matter content of 20-40% in the freezing ditch. The final dry matter result for the DFTD ditch was 20-40%. The summers included were similar to the extent that both late summers were unusually warm, assisting to produce sludge of high final dry matter content. The first summer, being somewhat warmer and with a lower sludge loading, yielded a sludge of 60-90% dry matter in the drying ditch. The second summer, when the sludge load was approximately double the preceding year, resulted in a sludge of 20-60% dry matter.

Key words: natural sludge dewatering, combined freezing and drying, northern Sweden, cold climate engineering.

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INTRODUCTION

Sludge conditioning and dewatering can be costly problems to solve for small wastewater treatment plants in Sweden. Conventional pieces of equipment, such as belt filter presses and centrifuges, are too expensive treatment methods for a small treatment plant to acquire. One solution is to transport the sludge from the smaller plants into a central plant that often has more sophisticated and expensive dewatering equipment such as digestion tanks and centrifuges. The solution as such is, however, not very efficient. First, basically it means hauling water several miles from places that are remote and isolated, which is often the case in northern Sweden. This is expensive, considering the costs of personnel, equipment and fuel for accomplishing the transportation. Another drawback of this solution is the mixing of sludge from smaller plants, relatively low in heavy metal content, with sludge of inferior quality originating from the central plant. This course of action decreases the possibility of utilizing the sludge from smaller plants in agriculture.

Another approach to sludge treatment at smaller wastewater treatment plants is to employ natural sludge treatment methods. These include drying and freezing in a temperate climate. These methods must be combined in a northern country such as Sweden to avoid storing facilities for the sludge.

OBJECTIVES

The objective of the present project was to evaluate an all-year-round concept of natural sludge dewatering by a combined freezing-thawing and drying processes. The object studied was a full-scale sludge dewatering facility, treating sludge from a small wastewater treatment plant located in northern Sweden. The dewatering results were studied by investigations of the dry matter content for each component of the sludge dewatering facility. The present paper also describes how the different components of the sludge dewatering facility were used during the different seasons.

BACKGROUND

Freezing beds

Freezing and thawing as an efficient method of sludge conditioning has been known for many years and is well represented in the literature. It is known that non-dewatered sludge freezes approximately at the same speed as water (Reed et al., 1986; Farrell et al., 1970). The freezing of sludge is, however, much more complex due to its content of, among other things, electrolytes, microorganisms, and organic and inorganic particles (Vesilind & Chen, 1994). The mechanism by which the increased dewaterability is achieved when sludge is undergoing freeze-thawing is not well understood (Vesilind & Martel, 1990), and different models have been presented over the years. It seems, however, that the first separation of sludge particles and water is achieved when water freezes to ice, as presented below.

When water freezes it cannot accommodate any impurities, since the ice crystal has great symmetry and regularity. Hence, impurities, such as sludge particles, are rejected from the advancing surface of a growing ice crystal, provided a sufficiently low freezing velocity is employed (Chalmers, 1959). A transportation of impurities is
thereby obtained from the advancing ice front (Corte, 1962; Logsdon & Edgerley Jr., 1971; Cissé & Bolling, 1971; Ezekwo et al., 1980; Halde, 1980; Vesilind & Martel, 1990).

The second phase of the process of sludge particle and water separation is not well known, and different hypotheses have been presented over the years. Doe et al. (1965b) suggest that the dramatic increase in dry matter content obtained by the freeze-thaw cycle is due to the expansion of ice, which then compresses the sludge to more dense particles. Another model is suggested by Vesilind & Martel (1990), where the dehydration of flocs is due to extraction of sludge water by the surrounding and growing ice crystals.

The separation of sludge particles and water is irreversible as long as the sludge after thawing is not subjected to high shear forces (Ezekwo et al., 1980; Baskerville, 1971). The final separation is obtained when the released water drains away upon thawing and thereby leaves a product of about 20-30% DM content, having a porous structure.

The importance of complete freezing of the sludge has been stressed in the literature (Doe et al., 1965a; Clements et al., 1950). Farrell et al. (1970) conclude, after experimentation, that the filterability of a completely frozen sludge is superior to that of a partially frozen one.

Natural dewatering of sludge in outdoor freezing beds has been described by Hernebring & Lagesson (1986), for example. Farrell et al. (1970) suggested sludge application in thin layers in order to avoid snow problems. Reed et al. (1986) recommended a layer thickness of 8 cm, which was adopted by Martel (1989) in his presentation of the freeze-thaw concept as a unit operation for sludge dewatering.

Drying beds

The use of sand drying beds for natural dewatering is a well-known method. However, most of the experiences obtained are from plants with mechanical and/or biological wastewater treatment processes. The plants are, for natural reasons, mostly located in warmer climates than the treatment plant described in this paper. Most of the open drying beds are designed for 50 to 125 kg DM/m²/year (WEF, 1992).

Drying-Freezing-Thawing and Drying beds (abbreviated to DFTD beds)

The early suggestions for freezing beds were simple outdoor sludge lagoons where a single thick layer of sludge was to be frozen during the winter months (Bishop & Fulton, 1968). Rush & Stickney (1979) suggest both freezing and drying in the same bed to achieve the required dewatering of the sludge. The Drying-Freezing-Thawing and Drying concept presented in this paper is similar to that presented by Rush & Stickney (1979).

Freezing and drying beds combined

Hernebring & Lagesson (1986), Reed et al. (1986), and Martel (1993) all suggest a combination of sludge freezing and drying in order to obtain a satisfactory sludge dewatering all the year round.
DATA FOR LÖVÅNGER WASTEWATER TREATMENT PLANT

The treatment plant has approximately 1 200 pe connected. The plant employs a primary precipitation in which the phosphorus is removed from the effluent using aluminum sulfate (AVR). The sludge production is about 500 m$^3$/year, and the local sludge treatment at the plant includes a sludge thickener, polymer addition and storage. The storage facility has a capacity for around two weeks of sludge production.

FULL-SCALE PILOT PLANT DATA

The design of the full-scale pilot plant is based on previous work performed by Hernebring & Lagesson (1986). It consists of a simple outdoor construction without a roof. This is an important difference between this pilot plant and the freeze-thaw unit operation presented by Martel (1989). Martel suggests a quite advanced concrete construction with a roof in order to protect the bed against snowfall, which Martel considers as a necessity if the freezing bed is to operate properly. Both Hernebring & Lagesson and Martel suggest a construction where the bed foundation is designed for driving upon, while the ditches presented in this paper have foundations of sand, 0.3-0.5 m in thickness, hence front loaders and other heavy pieces of equipment cannot be used for driving on the surfaces.

The all-year-round sludge conditioning facility consists of two uncovered and parallel ditches, 40 m in length as shown in Figure 1. One ditch is operated as a freezing ditch. The other ditch was divided into two separate parts, one of which was operated as a drying ditch, and the other operated as a DFTD ditch.

A representative section of the freezing ditch may be seen in Figure 2. This ditch design with widths of 5-7 m was chosen in order to facilitate sludge harvesting by an excavator from the long sides.

Figure 1: Draft of sludge treatment facility.
The sludge is pumped to the ditches through HDPE piping and distributed by insulated, manually operated valves located along the long sides of the ditches.

**OPERATION OF PILOT PLANT**

A complete sludge application year cycle is displayed in Figure 3. Using this approach the sludge is efficiently dewatered all the year round.

**Figure 3.** Sludge application and harvesting schedule for the different ditches.
Freezing ditches

The freezing ditch is operated as a typical freezing bed, which means that sludge is applied, starting in early winter (November), in layers of approximately 10 cm in thickness, ideally allowing each layer to freeze before the next sludge layer is applied. The sand surface is covered with water that is allowed to freeze before the first layer of sludge is applied, consequently no immediate draining of the sludge occurs. Sludge application at the freezing ditch ends in early spring (April), see Figure 3. The freezing ditch was divided into two sub-ditches for 1995, one of which was run with polymer-blended sludge, and the other with sludge that had not been subjected to polymer treatment.

Drying ditch

The drying ditch is operated from spring until midsummer (May-June). The sludge conditioning is achieved by drainage and evaporation. This ditch was also, like the freezing ditch, divided into two sub-ditches for 1995. Polymer-blended sludge and non-polymer-blended sludge were applied in the sub-ditches, respectively.

DFTD ditch

The DFTD ditch is in operation from midsummer until early winter (July-November), and here the sludge is allowed to drain before freezing. The reason for having this ditch is that sludge produced in July-November is not completely treated by either drying or freezing, but both methods must be employed on the sludge in order to achieve reasonable dewatering.

Methods of investigation

The depth of frozen and thawed sludge, the dry matter content and the temperature in the sludge were measured during the test period. Samples for estimations of the dry matter content were collected by careful digging or by using a plastic cylinder with a diameter of 0.10 m. A bore, designed for the experiment, was used to collect samples of frozen sludge before the thawing period started. The dry matter contents in the sludge were determined by using an analytical method according to Swedish Standard SS 02 81 13.

The temperature in the sludge was measured with thermistors directly connected to small loggers. The temperature loggers, with the attached thermistors, were placed in small, 40 ml containers. The containers, containing the temperature equipment, were located in the middle of the ditches, respectively. The space between the containers was about 0.3 m, which means that the temperature was not measured in all layers. The temperature was also, at some places, measured manually by using thermocouples. Sensors for this were located in the same way as the containers containing the thermistors.
WEATHER DATA

The climate data for the pilot plant was obtained from SMHI (the Swedish Meteorological and Hydrological Institute), which has a climate station located about 500 m from the treatment plant. The only parameters measured at the station are temperature and precipitation. The air temperature was also recorded at the treatment plant and the differences between the recordings at the plant and at the climate station were negligible. Thus, it was concluded that data from SMHI could be used for the study.

The full-scale experiment was initiated in January 1994, and completed in August 1995, hence data from two winters are available. Temperature and precipitation data from these winters are presented in Figure 4 and Figure 5. The unusually cold winter of 1993/1994 and the unusually warm winter of 1994/95 are worth noting. Another interesting fact is the unusually dry late summers both in 1994 and 1995.

Figure 4: Air temperature during the test period. The figure also includes the air temperature for a "normal" year (average for 1961-1990). Data received from SMHI.
Figure 5: Accumulated precipitation during the test period. The figure also includes the accumulated precipitation for a “normal” year (average for 1961-1990). Data received from SMHI.

RESULTS

Freezing ditches

Application data and results obtained for the seasons studied are shown in Table 2.

Table 2: Sludge application data and results obtained from the freezing ditch.

<table>
<thead>
<tr>
<th></th>
<th>1994</th>
<th>1994/95 with polymer</th>
<th>1994/95 without polymer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied volume (m³)</td>
<td>110-130</td>
<td>100-120</td>
<td>110-130</td>
</tr>
<tr>
<td>Average DM content (%)</td>
<td>6-10</td>
<td>4-9</td>
<td>2-8</td>
</tr>
<tr>
<td>DM load (metric ton)</td>
<td>8-10</td>
<td>6-8</td>
<td>5-7</td>
</tr>
<tr>
<td>Sludge level before thawing (m)</td>
<td>1.05</td>
<td>1.10</td>
<td>1.00</td>
</tr>
<tr>
<td>Date for complete thawing</td>
<td>1/7/94</td>
<td>18/7/95</td>
<td>30/6/95</td>
</tr>
<tr>
<td>Date for harvest</td>
<td>23/8/94</td>
<td>14/8/95</td>
<td>14/8/95</td>
</tr>
<tr>
<td>Final sludge level (m)</td>
<td>0.4-0.5</td>
<td>0.5-0.6</td>
<td>0.4-0.5</td>
</tr>
<tr>
<td>Final sludge volume(m³)</td>
<td>50-60</td>
<td>45-55</td>
<td>35-45</td>
</tr>
<tr>
<td>Final DM content (%)</td>
<td>53 (32-72)</td>
<td>26 (20-33)</td>
<td>26 (21-31)</td>
</tr>
</tbody>
</table>

It is noteworthy that the loading for the two seasons studied is quite different, which is not the case for the measured levels. One explanation is that drainage occurred before
freezing during 1994/95. Another reason for similar sludge levels in spite of different loading rates is that the freezing bed was less efficiently used during 1994, due to drifting snow. Hence, less of the bed was filled with sludge during 1994 than during 1994/95.

The dry matter contents obtained in 1994 exceed those obtained in 1995. The most obvious reason is the different winter conditions during the two seasons in question. It was obvious that all of the sludge was frozen in 1994, and that this was not the case in 1994/95. The sludge cores drilled in April 1995 revealed layers that obviously had not been subjected to freezing. It was also very clear, while sampling the ditches during the summer of 1995, that there were layers of sticky, black, anaerobic appearance in between the more porous, less dense and completely frozen and thawed layers. However, the dry matter results obtained in 1995 are still satisfactory. A satisfactory result implies that the dry matter obtained is equal to or exceeds that normally obtained by mechanical equipment such as a centrifuge. The dewatered sludge was easily removed with an excavator, even if the incompletely frozen sludge was a little more sticky than the year before, when the sludge was more porous and less dense.

**Drying ditch**

The sludge loading and results acquired for the drying bed are shown in Table 3.

**Table 3: Sludge application data and results obtained from the drying ditch.**

<table>
<thead>
<tr>
<th></th>
<th>1994 with polymer</th>
<th>1995 with polymer</th>
<th>1995 without polymer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period of application</td>
<td>22/4/94-1/6/94</td>
<td>9/6/95-13/7/95</td>
<td>5/5/95-8/6/95</td>
</tr>
<tr>
<td>Applied volume (m³)</td>
<td>50-60</td>
<td>35-45</td>
<td>65-75</td>
</tr>
<tr>
<td>Average DM content (%)</td>
<td>7-9</td>
<td>6-10</td>
<td>3-7</td>
</tr>
<tr>
<td>Sludge load (metric ton DM)</td>
<td>4-5</td>
<td>3-4</td>
<td>3-4</td>
</tr>
<tr>
<td>Date for satisfactory dewatering result²</td>
<td>29/6/94</td>
<td>14/8/95</td>
<td>28/6/95</td>
</tr>
<tr>
<td>Harvest date</td>
<td>early Sept. '94</td>
<td>14/8/95</td>
<td>14/8/95</td>
</tr>
<tr>
<td>Final sludge level</td>
<td>8-12</td>
<td>8-12</td>
<td>10-14</td>
</tr>
<tr>
<td>Final sludge volume (m³)</td>
<td>5-10</td>
<td>5-10</td>
<td>5-10</td>
</tr>
<tr>
<td>Final DM content³</td>
<td>60-90 (20/7/94)</td>
<td>20-30 (14/8/95)</td>
<td>40-60 (14/8/95)</td>
</tr>
</tbody>
</table>

The dry matter content achieved in 1994 exceeds that obtained in 1995. To achieve a reasonable comparison between the years it is advisable to compare the results of 1994 with the results obtained for the ditch with no polymers, since the sludge application periods coincide for these ditches. But, even so, the dry matter content achieved in 1994 is higher when compared with the results obtained in 1995.

² The date when a more or less solid product with 25-30 % dry matter is obtained.
³ The date in brackets indicates the final sampling event. This final sampling event coincides with the harvest date in 1995.
After the last application of sludge, less than one month was needed to achieve a satisfactory dewatering result during 1994, see Table 3. This result was achieved during a month with a precipitation that was about 50% higher when compared with a “normal” year, and with an average air temperature slightly below that of a “normal” year. However, most of the precipitation derives from two rainfalls at the beginning and at the end of the actual period, respectively.

An interesting fact concerning the drying ditch in 1995 is that a layer of considerable thickness was applied relatively late, in mid-July, in the ditch containing polymer-blended sludge. The dry matter content was satisfactory about a month after the application, which coincides with the harvest. Considering a dry late summer, it can be concluded, for a single thick sludge layer application, that the upper loading limit of the bed was touched.

Another approach was made to evaluating the drying process. The approach in question was an estimation of the amount of cracks in the sludge surface of the drying ditch. Manual measurements resulted in an estimate that 16% of the total area was covered by cracks by the end of August 1995.

The dried sludge was compact and had a consistence resembling that of chipboard. It was also impermeable, allowing water puddles to form on the sludge surface during rainfall.

**DFTD ditch**

Application data and results obtained for the DFTD ditch are displayed in Table 4.

<table>
<thead>
<tr>
<th></th>
<th>1994/95</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied volume (m$^3$)</td>
<td>190-200</td>
</tr>
<tr>
<td>Applied volume (m$^3$/m$^2$)</td>
<td>1.10-1.15</td>
</tr>
<tr>
<td>DM content in applied sludge (%)</td>
<td>5-9</td>
</tr>
<tr>
<td>DM load (metric ton)</td>
<td>12-15</td>
</tr>
<tr>
<td>DM content before winter/freezing period (%)</td>
<td>8-25</td>
</tr>
<tr>
<td>Sludge level before thawing (m)</td>
<td>0.49</td>
</tr>
<tr>
<td>Date for complete thawing</td>
<td>20/5/95</td>
</tr>
<tr>
<td>Date for harvest</td>
<td>14/8/95</td>
</tr>
<tr>
<td>Final sludge level (m)</td>
<td>0.42</td>
</tr>
<tr>
<td>Final sludge volume(m$^3$)</td>
<td>60-70</td>
</tr>
<tr>
<td>Final DM content - average and interval (%)</td>
<td>29 (20-40)</td>
</tr>
</tbody>
</table>

The DFTD ditch has but one result, due to the fact that it was charged in the summer of 1994 and then harvested one year after, in August 1995. Hence, only one final result is available for that ditch.

As is obvious in Table 4, dewatering occurred before the freezing period due to drainage and evaporation. During the late summer of 1994 the ditch worked as a drying ditch. Due to relatively dry weather, a considerably high dry matter content.
(> 60 %) was achieved in the sludge applied during this period. The amount of sludge applied in this period was about 50 m³, which equals 25 % of the total volume applied. Sludge applied in the autumn was mostly dewatered by drainage. The combination of drying and drainage led to an increase in dry matter from the initial 5-8 % to 8-25 % before the onset of winter. Complete freezing was not achieved, due to the mild winter period of 1994/95. The freezing of the sludge was also hindered by the presence of snow and ice above the applied sludge. Notwithstanding, an increase in dry matter was obtained during the winter months, as can be seen in Table 4.

According to the application schedule shown in Figure 3, the DFTD ditch should be emptied during early summer. The results of the experiment show that an early summer harvest was possible. The DFTD ditch thawed quickly compared with the freezing ditches. The dry matter content in the sludge upon thawing was sufficient to allow harvesting by an excavator. However, the sludge was dewatered further during the summer. Nevertheless, the increase in dry matter content achieved by allowing the sludge to remain during the summer in the DFTD ditch was a few percent. Hence, not much effect was attained by leaving the sludge in the ditch through the summer.

DISCUSSION

Freezing ditch

The amount of sludge that can be applied will be limited by the thawing rate in normal Lövånger climatic conditions. The total sludge depth should not exceed 1.5 m at the end of the freezing season, according to Hemebring & Lagesson (1986). However, the actual sludge depth before thawing started was never above 1.1 m at this plant. Thus, the predicted limiting depth could not be fully tested. The reasons for the reduced depths of applied sludge were different for the two winters studied. The reason during the first winter was that the freezing ditch was not in operation before January 1994. The reason during the second winter was a very slow and incomplete freezing which allowed the sludge to drain during the freezing season. Hence the applied volume was reduced before the thawing period started.

Due to a combination of a relatively cold winter and low sludge load, a relatively high dry matter content was achieved the first year. However, it is interesting to note that a satisfactory result was obtained even during the second year in spite of the warm winter of 1994/95, see Tables 2 and 4. Even though the sludge was incompletely frozen in 1994/95, it yielded resulting dry matter contents of 20-30%, which is well in line with dry matter contents normally produced by mechanical equipment such as centrifuges.

During both years it was possible to harvest the sludge by an excavator soon after complete thawing. It should also be noted that the sludge was entirely thawed about one month before the scheduled harvest. The time necessary to achieve complete thawing was not only shortened by a reduced sludge depth and incomplete freezing, but also by thawing from the sides. The reason for this was snow and sludge interactions in the ditch. The sludge spread somewhat evenly around the valves, but did not manage to spread all the way to the sides when snow was present on the sludge surface. These snow cushions along the sides melted early, leaving the sides of the sludge exposed. This effect was most obvious during the first season’s treatment, because a larger amount of snow was entrapped during that winter. However, the
effect was significant even for the treatment during the second season. It should also be remembered that the amount of unfrozen sludge was significant only during the second season (1994/95).

It is clear that the snow has some drawbacks, in that it occupies some of the sludge ditch volume and insulates the sludge. On the other hand, the snow may refrigerate the sludge when it is present on the sludge surface. The snow appeared in the freezing ditch as ice layers, as observed in cores drilled both in the winters of 1994 (Jan-March) and of 1994/95. The ice layers, when melted during breakup, cause the sludge surface to crack and this may enhance the drying process in the sludge. All in all the extra costs of constructing a roof or shovelling snow seem to be unnecessary.

**Drying ditch**

The sludge dewatered only by drainage and evaporation had a relatively compact consistence when compared with sludge subjected to freezing. Thus, the volume reduction was larger in the drying ditch compared with that of the freezing ditch.

The results for the sub-ditch with polymer-blended sludge in 1995 indicate that the last sludge should be applied before early July in a climate similar to that of Lövånger. This is because the sludge did not have more than a satisfactory content of dry matter in the middle of August, in spite of the dry late summer of 1995.

The combined experience from the drying and DFTD ditches indicates that more sludge could have been dewatered than actually was the case during 1994-1995. The results from 1995 also show that the sub-ditch with polymer was not fully utilized. An estimation of the capacity for the drying ditches would then be that about 0.8-1.0 m³/m² or 50-80 kg DM/m² could be dewatered efficiently.

During the drying process the sludge shrinks and cracks will appear. The presence of cracks will allow the next applied layer to be in direct contact with the sand drainage layer. Thus, one could form the hypothesis that allowing a layer to crack will improve the drainage of the next layer, since the dried sludge seems to be rather impermeable.

**DFTD ditch**

The purpose of the DFTD ditch is to handle and store sludge produced during the period when satisfactory dewatering by evaporation cannot be expected, under normal climatic conditions. The applied sludge is stored in the DFTD ditch, allowing it to freeze during the winter. Hence, the total depth of the applied sludge should not exceed the expected freezing depth. For design purposes it is suitable to calculate on a drainage effect and reduction in volume before the freezing season. Before the construction of a DFTD ditch it would therefore be recommended that drainage tests should be performed for estimations of the expected volume reduction. Drainage tests are recommended due to different drainability properties for different sludges.

The drawback of allowing snow to accumulate above the sludge applied is most obvious in the DFTD ditch. Since no new sludge was applied during the winter months, therefore quite a bulky layer of snow accumulated on top of the sludge, insulating it from the cold. Hence, it seems that shovelling snow off the ditch a few
times during the winter would be suitable. However, even for the DFTD ditch, the treatment result was satisfactory in spite of the incomplete freezing.

CONCLUSIONS

The following conclusions are valid for a treatment plant operated in a climate similar to that in Lövånger.

The whole plant

The concept of combined natural treatment methods for sludge dewatering was successfully used. The plant showed great flexibility considering routines for sludge application, and a robustness to unexpected weather conditions. The results also showed that the presented schedule for application and harvesting (Figure 3) could be followed and that a correctly designed and operated treatment plant always will have at least one bed or ditch available for application of sludge.

Our experience also shows that it is favourable to have a sludge storage facility that can handle a few weeks of sludge production. The storage facility enhances the flexibility of the plant, allowing sludge to be stored for shorter periods of unfavourable weather conditions, namely are warm spells in the wintertime and rainy periods in the summertime. It should be emphasized that the storage capacity for a treatment plant using natural sludge dewatering is less than the normal storage requirement for a small WWTP having non-dewatered sludge transported to a central plant for mechanical dewatering.

Freezing ditch

During a season with complete freezing an overall average dry matter content of at least 30 % could be expected. However, the results from the second season show that it is possible to achieve satisfactory dewatering results (> 25 % DM) even if all the sludge is not completely frozen. Hence, the design seems to be rather robust to climatic variations.

The design should be based on the volume of applied sludge and the thawing rate. The main drawback with snow in the freezing ditch seems to be that the effective ditch volume is reduced.

The drying ditch

The overall final dry matter content was over 50 % after the treatment of the first year when the last application was made in early June. The same figure for the second year's treatment was over 25 % DM for the ditch where the last application had been made in the middle of July. Thus, it could be concluded that sludge applied during May-June, in a climate similar to that in this study, will be satisfactorily dewatered. The results indicate that about 0.8-1.0 m$^3$/m$^2$ or 50-80 kg DM/m$^2$ could be dewatered.

The DFTD ditch

The design should be based on the total depth of applied sludge after an initial drainage. To improve the freezing it is recommended that the snow should be
removed a few times during the winter. A final overall dry matter content near 30% shows that it is possible to achieve satisfactory dewatering results even if all the sludge is not completely frozen.

ACKNOWLEDGMENTS

The full-scale study in Lövånger was financially supported by VA-forsk (the Research Foundation of the Swedish Water and Wastewater Works Association) and the Municipality of Skellefteå, which are gratefully acknowledged. The valuable support offered by Bernt Johansson, sanitary engineer at Skellefteå Municipality Sanitary Department, was highly appreciated, as was the work performed by the staff at the Lövånger Wastewater Treatment Plant. The author is also grateful to Professor Jörgen Hanæus at the Div. of Sanitary Engineering, Luleå University, for all his assistance and support during this project.

REFERENCES


THE THAWING-DRYING PROCESS IN FULL-SCALE
SLUDGE FREEZING DITCHES

Daniel Hellström

Abstract: The thawing and drying process in full-scale sludge freezing ditches was studied. The ditches are located in northern Sweden. The treated sludge derived from a small wastewater treatment plant with mechanical and chemical treatment. Due to the relatively warm winter of 1994/95 it became possible to study the effect of incomplete freezing. The results show that frozen and thawed sludge has a porous and humus-like structure, whereas unfrozen sludge has a compact and smeary consistence. The study also shows that incomplete freezing decreases the dewaterability of the sludge, but that the result measured as solid content is satisfactory even if all the sludge is not well frozen. The study also shows that the thawing rate in the studied ditches could be described by a simple equation based on the number of positive degree-days.

Key words: natural sludge dewatering, freezing, thawing, northern Sweden, cold climate engineering

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INTRODUCTION

By using natural methods, such as freezing and thawing, it is possible to dewater sludge at smaller wastewater treatment plants. This means that long transports of undewatered sludge or investments in expensive mechanically dewatering equipment could be avoided. Another advantage of local sludge dewatering is that sludge from smaller plants, which have relatively low concentrations of heavy metals, is not mixed with sludge of inferior quality originating from a central plant. Hence, the possibility of utilizing sludge from smaller plants in agriculture is increased.

As has been described by several authors (Hernebring and Lagesson 1986; Martel 1993; Reed et al. 1986; Vesilind 1990), the sludge is dewatered by freezing it in thin layers and then letting it thaw during the following spring/summer. This strategy will allow a considerable amount of sludge to be frozen per unit area, and hence the thawing period will be the limiting design criteria in large regions. This makes it desirable to study the thawing process and provide the possibility of predicting the time and capacity needed for a satisfying treatment result.

A model for predicting the thawing design depth has been proposed by Martel (1993). The model includes parameters describing the thermal characteristics of sludge and climate data such as insolation and temperature. The model also assumes that the bed is covered to keep out precipitation. A simpler model has been suggested by Reed et al (1986). This model only considers the number of days when the temperature is above 0 °C and the mean daily temperature for each day. The thermal characteristics of the sludge and other climate factors than temperature are included in a degree-day coefficient as follows:

\[ z = \sqrt{z' \times V} \]  

(1)

where

- \( z \) = actual depth of thawing (cm)
- \( z' \) = degree-day coefficient (cm/°C*days)
- \( V \) = added number of non-freezing days multiplied by the mean daily temperature for each day. (°C*days)

Hernebring and Lagesson (1986) concluded that the equations above correlate well with experimental experience of freezing and thawing sludge on open beds. They carried out a full-scale study on three separate beds in northern Sweden. The measured \( k' \) value for thawing was between 3.8 and 4.1 cm/°C*days).

As has been described in the literature, the dewatering by freezing is accomplished through the separation of solid and liquid fractions during ice crystal formation (Halde 1980; Martel 1989; Vesilind and Martel 1990). An ice crystal grows by adding water molecules to its structure. Impurities such as the solid particles in sludge are rejected to the boundary of the crystal where these particles become consolidated. During thaw, the ice crystals melt away, leaving the consolidated and dewatered particles (Martel, 1993).
Sludge treated by freezing and thawing has a loose, earthy humus-like structure (Hemebring and Lagesson, 1986; Rush and Stickney 1979). The freeze-thaw conditioning also remarkably improves the drainability of the sludge (Martel, 1989). This means that the sludge normally could be harvested in a very short period after complete thawing is achieved (Martel 1993).

Since the ice-crystal formation is important for the separation of solid and liquid fractions, it should be interesting to know the effect of incomplete freezing. This study shows the effect of incomplete freezing on the thawing-drying process.

The data presented in this paper were collected from a full-scale plant at which a natural all-year-round concept was used. The plant is located in Lövånger (N: 64°22', E:21°13') in northern Sweden. The concept included a combination of drying and freezing/thawing ditches and has been described elsewhere (Hellström and Kvarnström, 1996). This paper will only focus on the thawing process in the freezing ditches.

OBJECTIVES

The main objective of the project presented in this paper was to study changes in solid content during the thawing and drying of frozen sludge from a treatment plant using chemical treatment. Another objective was to estimate the correlation between a simple equation describing the rate of thawing with experiences from a full-scale pilot plant experiment. A third important objective was to evaluate the effect of incomplete freezing on the dewatering process in freezing-thawing beds.

A description of the treatment plant

The all-year-round sludge conditioning facility consists of two uncovered and parallel ditches (see Figure 1). The bottom of the ditches is under-drained with sand and all excess meltwater is collected and pumped back to the wastewater treatment plant (WWTP). The first ditch is operated as a typical freezing bed, which means that sludge is applied during the winter in layers of approximately 10 cm in thickness. The dewatered sludge is harvested at the end of the following summer. The second ditch is divided into two sub-ditches. The first sub-ditch is operated as a pure drying ditch where the sludge conditioning is achieved by drainage and evaporation. The drying ditch is harvested at the end of that summer. The second sub-ditch (Drying-Freezing-Thawing-Drying ditch, abbreviated to DFTD ditch) is in operation from late summer until early winter, and here the sludge is allowed to drain before freezing. Further dewatering is achieved by freezing and thawing. The sludge can be harvested during early summer. The most important design data for the freezing ditches and DFTD ditch are given in Table 1. A more complete description of the pilot plant is given by Hellström and Kvarnström (1996).
The applied sludge came from a small (~1200 pe) wastewater treatment plant (WWTP) with mechanical and chemical treatment. The precipitant used was AVR (Aluminum sulfate containing some percentage of iron sulfate). The chemical sludge was normally stored for 2-3 weeks before it was applied to the dewatering ditches. The storage tanks also worked as a manually aerated gravity thickener without stirring. However, during April-May 1995 the WWTP was rebuilt and daily outputs of sludge were necessary.

Since polymer was added to the sludge before storage, a considerable solid concentration was achieved (see Table 1) even before pumping the sludge to the ditches. During the winter of '94/95, the freezing ditch was divided into two sub-ditches of equal size for the purpose of testing the influence of closing the polymer addition. However, the solid content was only marginally changed by the closure (see Table 1). It should be noted that it was not possible to run the two ditches parallel, since there is only one sludge storage tank in the WWTP.

The freezing and DFTD ditches were designed on the basis of the observations of Hernebring and Lagesson (1986). According to their results the thawing period will limit the possible amount of applied sludge in the freezing ditches, while the freezing period will set the limit in the DFTD ditch. However, the design was based on a lower content of dry matter than that which occurred during the experiment, and hence the freezing ditches were a bit oversized and not fully utilized.

A combination of a relatively high viscosity of sludge and the presence of snow in the ditches led to an uneven distribution of sludge. To achieve comparable data it was necessary to focus on central sections, where influences from the sides were negligible. Data for those sections are given in Table 1.
Table 1. Description of the freezing and DFTD ditches. Note that the freezing ditch was divided into two separate units before the second winter to freeze sludge with and without a polymer addition separately. The data for total solids load is mainly based on measurement of the sludge level and DM-content in the ditches after dewatering.

<table>
<thead>
<tr>
<th></th>
<th>freezing ditch</th>
<th>freezing ditch</th>
<th>freezing ditch</th>
<th>DFTD ditch</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(with polymer)</td>
<td>(with polymer)</td>
<td>(without polymer)</td>
<td>(with polymer)</td>
</tr>
<tr>
<td><strong>Design data</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length (m)</td>
<td>40</td>
<td>20</td>
<td>20</td>
<td>25</td>
</tr>
<tr>
<td>Depth (m)</td>
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<td>1.5</td>
<td>1.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Width, bottom (m)</td>
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<td>4.6</td>
<td>4.6</td>
<td>6.4</td>
</tr>
<tr>
<td>Width, top (m)</td>
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<td>9.8</td>
<td>9.8</td>
<td>7.6</td>
</tr>
<tr>
<td>Volume (m³)</td>
<td>430</td>
<td>210</td>
<td>210</td>
<td>90</td>
</tr>
<tr>
<td><strong>Time schedule</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>sludge</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>date for harvesting</td>
<td>Sept. 1994</td>
<td>16/8/95</td>
<td>16/8/95</td>
<td>16/8/95</td>
</tr>
<tr>
<td><strong>Applied load</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Volume (m³/m2)</td>
<td>0.9-1.0</td>
<td>1.4-1.6</td>
<td>1.5-1.7</td>
<td>1.1-1.3</td>
</tr>
<tr>
<td>Total solids (kg TS/m²)</td>
<td>70-90</td>
<td>100-120</td>
<td>90-110</td>
<td>80-90</td>
</tr>
<tr>
<td>TS (%)</td>
<td>6-10</td>
<td>4-9</td>
<td>2-8</td>
<td>5-9</td>
</tr>
</tbody>
</table>

The depth of frozen and thawed sludge, the solid content and the temperature in the sludge were measured during the test period. Samples for profiles of solid content were taken by careful digging, allowing one specific sample for each applied layer. Samples used only for estimation of average solid content were taken with a plastic cylinder with a diameter of 0.10 m. A specially designed bore was used to take samples of frozen sludge before the thawing period started. The boring equipment made it possible to take up an intact cylinder with a diameter of 0.20 m. Some of the frozen sludge was allowed to drain in the laboratory to estimate the direct effect of freezing and thawing. The total and volatile solid contents in the sludge were determined by using analysis methods according to Swedish standard SS 02 81 13.

The temperatures in the sludge were measured with thermistors directly connected to small loggers. The temperature loggers, with the attached thermistors, were placed in buckets with a volume of about 40 ml. The buckets, containing the temperature equipment, were placed in the middle of each respective ditch. The space between the buckets was about 0.3 m, which means that the temperature was not measured in all layers. At some places the temperature was also measured manually by using thermocouples. Sensors for this were placed in the same way as the buckets containing the thermistors.

The climate data for the pilot plant were collected by SMHI (the Swedish Meteorological and Hydrological Institute), which has a station located about 500 m from the treatment plant. The only parameters measured at that station were temperature and precipitation. The temperature was also measured at the treatment
plant and the differences were negligible. Thus, it was concluded that the data from SMHI could be used.

The amount of accumulated negative degree-days and the accumulated positive degree-days are shown in Figures 2a and 2b. The accumulated precipitation during the freezing and thawing-drying period is shown in Figures 2c and 2d. However, the data for precipitation during winter do not give a satisfactory description of the snow condition in the freezing ditches. The reason is that the construction of the freezing ditches allows snow from the surroundings to blow in and be accumulated above the applied sludge. The snow depths were only measured sporadically and the average depths varied between 0.1-0.2 m on the freezing ditches. However, the snow depths varied considerably from time to time and from place to place. The amount of accumulated snow in the DFTD ditch correlates relatively well with the amount of precipitation shown in Figure 2c. This is because the ditch was filled with sludge before the freezing period and hence the sludge surface was just below the walls of the ditch before the first snowfall. The snow depth at the end of the winter was about 0.4 m on the DFTD ditch.

Figure 2a. The accumulated number of negative degree-days during the two actual freezing seasons and for a “normal” year (average for 1961-1990). Data received from SMHI. Note that the very first sludge was applied during January 1994, which explains why the curve for 1994 starts on the curve for a normal year at 1 Jan.
Figure 2b. The accumulated number of positive degree-days during the two actual thawing seasons and for a “normal” year (average for 1961-1990). Data received from SMHI.

Figure 2c. Accumulated total precipitation and precipitation as rain during the two actual freezing seasons and for a “normal” year (average for 1961-1990). Data received from SMHI.
Figure 2d. Accumulated precipitation during the two actual thawing seasons and for a “normal” year (average for 1961-1990). Data received from SMHI.

RESULTS

The results for the different ditches are first shown separately and then compared at the end of this section.

Freezing ditch 1994 - with an addition of polymer

The number of degree-days during the winter indicates that all the sludge probably was completely frozen (see Figure 2a). Temperature measurements and observations on sampling occasions also indicate that all the sludge was completely frozen. However, the temperature in the sludge was close to 0 °C during the whole freezing season. This indicates that only a smaller amount of the sludge was deep-frozen.

The sludge level before thawing, in the center of the ditches, was about 1.05 m and at the end of August the level in the center was about 0.4-0.5 m. The level of frozen sludge was not measured during the thawing period, but from the temperature measurement it is possible to estimate a degree-day coefficient. In the upper half of the applied sludge the thawing occurred mostly in one dimension and the degree-day coefficient was 3.7 cm/√(°C*days). The snow that had been entrapped in the sludge during the winter melted away during the thawing period. This caused a collapse of the sludge level along the edges and the thawing process became more two-dimensional as the thawing proceeded. Thus, it was not possible to calculate a degree-day coefficient for the lower half of the applied sludge.

A cylinder of frozen sludge was taken up for analysis on 18 April. The cylinder had a length of 50 cm, which means that about half of the total sludge depth was represented in the sample. The analysis showed that the total solid content was about 28 %
immediately after thawing. It is also noteworthy that the volume of the boring cylinder only changed marginally during the thawing process and that the sludge structure had a porous texture when the thawing was complete.

On 23 August, three profiles were taken at different points along the central section of the freezing ditch. The total solid content varied between 70 % in the upper layer and 30 % in the lower layer (see Figure 3). The sludge was full of smaller and larger cracks and had a porous and fluffy structure. The sludge had a brown and gray color.

![Figure 3](image-url)

**Figure 3.** Total solid content at different depths at three different sampling points along the central section of the freezing ditch. The depth shows the distance below the sludge surface. Note that the total sludge depths were not equal for the three sampling points. A dotted line between two cursors represents the average total solid content for that specific layer in that specific sampling point.

*Freezing ditch 1995 - with an addition of polymer*

The number of negative degree-days during the winter also shows that problems connected with incomplete freezing could be expected. Observations of the boring core from 5 April and samples taken during the thawing period show that the freezing of the sludge was incomplete. The temperature measurements indicate that only the first applied layer of sludge had been deeply frozen. The sludge applied afterwards never reached a temperature significantly below 0 °C.

The changes of total sludge depth and the level of frozen sludge are shown in Figure 4. As shown in Figure 4, the rate of thawing could be described well by using equation (1). The constant used in the model is 3.1 cm/√(°C*days) and has been calculated by using data for temperature and levels of frozen sludge between 26/4 and 28/6. After 28 June, the thawing process becomes more and more two-dimensional.
Figure 4. Measured and modeled levels for total and frozen sludge during the thawing and drying period. The data represent average values for levels in the central section of the ditches. The fluctuation between the two last values for total sludge level is probably due to small differences in measurement techniques.

The changes in total solid content during the thawing period are illustrated by Figure 5. The figure shows the average solid content in thawed sludge and the relative amount of thawed sludge.

Figure 5. Changes in solid content during the thawing and drying period (freezing ditch 1995 - with polymer). The values are based on data from two sampling points along the central section of the freezing ditch. The percentage of thawed sludge is based on the relationship between the initial height of frozen sludge and the actual depth of frozen sludge.
The effect of thawing partially frozen sludge is illustrated by Figure 6a. The presence of a relatively thick layer of unfrozen sludge in the upper part (0.05-0.15) could be noted. The presence of snow and ice is explained by a longer period when the sludge was applied on the other freezing ditch. The figure also illustrates a drainage effect on unfrozen sludge and that the solid content in unfrozen sludge is higher than in frozen sludge.

![Figure 6a](image)

**Figure 6a.** Total solid content in frozen and thawed sludge from boring cores (1995-1996) with polymer. The depth shows the relative distance below the sludge surface (1.0 = sand bottom). A vertical line between two cursors represents the average total solid content for that specific layer.

The progress of the thawing-drying process is further described by Figure 6b. It should be mentioned that the consistency of the different layers varied considerably. Sludge in layers with higher solid content had a porous structure, indicating that it had been frozen. On the other hand, sludge with low solid content was compact and had a consistence similar to very thick oil. The upper layer had a brown-gray color, but most of the sludge had a black color. The decrease in solid content from 28 June to 6 July is explained by rainfall of about 45 mm between those days.
Figure 6b. Total solid content in thawed sludge on three different dates. The values are based on data from two different sampling points along the central section of the freezing ditch. The depth shows the relative distance below the sludge surface (1.0 = sand bottom). A vertical line between two cursors represents the average total solid content for that specific layer.

**Freezing ditch 1995 - without any addition of polymer**

The results for this ditch are similar to the results presented for the ditch with an addition of polymer. However, most of the sludge was applied during a period lasting from 10 February until early May. This means that the amount of unfrozen sludge is higher compared with the ditch described above.

The rate of thawing and the variation of the total sludge depth are illustrated in Figure 7. The dotted line in the figure is the expected level of frozen sludge according to equation (1). The degree-day coefficient for this ditch was $3.4 \text{ cm/}({\degree}{\text{C}} \cdot \text{days})^{1/2}$ and has been calculated in the same way as was described above.
Figure 7. Measured and modeled levels for total and frozen sludge during the thawing and drying period (freezing ditch without polymer). The data represent average values for levels in the central sections of the ditches. The fluctuation between the last two values for total sludge level is probably due to small differences in measurement techniques.

Variations of the average solid content in thawed sludge and the percentage of thawed sludge are shown in Figure 8.

Figure 8. Changes in total solid content during the thawing and drying period (freezing ditch 1995 - without polymer). The values are based on data from two sampling points along the central section of the freezing ditch.
The progress of the thawing-drying process is also illustrated by Figure 9. The total content of solids in each layer was connected with the consistence of the sludge as was described above. The results for 14/8 could be used an example. The sludge in the bottom layer had a porous structure indicating that it had been frozen, whereas the layer above that was compact with a smeary consistency.

![Figure 9](image.png)

**Figure 9.** Total solid content in thawed sludge on three different dates. The values are based on data from one sampling point along the central section of the freezing ditch. The depth shows the relative distance below the sludge surface (1.0 = sand bottom). A vertical line between two cursors represents the average total solid content for that specific layer.

**DFTD ditch**

As a result of the relatively mild winter 1994/95 and the presence of a snow coverage, only 30-40% of the sludge was frozen and the thickness of the frozen sludge was only 15-20 cm at the end of the freezing season. Consequently, the sludge was completely thawed on 20 May and only 90-95 positive degree-days were required. It should be mentioned that there was a 5-10 cm thick ice layer above the sludge at the end of freezing season. The ice layer was probably due to periods of rain and melting of snow during the freezing season.

The sludge depth decreased from 49 cm to 43 cm during the thawing period (26/4-20/5) and from 43 cm to 41 cm during the drying period (21/5-14/8). Thus, the depth changed marginally compared with the freezing ditches and most of the changes were a result of the thawing of frozen sludge. In contrast to the freezing ditches, where entrapped snow caused an uneven distribution of thawed sludge, the sludge surface in the DFTD ditch was even during the thawing and drying period.

The changes in total solid content during the thawing period are illustrated by Figure 10. The figure shows the average solid content in thawed sludge.
Figure 10. Changes in solid content during the thawing and drying period (DFTD ditch). The values are based on data from two sampling points along the central section of the DFTD ditch.

In Figure 11 four solid content profiles are presented. The profile for 5/4 is based on data from one sampling point and shows the solid content before the thawing period started. The other profiles, which are based on data from two sampling points, show the progress of the drying process for different layers. Most of the sludge represented in samples from the bottom layer (about 0.7-1.0) derives from sludge that was applied during the previous summer. During the previous summer the ditch worked, as the name indicates, as a drying ditch. Due to relatively dry weather, a considerably high solid content was achieved in the sludge applied during this period. As a result of the drying process the sludge shrunk and cracks appeared. The presence of cracks resulted in open volumes between the pieces of dried sludge. Thus, the sludge in the next applied layer could fill the empty volumes in the bottom layer. Hence, some of the sludge represented in samples from the bottom layer could derive from sludge applied after the previous summer. The middle layer (about 0.35-0.7) consists of sludge that was applied after the summer period. Sludge applied after the summer period was mostly dewatered by drainage. Thus, the sludge in the middle layer consists of sludge that was neither frozen nor applied during a period that allowed the sludge to dry. This sludge had a black color and a smeary consistency. The upper layer (about 0-0.35) consists of sludge that was applied during late autumn. Sludge applied just before the freezing period started was only marginally dewatered by drainage before the winter. However, the freezing of the sludge in the upper layer resulted in a product with a porous structure and gray color. It should be noted that for 28/6 and 6/7 the porous sludge in the upper layer was divided into two separate sub-layers.
Figure 11. Total solid content in sludge on four different dates. The values for 5/4 are based on data from one sampling point and the others are based on data from two sampling points along the central section of the DFTD ditch. The depth shows the relative distance below the sludge surface (1.0 = sand bottom). A vertical line between two cursors represents the average total solid content for that specific layer.

Comparison of the different ditches

The results for the different ditches are presented in Table 2.

Table 2. Results for the different ditches presented as average values for central sections along the respective ditches. Numbers put in brackets show the interval. 1Analyses of sludge from boring core samples. 2Data based on samples from 23/8/94 and 14/8/95 respectively.

<table>
<thead>
<tr>
<th></th>
<th>freezing ditch (with polymer) 1993/94</th>
<th>freezing ditch (with polymer) 1994/95</th>
<th>freezing ditch (without polymer) 1994/95</th>
<th>DFTD ditch (with polymer) 1994/95</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid content (%) In applied sludge</td>
<td>(6-10)</td>
<td>(4-9)</td>
<td>(2-8)</td>
<td>(5-9)</td>
</tr>
<tr>
<td>Immediately before thawing 1</td>
<td>11 (8-15)</td>
<td></td>
<td>15 (8-19)</td>
<td>15 (8-25)</td>
</tr>
<tr>
<td>Immediately after thawing 1</td>
<td>28</td>
<td>16</td>
<td>17 (16-19)</td>
<td></td>
</tr>
<tr>
<td>before harvesting 2</td>
<td>53 (32-72)</td>
<td>26 (20-33)</td>
<td>26 (21-31)</td>
<td>29 (20-40)</td>
</tr>
<tr>
<td>Sludge depth (cm) before thawing</td>
<td>105</td>
<td>110</td>
<td>100</td>
<td>50</td>
</tr>
<tr>
<td>before harvesting</td>
<td>45 (40-50)</td>
<td>54 (50-60)</td>
<td>46 (40-50)</td>
<td>40-45</td>
</tr>
</tbody>
</table>
DISCUSSION

The different treatment results for the two freezing seasons show the effect of incomplete freezing of applied sludge. During the first season almost all the sludge was completely frozen, but during the second season a significant amount of the applied sludge remained unfrozen. Frozen and thawed sludge had a porous and fluffy structure with a relatively high solid concentration immediately after thawing. The porous structure, in combination with larger cracks caused by the melting of the encapsulated snow, also improved the evaporation. That conclusion is confirmed both by the high solid content and the gray-brown color of the sludge after the first years' treatment. That the larger cracks derive from the melting of entrapped snow is shown by a comparison of the sludge surfaces on the freezing ditch and DFTD ditch respectively. At the DFTD ditch all the sludge was applied before the first snowfall and the distribution of thawed sludge was even compared with the freezing ditches. The unfrozen sludge had a compact structure and a consistency similar to sludge dewatered by centrifugation. The black color and the relatively low solid content imply that the sludge has not been exposed to air and that evaporation was hindered. Analyses of profiles from the second year also showed that a layer of frozen and thawed sludge beneath a layer of unfrozen sludge often had a black color. This indicates that exposure to air and evaporation from the thawed sludge was hindered. This is also indicated by a comparison of the solid content profiles for the different ditches. The profile from the first year (Figure 3) shows that the solid content continually decreased with the distance from the sludge surface. This was not the case during the second year (Figures 6b and 9). Those profiles show that a layer of frozen and thawed sludge had a higher solid content than the layer of unfrozen sludge above. Thus it could be concluded that exposure to air and evaporation from the thawed sludge was hindered by layers of unfrozen sludge. The profiles from the second year also indicate different drainability for the different sludges and different capacities to keep water. That evaporation from the thawed sludge was hindered during the second summer is also confirmed by the slow increase in solid concentration (Figures 5 and 8).

As has been mentioned, the structure and the drainability of the sludge were drastically changed by the freezing and thawing process. However, it should be noted that the solid content in incompletely frozen sludge was over 20% for all layers at the end of the summer. The results show that a satisfactory solid concentration was achieved when all the sludge had thawed completely. This was true even for the DFTD ditch and that ditch could have been emptied during the early summer.

The results from the experiment also show a larger reduction in weight than in volume. It is also noteworthy that most of the decrease in sludge depth occurred during the thawing process and that a significant part of this was due to encapsulated snow that melted away.

The relatively dry periods during the end of each summer had a positive effect on the final solid content. Most of the rain during the second summer occurred between 30/6 and 6/7. The amount of precipitation between those days was about 45 mm. The decrease in solid content as a result of the rain is shown in Figures 6b, 9 and 11. However, figures for average solid content (Figures 5, 8, 10) show that the solid content in a few days returned to a value above the value before the rain. Hence, the results suggest that a satisfactory result could be achieved even during a relatively
rainy summer. The results also indicate that the increase in water content is due to the obstruction of drainage due by the presence of layers of unfrozen sludge.

Considering the DFTD ditch, it is noteworthy that the sludge that had dried during the previous summer had a larger solid content than the layer above. This indicates a relative irreversibility of the drying process. However, as was mentioned above, some of the measured increase in solid content in the bottom layer could to some extent be explained by variation in solid content due to cracks.

Figures 4 and 7 show that the thawing rate was described well by equation (1). However, it is confusing that the constant is relatively low for the thawing process during the second year compared with results presented by Hernebring and Lagesson (1986). Because of the incomplete freezing, it was expected that the thawing rate should be higher during the second year. One possible explanation is that the thermal characteristics for incompletely frozen sludge are different compared with completely frozen sludge. Another explanation is probably that the thawing from the sides was different during the two years. The reason for this was that more snow was encapsulated during the first year compared with the second year. When the encapsulated snow along the sides melted, the sides of the sludge became exposed to air and direct insolation. Thus, it could be assumed that the thawing process was more one-dimensional during the second year compared with the first year.

CONCLUSIONS

The study shows that complete freezing is not necessary to achieve a satisfactory final solid content in sludge freezing beds. The results show that it is possible to operate an uncovered freezing bed with the presence of snow, even if the winter is relatively mild. Thus, the construction could be considered as rather robust to climate changes. However, the results also show that the dewaterability and the structure of the sludge is dramatically influenced by the freezing-thawing process. The study of solid content for different layers in the freezing bed showed that the presence of an unfrozen layer hindered the drying process of the thawed layers beneath. Another conclusion is that a simple equation based on the number of positive degree-days could be used to estimate the thawing rate.

ACKNOWLEDGMENTS

This work was supported by the Research Foundation of the Swedish Water and Wastewater Works Association (VA-FORSK) and the Municipality of Skellefteå, which are gratefully acknowledged. The author is also grateful to PhD student Elisabeth Kvarnström and Professor Jörgen Hanæus at the Div. of Sanitary Engineering, Luleå University, for all their assistance and support during this project. The author wishes also to thank the technical staff working for the Municipality of Skellefteå for valuable assistance during the field work.
REFERENCES


PAPER III
NITROGEN AND PHOSPHORUS IN FRESH AND STORED URINE

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Keywords: nitrogen, phosphorus, urine, storage, separation, wastewater, sewage, recycling

Abstract

One strategy for nutrients recycling from wastewater is to handle urine separately and use it as a fertilizer for agricultural applications. At present, there are only a few applications of urine separation in Sweden and, in most of the applications, the urine is separated in the toilet and stored in a tank. This study was divided into an investigation of the composition of fresh urine and a study of nutrient retention and transformation during storage of stored urine. The aim of the investigation of fresh urine was to determine the content of phosphorus and nitrogen in urine per person and day, and to study the daily variation of the same substances. Average values were 1.0 gP/day and 13 gN/day. The study of daily variation showed that the largest part of the quantities of phosphorus and nitrogen will appear in urine, produced at home, between 17.00-08.30. The aim of the storage studies was to estimate nitrogen losses and changes of pH and NH₃-N concentration during different storage conditions. Laboratory experiments with undiluted urine were carried out during a period of three months. The results indicate that the nitrogen concentration decreases in sampled urine through some separation process in the urine, but that losses through evaporation of ammonia were small. The increase of NH₃-N and pH is a slow process in undiluted urine and is inhibited by acidification or a low storage temperature.

Background

Today, there is an ongoing discussion concerning nutrient recycling from human urine and faeces. Phosphorus is a non-renewable substance and is therefore important to recycle. By using sewage sludge from wastewater treatment plants as a soil improver in agriculture, the greater proportion of phosphorus from wastewater can be recycled [1]. In spite of this, there is a concern over the quality of, and health risks related to, the use of sewage sludge. In the sewer system, urine and faeces are mixed with household wastewater, stormwater and industrial discharges, and will inevitably be polluted by heavy metals and toxic organic substances. These substances will be found in sewage sludge. As a result of this, sewage sludge is often disposed to a landfill. A strategy for recycling of nutrients is to handle urine separately and use it as a fertilizer [2]. A literature review concerning the content of several substances in the fractions; greywater, urine and faeces has been carried out by Sundberg [3]. One part of Sundbergs combination of data shows that urine is the source of around 70% of phosphorus and around 90% of nitrogen in blackwater (wastewater from water closets). The fact that urine contains almost all nitrogen from food increases the advantages of urine separation. Examples of advantages of recycled sewage sludge are nitrogen recycling to agriculture and minimisation of discharges of nitrogen to receiving waters. Sundbergs [3] study is based on data from studies of very specific groups of persons. The intake of food varies between groups of persons [4], which motivates the analysis of urine from a wide population of people.
There are only a few applications of urine separation in Sweden as yet. In most of the applications, the urine is separated in the toilet and stored in a tank. The tank is emptied by a farmer who collects the urine to use it as a fertilizer for agricultural applications. It is important that the system for collection, storage and handling of human urine is constructed for minimizing losses. The experience from storage and handling of animal urine is that nitrogen losses can be large. Thus, it is also desirable to study how different storage conditions influence the risk of losses of nitrogen, during storage and distribution of human urine. It is also known that urea in contact with wastewater relatively quickly decomposes into ammonia. Thus, it is interesting to study how fast the speciation of nitrogen in urine changes. The main losses are expected to occur through ammonia evaporation and thus the pH, concentration of total nitrogen and ammonia were investigated.

**Objectives**

The aims of the experiments in this study were:

- To estimate the content of phosphorus and nitrogen in whole day samples of urine, and to study the daily variation of the same substances.
- To study the losses of nitrogen as well as changes in pH and ammonia concentration under different storage conditions.
- To study the effect of urine handling on ammonia and nitrogen concentration.
- To compare the urine quality after storage of undiluted urine with the quality of stored urine from houses with systems for urine separation.

**Experiments with fresh urine**

**Experimental**

The aim of this study was to determine the content of phosphorus and nitrogen from one person during one day (24 hours), and to describe the daily variation of the same substances. One sample containing the total urine volume from one day was collected from each person, which means that the study can only describe urine in general, and not show any differences between various groups of people. The studied group of people is office working adults (not manual labour workers). The study includes analysis of daily samples of urine from 30 persons, with ages between 23 and 62 years. The sample of people included 15 females and 15 males. The daily variation was studied for 10 of the 30 persons. For these 10 persons each urination was collected separately, which means that 4-10 samples were collected per day for each person. Phosphorus analysis was made by a HACH method. The methods for analysing total phosphorus and phosphate were compared. No significant difference between the two methods in terms of concentration was found, so the less complicated phosphate method was chosen. The nitrogen analysis was carried out by means of Dr. Langes method for total nitrogen.

**Results**

The volume of urine and the content of phosphorus and nitrogen from the 30 persons in the sample are presented in table 1. The results of phosphorus and nitrogen for the whole group correspond with results from analysis of urine from persons with a normal diet [5]. There is a notable difference in quantity of phosphorus between females and males (see table 1). This is probably a result of the lower body weight of females. In a biological handbook, phosphorus in urine is related to body weight [6]. Urine from a person with a body weight of 70 kg is usually in the range of 130-300 mg N/day, kg and 10-15 mg P/day, kg. Recalculated to a value per person with a body weight of 70 kg gives 9-21 gN/pd and 0.7-1.1 gP/pd, which are values close to the results presented in table 1.
Table 1  Volume of urine and content of phosphorus and nitrogen.

<table>
<thead>
<tr>
<th></th>
<th>Volume (l/person,day)</th>
<th>P (g/person,day)</th>
<th>N (g/person,day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>The whole group</td>
<td>1.5 ± 0.5</td>
<td>1.0 ± 0.4</td>
<td>13 ± 3</td>
</tr>
<tr>
<td>Females</td>
<td>1.5 ± 0.5</td>
<td>0.8 ± 0.3</td>
<td>12 ± 3</td>
</tr>
<tr>
<td>Males</td>
<td>1.5 ± 0.5</td>
<td>1.1 ± 0.3</td>
<td>14 ± 3</td>
</tr>
</tbody>
</table>

The results from the studies of the daily variation of phosphorus and nitrogen in 10 persons urine are presented in figure 1.

![Graph of phosphorus and nitrogen daily variation](image)

Figure 1  Daily variation of phosphorus and nitrogen in urine from 10 persons.

The day has been divided into four periods, in figure 1. The morning period is between 05.00 and 08.30 (15% of the day), the day period is between 08.30 and 17.00 (35% of the day), the evening period is between 17.00 and 24.00 (30% of the day), and the night is between 00.00 and 05.00 (20% of the day). It can be noticed from figure 1 that the morning urine includes around a third of the total quantity of phosphorus and nitrogen from one day. One reason for this is that the test persons had not urinated for several hours before the morning urination. All the ten test persons were urinate at least one time during the morning period. Only two of the ten test persons urinated during the night period. Test persons are usually at home during the time periods, represented with filled staples in figure 1, and at work during the time period, represented with an unfilled staple, and consequently 75% of the daily quantity of phosphorus and 67% of nitrogen can be found in the household urine. Concerning nutrient recycling, it would therefore be advantageous to give priority to the construction of urine separation systems in residential houses, while urine separation at work may be less beneficial.

Experiments with stored urine

Experimental

Two laboratory experiments were performed to investigate how the nitrogen and ammonia concentration changed during storage. A third experiment was performed to investigate the loss of nitrogen by poor handling after storage. In addition to these experiments, samples of stored urine were taken from an “ecological village”. In water closet systems for separation of urine and faeces there will always be some amount of flushwater and probably some contamination of faeces into the urine storage tanks. Therefore, it was desireable to compare the results from the laboratory experiments with the composition of stored urine from an “ecological” village with a separated toilet system. The village, Björsbyn, is located about 5 km from Luleå. Urine was sampled from a urine tank with a volume of 10 m³. The urine has been continuously collected since september 1994 and the samples were taken in May 1995. The tank is placed underground which means that the temperature was below 5°C during the storage period.
In the laboratory experiments, bottles containing 80-85 ml of urine were used. In experiment 1, the urine was sampled by decanting 60 ml from each bottle, after storage. The aim of the decanting procedure was to investigate if there are any separation processes in the urine during storage. Instead of decanting, the whole samples were used for analysis in experiment 2. All samples in the three experiments have been frozen until analysis for NH$_3$-N, total nitrogen and phosphorus. The pH was determined immediately after sampling (before freezing). The preparation of samples for measurement was done according to Swedish standard (SIS 02 81 02, SIS 02 81 31 and SIS 02 81 34). The concentrations of total nitrogen, NH$_3$-N and total phosphorus were then measured by using an automated procedure for analysis (an autoanalyser - TRAACS 800 - Bran+Lubbe). It should be noted that both dissolved ammonia and ammonium are measured in the NH$_3$-N analysis.

The laboratory experiments were performed with undiluted urine from five males and five females, ages between 25 and 50 (see table 2).

<table>
<thead>
<tr>
<th></th>
<th>pH</th>
<th>Tot-N, g/l</th>
<th>Tot-P, g/l</th>
<th>NH$_3$-N, g/l</th>
<th>N/P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Morning urine</td>
<td>5.88</td>
<td>8.5</td>
<td>0.94</td>
<td>0.50</td>
<td>9.09</td>
</tr>
<tr>
<td>Day urine</td>
<td>6.08</td>
<td>7.25</td>
<td>0.98</td>
<td>0.41</td>
<td>7.44</td>
</tr>
</tbody>
</table>

**Experimental design**

Experiment 1 was run as a two level factorial design experiment, where effects of several storage conditions were investigated. A $2^5$ factorial design allows a preliminary screening of factors that might effect urine quality without unnecessarily detailed experiments. A $2^5$ factorial design requires 32 samples. Two levels of exposure were tested for five parameters:

- **Storage time.** The urine was stored for 9 and 64 d, respectively.
- **Temperature.** The samples were either stored at room temperature (about 23 °C) or in a refrigerator (about 6 °C).
- **Acidified/unacidified.** A dosage of 0.60 ml 4 M H$_2$SO$_4$ /100 ml urine was used to achieve an initial storage pH 3 in 16 of the 32 storage bottles.
- **Type of urine.** The urine was separated into two categories, morning- and dayurine, see table 2. The time-periods are defined in figure 1.
- **Sealed/unsealed storage.** Sixteen (16) samples were stored sealed and the remaining were stored unsealed. The samples were further placed in a sealed plastic box with a volume of three litres.

Only two different storage times were investigated in experiment 1. Thus, to follow the changes in concentrations as a function of storage time, experiment 2 was performed. In experiment 2, sixteen samples of mixed urine (50 % of each urinetype) stored for 1, 2, 5, 9, 15, 30, 64 and 87 days. Eight of the samples were stored in 4-6°C and the remaining were stored at room temperature. The urine was mixed after storage, and thus the effect of precipitation/sedimentation was eliminated.

In experiment 3 urine samples, stored for 9 and 64 days respectively, were stirred in an open 400 ml beaker for 24 hours. Before mixing, the urine had been stored in sealed bottles at room temperature. The pH, ammonia and nitrogen concentration were measured at selected intervals during the stirring period.

**Results**

In experiment 1, it was found from the factorial design, that the changes in nitrogen concentration only depend on length of storage time. No other significant effects were observed. The average
concentration of nitrogen stored for 64 d was about 7.4 g tot-N/l and urine stored for only 9 d had an average concentration of 10.1 g tot-N/l. The 95% confidence interval for the difference in nitrogen concentration between urine stored for 9 and 64 days respectively, was (1.71, 3.57) g tot-N/l. The 95% confidence interval for the difference in nitrogen concentration between urine stored during 9 and 64 days respectively, was (1.71, 3.57) g tot-N/l.

Of the studied variables, time, addition of acid and storage temperature and interactions of these, had a significant effect on the NH$_3$-N concentration. It is noteworthy that the increase in NH$_3$-N concentration is detectable for short storage times only if the urine is stored in room temperature and stored without addition of acid. For long storage times it seems to be no increase in NH$_3$-N concentration, if the temperature is kept low and acidification has been done. If one of these variables is on the high level, the increase is marginally (from 0.45 to 0.52-0.56 g amm-N/l). It is only during long storage time, high temperature and no acidification that the increase is “dramatic” (from 0.45 to 1.25 g amm-N/l).

Considering pH it is noteworthy that a combination of high temperature, long time, no acidification and unsealed storage gives the highest increases. The final pH with this combination was about 8.1-8.6. As a comparison it could be mentioned that storage in unsealed bottles placed in a refrigerator gives negligible increase in pH even if the urine was stored for 64 days.

From experiment 2, no decrease in nitrogen concentration could be detected. The concentration of NH$_3$-N and the pH increase during storage in room temperature but not when the samples were stored in a refrigerator (see figure 2). It should be noted that the NH$_3$-N concentration increases during the whole period of analysis.

![Figure 2](image)

*Figure 2* Changes in pH and NH$_3$-N during storage in 6°C and 23°C, respectively.

In experiment 3 an increase in pH for both 9 days and 64 days storage time was found. A small increase of NH$_3$-N and nitrogen concentration due to evaporation could be noted during both runs. No losses of nitrogen were detected.

The samples for analysis in the storage tank at Björsbyn were taken at three different depths. There was no large difference in concentration between the samples. The urine contained 0.90 g tot-N/l, 0.77 g NH$_3$-N/l, 0.037 tot-P g/l and 0.036 PO$_4$-P g/l. The N/P ratio was 24.7. The pH in the tank was 8.86.

**Discussions and conclusions**

The study of stored urine indicates that losses of nitrogen are small during storage of human urine. The decrease of nitrogen concentration during storage in experiment 1 is probably explained by a separation process within the urine, because the differences between different storage conditions
were insignificant. The statement about small nitrogen losses during storage is also confirmed by the fact that it was impossible to detect any losses of nitrogen in experiments 2 and 3, and that the N/P-ratio was high in the stored urine from the “ecological” village.

It has been shown that factors such as storage pH and temperature are important for changes in urine quality. The conversion of organic nitrogen into NH₃-N is a slow process, favoured by high temperature and inhibited by addition of acid. It is interesting that about 85% of the nitrogen in the long stored urine from the “ecological” village occurs as NH₃-N. This is probably explained by the relative long storage time and the dilution due to flush water and probably some fecal contaminants. It is interesting to compare the results from Björsbyn with the ratio between NH₃-N and total nitrogen in domestic wastewater and urine, which normally is 0.8. The relatively high concentration of NH₃-N combined with a high pH indicates that there is a risk for nitrogen losses due to ammonia evaporation during handling of stored urine. Thus, the problem with nitrogen losses from stored human urine needs to be further investigated.

Wastewater systems with urine separation have advantages compared to systems where nutrients are recycled from sewage sludge. Urine contains less quantities of heavy metals and toxic organic substances, but includes almost the whole quantity of nitrogen from food intake. There is still one aspect of urine separation to consider; the whole quantity of phosphorus from food intake will not be found in the urine. From a study of food habits in Sweden [7], the daily intake of phosphorus was determined as 1,3 g/p,d for adult females and 1,5-1,8 g/p,d for adult males. A comparison to the present study of fresh urine in table 1, shows that 30-40% of phosphorus from intake will not be found in urine. There is also a content of phosphorus in faeces [8]. An example of a study of metabolic balance in adult males [8], shows that for two different diets the faeces include 40% and 50% of phosphorus from intake, respectively. Recycling of phosphorus from faeces and maybe even greywater should be taken into consideration, while constructing a wastewater system with urine separation. Phosphorus is a non-renewable resource and the phosphorus from wastewater should therefore be recycled.

The results of the studies of daily variations of phosphorus and nitrogen in urine show that the urine separation system should on the first hand be applied to houses where people live. The morning, evening, and night urine contained 75% of phosphorus and 68% of nitrogen from the test groups one-day sample of urine.

Acknowledgement

This study was supported by the Swedish Council for Building Research.

References