Treatment of Log Yard Runoff

Purification in Soil Infiltration Systems and Constructed Wetlands

Åsa Hedmark
Faculty of Forest Sciences
Department of Forest Products
Uppsala

Doctoral Thesis
Swedish University of Agricultural Sciences
Uppsala 2009

Acta Universitatis agriculturae Sueciae
2009:52

Cover: Storage of logs at Heby sawmill, Sweden
(photo: P. Aronsson)

ISSN 1652-6880
ISBN 978-91-86195-99-1

Print: SLU Service/Repro, Uppsala 2009

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Abstract

Log yard runoff can be harmful to receiving watercourses, mainly because of the high concentration of organic substances and phosphorus that can cause eutrophication and oxygen depletion. This thesis assesses the effectiveness of soil infiltration and constructed wetlands to purify runoff from two log yards in Sweden storing mainly Norway spruce (*Picea abies* (L.) Karst).

The treatment efficiency of infiltration in a couch grass (*Elytrigia repens* (L.) Desv. ex Nevski) field was examined by comparing pollutant concentrations in the log yard runoff with resulting concentrations in groundwater pipes. The content of total organic carbon (TOC), total phosphorus (TP), total nitrogen (TN), suspended solids (SS) and distillable phenols was investigated during seven summer seasons. The results showed good purification capacity for TOC, TP and distillable phenols, but the infiltration had no effect on TN and SS. Intense irrigation led to increasing levels of TP in the groundwater after a few years. Reduced irrigation did not increase the purification efficiency for TOC but halted the increase of TP in the groundwater.

Infiltration in soil systems planted with four different species (*Alnus glutinosa* (L.) Gärtner (common alder), *Salix schwerinii x viminalis* (willow variety 'Gudrun'), *Lolium perenne* (L.) (rye grass) and *Phalaris arundinacea* (L.) (reed canary grass)) was assessed at a field-scale experimental site. No significant difference in treatment efficiency could be seen when comparing the different plants with each other. The infiltration was effective in reducing TOC and TP in the log yard runoff, but could not reduce SS. The self-organizing map (SOM) model was applied to the results to assess the relationships between different water quality variables, and the SOM model performed very well in predicting TN and TP concentrations.

A small constructed treatment wetland showed no significant effect when treating log yard runoff, possibly because the hydraulic load on the wetland was too high and the oxygen content too low for the biochemical processes in the wetland to reduce the concentrations of TP, TOC and SS, or because the particles in the runoff do not settle easily. A constructed wetland should either be made larger or supplemented by further treatment solutions. The results in this thesis support the use of soil infiltration rather than wetlands to treat log yard runoff.

Storage of aged windthrown logs on both log yards led to significantly higher content of TP in the runoff. Countries with a lot of forest should prepare for storing windthrown logs in a way that reduces the impact on receiving watercourses.

Keywords: Water quality, water treatment, runoff control, phosphorus, total organic carbon, forest industry, macrophytes, self-organizing map modelling, windthrown trees, wood degradation.

Author's address: Åsa Hedmark, SLU, Department of Forest Products, P.O. Box 7008, 750 07 Uppsala, Sweden
E-mail: asa.hedmark@sprod.slu.se

Dedication

To my family

Contents

List of Publications

This thesis is based on the work contained in the following papers, referred to by Roman numerals in the text:

I Hedmark, Å. & Jonsson, M. (2008) Treatment of log yard runoff in a couch grass infiltration wetland in Sweden. *International Journal of Environmental Studies* 65(2), 273-278.

II Hedmark, Å. & Scholz, M. (2008) Review of environmental effects and treatment of runoff from storage and handling of wood. *Bioresource Technology* 99(14), 5997-6009.

III Hedmark, Å., Scholz, M., Aronsson, P. & Elowson, T. Comparison of planted soil infiltration systems for treatment of log yard runoff (submitted).

IV Hedmark, Å., Zhang, L., Scholz, M., Aronsson, P. & Elowson, T. (2009) Self-organizing map analysis of planted soil infiltration systems for treatment of log yard runoff. *Forest Science* 55(2), 183-188.

V Hedmark, Å., Scholz, M. & Elowson, T. Treatment of log yard runoff impacted by aged logs in a free water surface constructed wetland (submitted).

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The contribution of Åsa Hedmark to the papers included in this thesis was as follows:

I Hedmark was responsible for the field work during 2005, performed the analysis of the results from 2003-2005 and was the main author of the paper. Jonsson was responsible for the field work during 2002-2004 and co-authored the paper.

II Hedmark performed the literature review and was the main author of the paper. Scholz reviewed the manuscript and contributed with proposals on the content.

III Hedmark was responsible for the study and the analysis of the results, and was the main author of the paper. Scholz reviewed the manuscript and gave valuable suggestions for the data analysis, structure and content of the paper. Aronsson and Elowson were responsible for the design of the study, and Aronsson provided important suggestions for the final paper.

IV Hedmark was responsible for the study and was the main author of the paper. Zhang was responsible for part of the data analysis and accompanying writing of the results and discussions. Scholz contributed to the writing and Aronsson provided valuable suggestions. Aronsson and Elowson were responsible for the design of the study.

V Hedmark was responsible for the design and implementation of the study, performed the field work and was the main author of the paper. Scholz reviewed the manuscript and contributed with important proposals for the content. Elowson initiated the research and assisted throughout the study.

Abbreviations

DOC	Dissolved organic carbon
n	Number of samples
n/a	Not analysed
PO_4^{3-}-P	Ortho-phosphate phosphorus
SS	Total suspended solids
Stdev	Standard deviation
TC	Total carbon
TIC	Total inorganic carbon
TN	Total nitrogen
TOC	Total organic carbon
TP	Total phosphorus

1 Introduction

Wood is an important natural resource and is used all over the world as an energy source, building material, raw material for paper, furniture and tools, for art and decoration purposes and a multitude of other things. All parts of the wood-handling chain, e.g. logging, transport, storage, debarking, sawing, milling, chopping and pulping can cause environmental impact (Puettman and Wilson, 2005; Zenaitis et al., 2002). The size of the impact depends on the scale and location of the operation, tree species, handling methods and preventative measures that have been implemented to reduce the impact on the environment and receiving watercourses (Zenaitis et al., 2002). This thesis presents the environmental problems associated with the runoff that is generated during the storage of logs, and provides information on methods based on biological processes that can be used to reduce the impact of the polluted runoff on natural waters.

1.1 Storage of Logs and Generation of Polluted Runoff

The logistics of the supply chain from felling of trees over transport and storage to processing of logs is of vital importance for the efficiency and economy of the forest industry (Liukko, 1997). It is often necessary to store logs in log yards to ensure smooth and continuous operation of the processing facilities despite seasonal variations in the wood supply chain. Log yard surfaces are usually made hard and impenetrable to make the ground in the storage areas more drivable for vehicles handling the logs and to reduce the amount of dirt and gravel on the logs, which could disturb further processing (Jonsson, 2004).

1.1.1 Reasons for Pollution Generation at Wood Handling Sites

Contaminated stormwater runoff from log yards is generated when precipitation comes into contact with wood, woody debris, equipment and vehicles at outdoor wood sorting, processing and storage facilities. Soluble compounds and particles from bark and wood are taken up by the water and become part of the site runoff (Bailey et al., 1999; Woodhouse and Duff, 2004). Runoff can also be generated by application of water for dust and fire control (Orban et al., 2002).

In northern Europe, Canada and South Africa it is also common that stored logs are sprinkled with water to protect them from biological attack and cracking due to dehydration (Eriksson et al., 2007; Malan, 2004; Webber and Gibbs, 1996). The sprinkling creates a protective water film on the wood surface and keeps the moisture content in the sapwood above 50%, which protects the logs from damages caused by drying cracks, fungi and insects (Liukko and Elowsson, 1999).

1.1.2 Runoff Quantity and Associated Problems

The quantity of runoff from a log yard that reaches groundwater or nearby watercourses depends on the permeability of the log yard, evaporation rate, if the runoff is collected for reuse or long-term storage and if sprinkling of the logs takes place at the storage site (Paper II). If sprinkling takes place, it can be climate-adapted to reduce the use of sprinkling water and the amount of the corresponding runoff. The sprinkling intensities can be decreased with this method by between 31% and 97% over a 24-h period (Liukko and Elowson, 1995). However, the creation of runoff is not completely eliminated because of required safety margins to ensure that the logs never become too dry and the necessary maintenance of water pressures in the sprinkling systems.

The water that accumulates on the impenetrable surfaces is sometimes collected and recycled for continued sprinkling of the logs. However, recirculation of the water can lead to a deterioration of the quality of the wood due to the presence of pollutants and microorganisms in the recycled water (Borgå et al., 1992). Furthermore, the presence of potentially pathogenic microorganisms in the recycled water might also lead to health hazards for workers in sawmills. In most cases, the water on both sprinkled and non-sprinkled log yards is therefore allowed to flow to the nearest watercourse as surface runoff (Staland et al., 2000; Woodhouse, 2004).

A medium-sized log yard in central Sweden with a climate-adapted sprinkling and non-re-circulating system uses approximately 100,000 m^3 water between May and September. During this period, the amount of log yard runoff may be as high as 70,000 m^3 (Jonsson, 2004). Such a large amount of water needs to be drained away to make it possible to operate vehicles in the log yard, and the runoff can negatively affect the flow and pollution levels in receiving watercourses.

When the sprinkling water is taken from a watercourse the abstraction of water can also cause problems, especially if the watercourse is small and has a low flow during the sprinkling season. The natural water level of the watercourse might be altered too much by the abstraction, leading to changes in the physical, chemical and biological conditions and functions of the ecosystem. A reduced flow of water can also negatively affect other water users downstream of the abstraction point (Richter et al., 2003). If the watercourse only has a low flow the emitted runoff might have a considerable negative effect on the ecosystem due to the resulting comparatively large proportion of contaminated water and high concentrations of pollutants.

1.2 Runoff Quality

There are considerable differences in the characteristics of runoff from storage of wood in different studies. The contamination level of the runoff that reaches the receiving watercourse depends on, for example, the species of tree stored on the log yard, the proportion of the runoff that has come in contact with stored wood, whether sprinkling is performed and if the water is collected and re-circulated, as well as the possible dilution or pre-treatment of the runoff (DeHoop, 1998; Paper II).

Different species of trees contain varying concentrations and types of soluble compounds, and the ease with which the resultant extractives are leached from the wood can greatly influence the runoff concentration and the corresponding toxicity (Zenaitis et al., 2002). According to studies where different tree species have been directly compared with each other, there are differences in the characteristics of the generated runoff. For example, emissions from storage of *Picea abies* (L.) Karst (Norway spruce) are generally greater than those from *Pinus sylvestris* L. (Scots pine) (Borgå et al., 1996b). In leaching experiments reported by Pease (1974), the relative chemical oxygen demand leaching rates of four species of trees were, in descending order; *Thuja plicata* (red cedar), *Chamaecyparis nootkatensis* (D. Don) Oerst. (yellow cedar), *Tsuga heterophylla* (Raf.) Sarg. (hemlock) and *Picea sitchensis* (Bong.) Carr. (Sitka spruce). It is also likely that the duration of time for which the wood has been stored before the samples are taken influences the concentration of pollutants in the runoff because of degradation processes in the wood (Feist et al., 1971).

In general, log yard runoff has the following characteristics (DeHoop, 1998; Paper II):

- High concentration of organic substances, some of which may be toxic to aquatic plants and animals;
- Relatively high amount of particles;
- Medium to high concentration of phosphorus;
- Low concentration of nitrogen;
- Usually low concentration of (heavy) metals; and
- Low to neutral pH.

Of the organic compounds extracted from softwood, tannins, lignins, phenols, tropolones, volatile fatty acids and resin acids are of greatest concern because they might contribute to runoff toxicity (Paper II; Samis et al., 1999). The amount of particles in the runoff can also be relatively high (DeHoop et al., 1998; Woodhouse and Duff, 2004). In addition, the increased concentration of phosphorus in log yard runoff might lead to considerable loads in the large runoff volumes produced from a sprinkled log yard every year. The concentration of nitrogen, however, is generally relatively low if compared to corresponding concentrations in natural watercourses (Paper II; Scholz, 2006). The pH has been shown to be very low in some studies (*Thuja plicata* (red cedar), *Chamaecyparis nootkatensis* (yellow cedar) and *Populus tremuloides* Michx. (trembling aspen)) (Tao et al., 2005; Taylor et al., 1996) and neutral in other studies (*P. abies* and *P. sylvestris*) (Paper II; Borgå et al., 1996b; Jonsson et al., 2004).

1.3 Effects of the Runoff on the Receiving Watercourse

Pollutants in the runoff influence the receiving watercourse in different ways, largely depending on the geographical location, water flow, size and chemical and biological characteristics of the watercourse. The organic material in runoff can cause oxygen depletion when it is biologically and chemically degraded. Furthermore, organic compounds and (heavy) metals can have a toxic effect on aquatic plants and animals, e.g. fish and planktonic crustaceans (Pease, 1974; Taylor et al., 1996).

The phosphorus in the runoff can cause eutrophication, and particles in the runoff can have a negative impact on plant and animal life due to clouding of the water and sedimentation on substrates (Bailey et al., 1999; Karrash et al., 2006; Scholz, 2006). The water chemistry of the watercourse can change, e.g. to a more eutrophic state, because of the discharge of log yard runoff, and the abundance and distribution of different species can be affected (Arimoro and Osakwe, 2006). If a lot of particulate matter and pieces of bark are released the benthic epifauna might be affected by burial and a reduction of available habitat (Pease, 1974; Wood et al., 2005). The environmental impact of log yard runoff is increasingly recognised by environmental authorities and regulators as an urgent problem that needs to be addressed through a reduction of pollutant emissions (McDougall, 2002).

1.4 Effects of the Storm 'Gudrun'

In January 2005, the storm 'Gudrun' devastated large parts of the forests of southern Sweden. Approximately 70 Mm^3 of timber were windthrown in just one night, equalling a mean annual felling in the whole country but impacting on less than 20% of the total forested area (Björheden, 2007). The gross value of the fallen timber was equivalent to over SEK 20 billion (Skogsstyrelsen, 2006).

The severe storm was a disaster for the Swedish forest industry, and a devastating blow for a lot of private forest owners who saw their livelihoods and the hard work of previous generations swept away. The storm also gave rise to logistical problems on a large scale. Insects such as *Tomicus piniperda* L. (common pine shoot beetle), *Ips typographus* L. (European spruce bark beetle) and *Trypodendron lineatum* (Olivier) (striped ambrosia beetle) pose a great risk to the forest industry (Lindelöw et al., 1992; Müller et al., 2002; Zhang and Schlyter, 2003). Because of the high risk of insect damage on standing trees due to the presence of windthrown trees, which are breeding substrate for these insects, excessive amounts of windthrown trees should be removed from the forest before July each year (Wichmann and Ravn, 2001).

Despite great efforts from the whole forestry sector, it was not possible to get all the windthrown trees out of the forests during 2005 (Skogsstyrelsen, 2006). Therefore, in 2006 and even 2007, a lot of sawmills and temporary storage sites in the southern half of Sweden were storing and sprinkling windthrown logs that had been left in the forest for more than a year before being transported to the storage area. Time pressure directly after the storm made it difficult to find suitable storage sites for the windthrown trees, and the runoff from the large temporary storage sites was considered by the environmental authorities to be a potential threat to local groundwater and receiving watercourses.

1.5 Overview of Applied Treatment Methods for Log Yard Runoff

Given the high load of organic compounds in the runoff, any method used to effectively treat this wastewater has to allow for the degradation of these compounds. When the level of phosphorus in the runoff is a problem, an efficient purification method must also be able to reduce the concentration of phosphorus in the water before it reaches the receiving watercourse. Several different technologies such as biological systems (e.g. aeration lagoon, activated sludge process and constructed wetland), and physical and chemical systems (e.g. carbon adsorption, coagulation, ion exchange, neutralisation, precipitation, reverse osmosis, chelation, and chemical oxidation using ozone, calcium hypochlorite, hydrogen peroxide and potassium permanganate) have been proposed for the treatment of runoff from wood handling sites (Orban et al., 2002; Samis et al., 1999).

Operators of log yards and sawmills are often relatively small companies with low turnover and low profit margins (Lähtinen and Toppinen, 2008). It is important to develop treatment methods with reasonable costs for installation and maintenance to ensure continued commercial survival of these companies. The content of organic compounds and nutrients in log yard runoff make it suitable for biological treatment, providing it does not contain too high concentrations of toxic substances. Semi-natural systems such as constructed treatment wetlands and soil infiltration systems do not require high technical maintenance, and the amount of labour necessary to keep them operating is low. In general, these systems are less costly than conventional techniques used for the treatment of wastewater (Kadlec et al., 2006), and have therefore been assessed for treatment of wood waste leachate and log yard runoff in different studies (Jonsson et al., 2004; Masbough et al., 2005).

1.5.1 Treatment Wetland

The use of vegetated wetlands usually leads to better purification results for different wastewaters than lagoons or ponds (Kadlec, 2005). There are various reasons for the better efficiency. Macrophytes act as mechanical filters and provide substrate for microorganisms, which take part in degradation and absorption processes of pollutants (Hempel et al., 2008; Huang et al., 2008). Furthermore, aquatic plants may aerate the water and sometimes also the root zone, creating aerobic conditions that lead to faster degradation of organic matter (Colmer, 2003; Gagnon et al., 2008). Macrophytes also reduce the flow speed of the incoming water, giving particles longer time to settle. However, the major mechanism for the removal of organic carbon from wood waste leachate during long-term operation is likely to be biological degradation (Tao et al., 2007).

There are several studies of constructed wetlands for treatment of wood waste leachate, and a few that investigate the treatment efficiency for log yard runoff (listed in Paper II). These studies found that the performance of wetlands for the treatment of wood waste leachate was partly regulated by the dissolved oxygen concentration and the availability of bacterial substrates, and that chemical oxygen demand, tannin and lignin were further removed through wetlands operating in series (Tao et al., 2006a). It was also noted that mass reduction efficiencies (%) increased significantly with hydraulic retention time (Tao et al., 2006b), and that the effectiveness of constructed wetlands for the treatment of wood waste leachate increased with the age of the wetland (Masbough et al., 2005). A comprehensive review of the results from these and further studies can be found in Paper II.

Most treatment wetland studies have mainly focused on the removal of organic matter from wood waste leachate and log yard runoff, and no studies have been found that assess the removal efficiency for phosphorus. However, constructed wetlands have shown good treatment effect with respect to the removal of phosphorus for other types of natural and industrial wastewaters (Braskerud, 2002; Scholz, 2006).

1.5.2 Soil Infiltration

Soil infiltration techniques have been shown to reduce the concentrations of several different types of pollutants in water (Kruzic, 1994; Scholz, 2007). During soil infiltration, the reduction of pollutants is due to physical, chemical and biological processes taking place in the combined soil, plant and water ecosystem (Wang et al., 1999). Biological degradation, mineralization and adsorption are the major mechanisms contributing to the reduction of organic substances in the soil column. The degree of degradation, assimilation, sorption, exchange and neutralisation during the infiltration also depends on the velocity of the solution through the soil. If contaminants are predominantly retained through adsorption, a breakthrough of pollutants can occur when the soil adsorption capacities are exceeded (Wang et al., 1999).

An early study by Peek and Liese (1977) in Lower Saxony (Germany) concluded that the purifying capacity of the soil in the area where windthrown timber was stored and sprinkled for a year was sufficient to prevent a decline of water quality in an adjoining well or stream.

More recent experiments by Jonsson et al. (2004, 2006) with lysimeters have shown relatively good purification results for organic matter and phosphorus in log yard runoff. There was no difference in purification efficiency for total organic carbon, distillable phenols, total phosphorus and total nitrogen when different lysimeters were planted with *Elytrigia repens* (L.) Desv. ex Nevski (couch grass), *Salix sp.* (willow) and *Alnus glutinosa* (L.) Gärtner (alder) and compared with each other. Furthermore, no clear differences were found between lysimeters containing sand or clay.

1.6 Assessment of Field-scale Experiments

It is often necessary to verify the results from laboratory studies before full-scale treatment systems can be constructed. Field-scale experiments can be used to test if similar treatment results as in the laboratory can be reached under real conditions without having to invest in a full-scale system before the results have been verified.

The main problem with field-scale experiments is that a lot of new variables that cannot be controlled can influence the outcome in comparison to laboratory experiments under controlled conditions (e.g. Noble and Morgan, 2002). For experimental treatment systems at log yards, examples of uncontrollable variables may be temperature, precipitation and flow of runoff, as well as operational process-governed variables including the amount of wood stored, changes in tree species that are stored and changed maintenance procedures such as removal of bark from the storage area (Paper II). A treatment system should be capable of functioning in different conditions that can arise during normal use of a log yard, but it is difficult to scientifically assess the results from studies over several years when environmental and operational boundary conditions keep changing.

Field-scale soil infiltration systems and constructed wetlands can be seen as black-box systems (Haberl et al., 2003). This means that the input into and the output from these systems, for example log yard runoff, can be investigated, but it is complex to determine what physical and biochemical processes are taking place within the treatment systems. When evaluating soil infiltration in a field-scale experiment, it is particularly complicated to determine the corresponding hydraulic and mass balances. It is seldom possible to make a direct and accurate comparison of the water that is spread for infiltration on the surface of the system with the drainage water that is collected. Precipitation and evapotranspiration are variable, and the time it takes for the water to pass through the system is difficult to measure in practice (Albertson and Montaldo, 2003).

It is particularly difficult to assess the treatment efficiency of infiltration systems where the drainage water is sampled through vertical collection pipes (also called groundwater pipes). It is not easy to determine if the sampled water is properly mixed or when it was spread and infiltrated. Moreover, groundwater is generally a flowing water body, and physical and chemical characteristics may vary over time and space (EPA, 1995).

For economical reasons, it is often necessary to limit the number of samples and parameters when assessing a treatment system for a log yard. Often the cost for sampling and analysis of runoff may be quite high. These costs can be reduced if models are used to predict the treatment results for some pollution parameters from the results for other parameters that are cheaper to analyse.

Modelling can also be used to optimize the design, operation, management and water quality monitoring strategy of a log yard runoff treatment system (Marsili-Libelli and Checchi, 2005). One tool that can be useful is the self-organizing map (SOM) model that is an unsupervised competitive learning neural network model that implements a characteristic non-linear projection from the high-dimensional space of input vectors onto a low-dimensional array of neurons.

The SOM can be used for predicting missing components of an input vector, because the codebook vectors of the SOM represent the local mean of the input vector. The SOM model has been applied to analyze, cluster and model various types of large databases. The model is trained by utilizing a training data set, which is removed from the vector to predict a set of variables as part of an input vector (Rustum et al., 2008). The SOM algorithm has great classification and visualization abilities, and it has been used as the first abstraction level in clustering and as a prediction tool for heavy metal removal in constructed wetland systems (Lee and Scholz, 2006).

1.7 Objectives of the Research

The objectives of this research study were to assess the following:

- If treatment in biological systems such as vegetated soil infiltration systems and constructed wetlands can reduce the concentrations of pollutants in log yard runoff;
- If a relatively small free surface flow constructed wetland ditch could be used as a cost-efficient and low-maintenance method to reduce the concentrations of pollutants in the runoff despite its small size;
- If different species of plants affect the purification efficiency when log yard runoff is infiltrated through vegetated soil infiltration systems;

- If decreased irrigation intensity and intermittent irrigation affects the purification efficiency for infiltration in soil-plant systems;
- If contaminants leach out of the biological treatment systems during the colder months of the year;
- If the severe storm in 2005 led to changes in the characteristics of the runoff when a large proportion of older, windthrown logs were stored at the studied log yards; and
- If a self-organizing map (SOM) model can be developed to predict expensive and time consuming water quality variables with low-cost and easy-to-measure variables.

This thesis contributes to the knowledge base for treatment of log yard runoff in biological systems, and will provide advice on how to design cost-efficient and low-maintenance treatment systems to reduce the environmental impact on receiving watercourses.

2 Materials and Methods

This section briefly summarizes the materials and methods that were used in the studies described in Papers I and III to V (appended). The text is limited to the information that is necessary for the understanding of the subsequent chapters of the thesis. The reader is referred to the individual papers for more detailed descriptions.

2.1 Infiltration in a Couch Grass Field (Paper I)

The study site, located close to Heby sawmill, Västmanland, central Sweden (59°56′N, 16°50′E), consisted of an irrigated slope covered with *Elytrigia repens* (L.) (couch grass). Along the slope, eight pipes were installed for groundwater sampling. Four of the pipes were placed inside the irrigated area, two pipes approximately 25 m downhill from the irrigated area, and another two pipes a further 25 m downhill. The slope has been irrigated with log yard runoff since 2001. The irrigation has coincided with the log yard sprinkling season, which usually runs from April/May until September/October every year, depending on the temperature.

The log yard runoff originated from a log yard storing *Picea abies* (Norway spruce) logs. The runoff was distributed over the experimental area with five sprinklers resulting in an irrigated area of 40×55 m. In the beginning of the study the irrigation intensity on the couch grass field was very high, 56-66 mm/d. The mean irrigation intensity was considerably reduced after three irrigation seasons, so that the intensity in 2005 and subsequent years was between 30 and 40% of the intensity during 2002 to 2004. The reduction of the intensity was due to rotation of different irrigated areas; the studied couch grass slope was repeatedly irrigated for one week at an intensity of approximately 69 mm/d followed by two weeks without irrigation, giving a mean irrigation intensity of approximately 23 mm/d.

Samples of irrigation water and groundwater were taken as grab samples once per month. The pH and the concentrations of pollutants in the irrigation water and in the resulting groundwater were compared with an analysis of variance (ANOVA) at $p<0.05$. The statistical analysis was performed using the Minitab 15 software package (Minitab, 2006).

2.2 Planted Infiltration Systems (Papers III and IV)

This study site was also located in a field near Heby sawmill (see above), and consisted of eight square (20×20 m) planted soil infiltration systems (called plots from here onwards), covering a total area of 40×80 m. The eight plots were planted with four different species (Figure 1): two plots were planted with *Alnus glutinosa* (L.) Gärtner (common alder); two plots were planted with *Salix schwerinii×viminalis* (willow variety ‘Gudrun’); two were sown with *Lolium perenne* (L.) (rye grass) seeds; and two were sown with *Phalaris arundinacea* (L.) (reed canary grass) seeds.

Each plot was fertilized with 20 kg nitrate of lime containing 15.5% N and 18% K (80 kg N/ha) in early July 2005, because a previous study had shown that the content of nitrogen was low, around 1.3 mg/l, in the runoff from the investigated log yard (Jonsson et al., 2006). The fertiliser contained no phosphorus and no organic matter.

Alnus glutinosa	*Salix schwerinii× viminalis*	*Phalaris arundinacea*	*Lolium perenne*
Salix schwerinii× viminalis	*Alnus glutinosa*	*Lolium perenne*	*Phalaris arundinacea*

Figure 1. Distribution of the different plant species (*Alnus glutinosa* (L.) Gärtner (common alder); *Salix schwerinii×viminalis* ‘Gudrun’ (willow); *Lolium perenne* (rye grass); *Phalaris arundinacea* (reed canary grass)) in planted soil infiltration systems (plots) at the pilot plant sized study site near Heby, Västmanland, Sweden.

The plots were irrigated with log yard runoff that was trickling out through a perforated plastic hose placed on the surface of each of the infiltration plots. During the sprinkling seasons (approximately the end of April/beginning of May to the end of September/beginning of October) in

2005, 2006, 2007 and 2008, the plots were irrigated with 8, 12, 12 and 12 mm/d, respectively. The drainage water was collected by drainage pipes after infiltration, and the drainage system was designed to drain each plot separately. The drainage pipes were placed 0.9 m below ground level and the distance from the pipes to the edge of each plot was at least 2 m. The drainage water was sampled by an automatic flow-proportional sampling system. Sub-samples were collected for analysis approximately once every two weeks. Between the sprinkling seasons, when no log yard runoff was spread on the infiltration system, sub-samples of the drainage water were collected approximately once per month.

Analyses of variance (ANOVA) at $p<0.05$ were performed to compare the contaminant concentrations in the drainage water from different plots. Two-sample T-tests were undertaken to directly compare mean values for different species. All statistical evaluations were completed using the Minitab 15 software package (Minitab, 2006).

The self-organising map (SOM) model was used to predict the effluent concentrations of TN from the input variables pH, TOC and SS, and the effluent concentrations of TP were predicted from the input variables TIC, TOC and SS. The SOM toolbox (version 2) for Matlab 7.0 developed by the Laboratory of Computer and Information Science at Helsinki University of Technology was used in this study. The toolbox is available for free online at http://www.cis.hut.fi/projects/somtoolbox (Vesanto et al., 1999).

2.3 Constructed Wetland Treating Log Yard Runoff (Paper V)

The treatment wetland study site was a sawmill in Boxholm, Östergötland, in the South of Sweden (58°11′N, 15°2′E), storing *Picea abies* (Norway spruce) and *Pinus sylvestris* (Scots pine) on an asphalted log yard. Grab samples of log yard runoff were taken at several locations along the flow of water from the log yard to the receiving watercourse during the sprinkling seasons 2004-2007.

In autumn 2005, a free surface flow wetland was constructed in a representative part of the log yard ditch to improve the treatment of the runoff before it was released to the watercourse from which water was taken and used for sprinkling. The runoff flowing through the wetland came from a part of the log yard where only *P. abies* was stored and sprinkled.

The wetland was constructed according to a conceptual model described by Braskerud (2002, 2003) that has been shown to be efficient for the reduction of TP and SS despite very small wetland sizes. Two wetland cells, each consisting of a deeper part for sedimentation of relatively large particles and a shallow vegetated part for filtering and subsequent sedimentation of finer particles, were retrofitted in series within the original ditch. The area that was possible to use for the constructed wetland was restricted in size by other land-use applications at the sawmill.

The vegetation that was planted during the construction of the wetland (*Typha latifolia* L. (bulrush), *Phragmites australis* (Cav.) Steud. (common reed) and *Carex* spp. (sedge)) did not remain firmly rooted, and the vegetation cover in the wetland was not satisfactory during the sprinkling season 2006; only about one macrophyte per square meter. In the middle of May 2007, the plant cover in the wetland was improved by planting of three *P. australis* plants per square meter.

Automatic flow-proportional samplers were placed at the inlet and outlet of the constructed wetland. Every two weeks sub-samples were collected from each sampler. During the intense monitoring of the wetland between late August and early October 2007, the automatic samplers were equipped with a 12-bottle sampling set each for sequential sampling. Between the sprinkling seasons 2006 and 2007 sub-samples were collected once per month. The samples were frozen until analysis. In 2007, part of the sub-samples were filtered without delay at the time of sampling and used for analysis of dissolved organic carbon (DOC) and ortho-phosphate phosphorus (PO_4^{3-}-P). Two-sample T-tests were performed to directly compare mean values of the different sampling points. All statistical evaluations were performed using the Minitab 15 software package (Minitab, 2006).

3 Results and Discussion

3.1 Treatment Efficiency of Infiltration in Planted Soil Systems

The first of two infiltration studies described in this thesis investigated the purification capacity of a sloping couch grass field that was irrigated with log yard runoff. The second infiltration study assessed the purification capacity of soil infiltration systems vegetated by different species of plants. Both studies are explained in different sections below.

3.1.1 Infiltration of Log Yard Runoff in a Couch Grass Field

The results from the first year when log yard runoff was spread on the field have been described by Jonsson et al. (2006), and the subsequent three years (2003-2005) are described in Paper I. This thesis reports on an expansion of these investigations by adding the results from 2006-2008 to the study, thereby presenting data from seven years of soil infiltration in the same system.

During the first three seasons, the couch grass blackened due to deposition of organic matter from the irrigation water. The deposition was restricting the photosynthesis and therefore the growth and well-being of the plants. After 2005, when the irrigation intensity was lower, the couch grass was less black and appeared to be in better condition. This indicated that the lower irrigation intensity was better adjusted to the tolerance level of the plants. The concentrations of total organic carbon (TOC), total phosphorus (TP) and total nitrogen (TN) in the irrigation water and the groundwater are presented in Figures 2, 3 and 4, respectively.

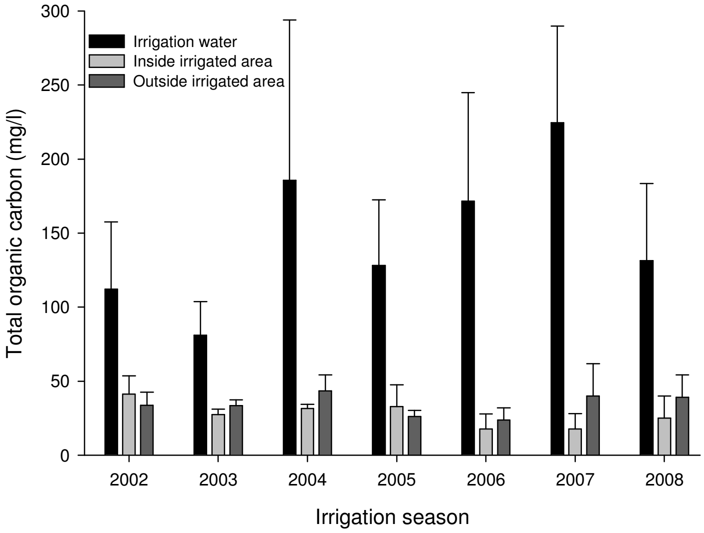


Figure 2. Means and standard deviations for total organic carbon of composite samples from the groundwater pipes inside and outside (downhill) the irrigated area of the couch grass field, and in the irrigation water during the irrigation seasons 2002-2008.

The concentration of TOC in the sampled groundwater inside and outside (downhill) the irrigated area of the couch grass field (Figure 2) was considerably lower (18-44 mg/l) than in the irrigation water (81-224 mg/l), showing that the infiltration treatment was efficient for organic compound removal from the runoff. The difference in concentration between irrigation water and groundwater was statistically significant ($p<0.05$) during the whole study. The concentrations in the groundwater are relatively stable over the entire investigation period despite considerable changes in concentration in the irrigation water. The reduction of TOC during infiltration is mainly due to biological degradation and filtration in the soil (Rauch and Drewes, 2004).

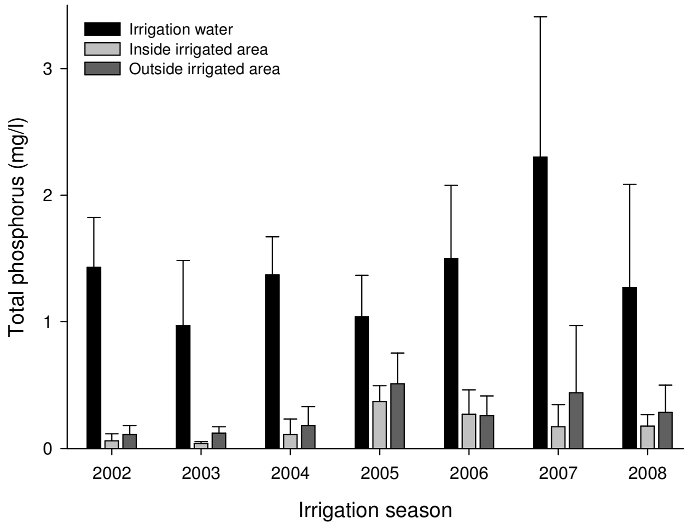


Figure 3. Means and standard deviations for total phosphorus of composite samples from the groundwater pipes inside and outside (downhill) the irrigated area of the couch grass field, and in the irrigation water during the irrigation seasons 2002-2008.

Figure 3 shows that the purification efficiency of the infiltration system was good for TP (a mean of approximately 88%) as well as for TOC (a mean of approximately 79%). The difference in concentration between irrigation water and groundwater was statistically significant ($p<0.05$) during the entire study. The concentrations of TP in the groundwater increased significantly in 2005 compared with previous years both inside and outside the irrigated area. The increase started in 2004, but was not statistically significant at that time. The increase of TP in the groundwater in 2005 occurred although there was no accompanying increase of TP in the irrigation water at that time, and this was interpreted as a sign that the soil was close to the saturation point for TP (Casson et al., 2006). After 2005, when the irrigation intensity and the subsequent load of phosphorus on the infiltration system were reduced, the groundwater concentrations decreased. The concentrations in the groundwater are still significantly higher than at the beginning of the study (0.18 mg/l inside the irrigated area in 2008 compared to 0.06 mg/l in 2002), but there does not seem to be an increasing trend anymore, despite very high TP concentration in the irrigation water in 2007.

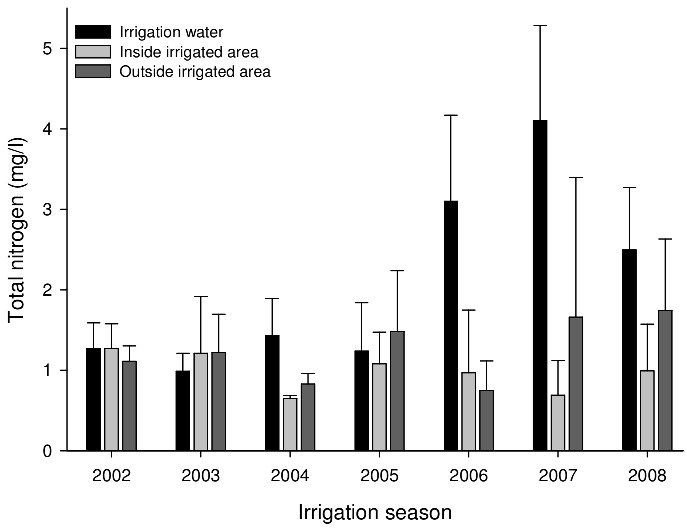


Figure 4. Means and standard deviations for total nitrogen of composite samples from the groundwater pipes inside and outside (downhill) the irrigated area of the couch grass field, and in the irrigation water during the irrigation seasons 2002-2008.

The soil infiltration system does not seem to have any clear purification capacity for TN, as shown in Figure 4. There was a statistically significant (p<0.05) difference in concentrations in the groundwater compared to the irrigation water during 2004, 2006 and 2007, but not during the other years. During 2003 and 2005, the concentrations in the groundwater were even higher than in the irrigation water, indicating that the system had a very variable performance for TN. The concentration in the irrigation water was much higher during 2006-2008 compared to the earlier years, but it is not clear if this has led to increased groundwater concentrations.

The parameters pH, distillable phenols and suspended solids have been analysed in the groundwater and in the irrigation water during only a few years of the study. Previous studies have shown that the concentration of distillable phenols in runoff from log yards storing *P. abies* is generally low in comparison to storage of other species of trees (Borgå et al., 1996b; Paper II). Distillable phenols have a low decomposition rate, but many microbes are capable of completely mineralising distillable phenols both under aerobic and anaerobic conditions (Agarry et al., 2008). The infiltration treatment led to significantly (p<0.05) reduced concentrations of distillable phenols in the groundwater (annual means of 0.02-0.03 mg/l) compared to the irrigation water (annual means of 0.07-0.11 mg/l) during 2002-2005, when the parameter was analysed, and no increase in groundwater concentration over time could be detected (Paper I).

The treatment did not affect the concentration of suspended solids. The results for suspended solids were very variable with high standard deviations around the mean values, and the concentrations in the groundwater outside the irrigated area were higher or of the same level as the concentrations in the irrigation water. The pH in the irrigation water was significantly ($p<0.05$) higher than in the groundwater during 2005, around 7.4 compared to 7.0 in the groundwater. During 2006 the mean pH in the irrigation water was 6.3, and that figure was significantly ($p<0.05$) lower than that for the groundwater where the values were around 7.0 as in the previous year. During 2007 there was no significant difference in pH between the irrigation water and the groundwater. The pH in runoff from log yards storing *P. abies* is generally close to neutral values (Paper II), so it is not expected that infiltration treatment of this water will negatively affect the pH of the soil or the water environment.

3.1.2 Infiltration of Log Yard Runoff in a Planted Soil Infiltration System

The results for 2005 to 2007 are presented in Papers III and IV. Treatment results from 2008 have been added to this thesis. In this section, the treatment efficiency of the infiltration system as a whole is evaluated, with the results from the different infiltration plots amalgamated. The next section evaluates if the different species of plants led to different treatment results for the different plots.

The treatment performance of the infiltration system was good for TOC and TP over the investigated period 2005 to 2008 (Figure 5). The mean treatment efficiency, measured as concentration difference between log yard runoff and drainage water, during the irrigation seasons over the whole investigated period was 52% for TOC (standard deviation (stdev) of 6.4) and 47% for TP (stdev of 4.1), but there was no treatment effect for SS (-5%), which was also associated with variable concentrations (stdev of 27.5). The soil infiltration system also had no treatment effect for total inorganic carbon (TIC) (27% in 2006, -8% in 2007 and 4% in 2008) and the drainage water had roughly the same concentration as the irrigation water.

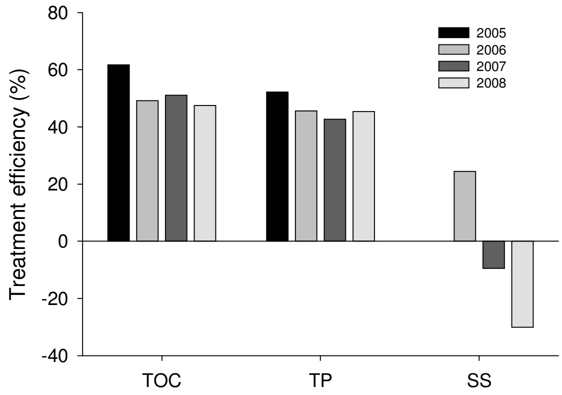


Figure 5. Mean treatment efficiency (%) of the infiltration system for total organic carbon (TOC), total phosphorus (TP) and suspended solids (SS) during the irrigation seasons 2005-2008.

The study was inconclusive with respect to SS. During 2006, the first year when SS was analysed, the SS concentration was lower in the drainage water (annual mean of 81 mg/l) than in the irrigation water (annual mean of 108 mg/l), but the difference was not statistically significant. The following two years the drainage water had a higher concentration of SS (annual mean of 128 and 96 mg/l) than the irrigation water (annual mean of 117 and 74 mg/l), so the soil infiltration system was functioning as a source of SS. This is common for vertical down-flow filtration systems due to gravitational flow (Al-Senafy and Al-Otaibi, 2002; Scholz, 2003; Scholz, 2006). Soil infiltration might therefore not be a suitable treatment method for log yard runoff in cases when a reduction of SS is the primary objective.

The drainage water generally had lower concentrations of TN than the log yard runoff, approximately 1.0-2.0 mg/l compared to 1.5-4.0 mg/l. Previous studies (Paper II) have shown that the concentration of TN in log yard runoff is usually low, and that no treatment to reduce the concentration is necessary except when the receiving watercourse is classified as 'very nitrogen vulnerable'. To ensure good vegetation growth during this study, the soil of the whole infiltration system (all eight plots) was fertilised with nitrate of lime in 2005. Therefore no assessment of the treatment efficiency of the infiltration system for TN has been done.

The pH was generally higher in the drainage water (around 6.8-7.5) than in the log yard runoff that was used as irrigation water. Both the runoff and the drainage water were in the range of what is commonly interpreted as an expected pH range for receiving watercourses (European Parliament, 2006). This confirms findings from previous studies highlighting that the pH of runoff from log yards storing *P. abies* is not harmful for the receiving watercourses (Borgå et al., 1996; Jonsson et al., 2004).

The treatment efficiency as illustrated in Figure 5 seems to decrease with time. However, it has to be taken into account that the loads on the infiltration system increased considerably from 2005 to 2006, and from 2006 to 2007, partly because the irrigation intensity on the system was increased from 8 mm/d in 2005 to 12 mm/d in 2006, 2007 and 2008, and partly because the concentrations of TOC, TN and TP in the irrigation water increased in 2006 and 2007. The loads received by the infiltration system have been calculated in kg/ha for total carbon (TC), TIC, TOC, TN, TP and SS (Table 1).

Table 1. *Loads (kg/ha) of selected water quality parameters on the infiltration system.*

Year	TC	TIC	TOC	TN	TP	SS
2005	n/a	n/a	1630	17	15	n/a
2006	3921	444	3491	63	30	1983
2007	4523	398	4124	75	43	2009
2008	3260	452	2808	52	26	1300

TC, total carbon; TIC, total inorganic carbon; TOC, total organic carbon; TN, total nitrogen; TP, total phosphorus; SS suspended solids; n/a, not analysed

The load of TP on the system seems to directly affect the treatment efficiency for that parameter. When the loads increased in 2006 and again in 2007 compared to 2005, the treatment efficiency decreased, although not significantly (Figure 5). When the load in 2008 decreased to about the same level as in 2006, the treatment efficiency increased slightly to the same level as in 2006. There does not seem to be a similar connection between the loads and the treatment efficiencies for TOC. The treatment efficiency decreased when the load in kg/ha increased from 2005 to 2006, but when the load increased even more during 2007, there was a slight increase in treatment efficiency of the infiltration system (Figure 5). When the load decreased considerably in 2008 there was no corresponding increase in treatment efficiency for TOC.

The treatment efficiency for SS decreased each year, and did not seem to depend on the load on the system. The change of the system from sink to source of SS from 2006 to 2007 cannot be explained by the relatively small increase in load on the system in 2007. The system also continued to be a source in 2008 when the load was considerably lower than in 2006.

The optimum ratio for biodegradation of most organic contaminants in wastewater treatment is 100 parts, 5 parts and 1 part of TOC, TN and TP, respectively (Scholz, 2006). Table 1 shows that the loads of TOC and TP closely follow the optimum proportion for biological degradation of 100 to

1. However, TN within the runoff is only between 20 and 37% of the optimum for biodegradation. A yearly addition of nitrogen through fertilisation of the infiltration system might increase the microbial activity, the degradation of TOC and the uptake of TP by plants. Nitrogen addition was only undertaken in 2005 on the investigated infiltration system, and it is possible that an optimised yearly addition of bioavailable nitrogen could have increased the treatment efficiency for TOC and TP in this study.

3.2 Comparison of Different Plant Species in Planted Soil Infiltration Systems

The results from the second infiltration experiment (Papers III and IV) were further analysed to assess if there were any statistically significant differences in treatment efficiency for plots vegetated by different plant species (Table 2). The results for 2008 have not been taken into account, because invasive grasses had by then taken over through vegetative competition and the originally planted grass species were no longer the dominating vegetation. A comparison between the different original species was therefore considered to be unsuitable.

Table 2. *Treatment efficiency (%) for soil infiltration plots vegetated with different species of plants (Figure 1).*

Plant species	TOC			TP			SS	
	2005	2006	2007	2005	2006	2007	2006	2007
Alnus glutinosa (plots 1 and 4)	55.6	48.5	51.8	40.3	46.2	46.5	36.7	-33.2
Salix schwerinii x viminalis (plots 2 and 3)	64.6	47.5	51.4	49.3	43.6	39.4	49.0	-23.3
Phalaris arundinacea (plots 5 and 8)	65.4	49.0	45.9	48.1	42.6	36.5	34.4	-6.8
Lolium perenne (plots 6 and 7)	62.3	52.3	55.3	54.9	50.9	48.4	52.5	25.2

TOC, total organic carbon (mg/l); TP, total phosphorus (mg/l); SS suspended solids (mg/l); *Alnus glutinosa* (L.) Gärtner, common alder; *Salix schwerinii x viminalis* 'Gudrun', willow; *Lolium perenne*; rye grass; *Phalaris arundinacea*, reed canary grass. Number of samples per species: n=7 in 2005; n=15 in 2006; n=14 in 2007.

Table 2 shows the removal efficiencies, when not taking the effect of precipitation into account, during the irrigation periods 2005-2007. The treatment efficiencies can be regarded as over-estimations because the dilution effect of the precipitation was not included in the calculation, but on the other hand no adjustment for evaporation was made either. The mean rainfall during the irrigation periods was 1.2 mm/d in 2005, 2.4 mm/d in 2006 and 1.6 mm/d in 2007, which equates to 15 %, 20% and 13% of the irrigation intensities in 2005, 2006 and 2007, respectively. The dilution factor was not higher in 2005 than 2006, and only slightly higher than in 2007, so the higher mean treatment efficiency of the system for TOC and TP in 2005 cannot be explained by a higher dilution factor.

Statistical analyses (one-way ANOVA and two-sample T-test) of the results showed that there was no statistically significant difference in treatment efficiency for the different species of plants for TOC, TP and SS, neither when analysing the results from the different years separately nor when analysing the results from the whole three-year period together. The grass *Lolium perenne* had the best mean treatment effect for TOC, TP and SS over the three-year period (i.e. 57%, 51 % and 39% for 2005-2007, respectively) but the results were not significantly better than for the other plant species. These results compare well with those published in previous lysimeter studies (Jonsson et al., 2004; Jonsson et al., 2006) where no differences in purification efficiencies for TOC, phenols, TP and TN were found when comparing treatments by *Elytrigia repens*, *Salix sp.* and *Alnus glutinosa* with each other.

The soil infiltration system had no significant treatment effect for TIC, and the drainage water had roughly the same concentration as the irrigation water as described in the previous section. An interesting result, however, was that the drainage water from the plots vegetated with *S. Schwerinii* × *viminalis* had higher concentrations of TIC than the drainage water from the plots planted with *L. perenne*. The difference was not greater than a few mg/l, but it was statistically significant ($p<0.05$). The difference could not be explained in this case study, but might be caused by differences between the plants regarding the mechanical and/or chemical interactions of their roots with the soil-water matrix.

3.3 Treatment Efficiency in the Constructed Treatment Wetland

The performance of the treatment wetland is described in detail in Paper V. During 2006 a small decrease in concentrations of TOC, TP and SS could be measured over the wetland. However, the decrease was not statistically significant. A few samples were analyzed for TN and the results confirmed that the concentrations in runoff from log yards storing Norway spruce and Scots pine are generally rather low. There was a small decrease in TN over the wetland, but there was no clear trend of decrease along the flow path from log yard to recipient watercourse. Considering that the vegetation cover was not satisfactory in the wetland (as described in section 2.3), it was assumed that the low treatment efficiency might be improved by increasing the plant cover before the next sprinkling season.

During 2007, some of the samples were filtered at the time of sampling to make it possible to analyze the concentrations of DOC and PO_4^{3-}-P. The results showed that as little as around 19% and 35% of the TOC and the TP, respectively, were present in dissolved form in the runoff. This should increase the possibility of a high treatment efficiency for log yard runoff in constructed wetlands.

The planting of *P. australis* that was performed in May 2007 led to an increase in plant cover during summer 2007. Towards the end of the sprinkling season, when the plant cover was at its maximum, the sampling frequency of the inflow and outflow of the wetland was increased. From 23 August to 4 October, 25 composite samples were taken from each of these sampling points. The number of samples increased the statistical confidence in the results from the treatment wetland.

Despite the increased plant cover, no improved treatment effect could be measured over the wetland in 2007. There was no significant reduction in concentrations of TOC, TP, SS or TN. This was an unexpected result considering the reductions in concentration of TOC and TP that had been measured in the ditches along the flow path of the runoff during previous years. Probable explanations for the lack of treatment effect are the high hydraulic loading rate and the low dissolved oxygen content in the runoff. The hydraulic loading rate during 2007 was 0.68 m/d, the mean flow was 7.4 m^3/h and the retention time for the runoff in the wetland was as low as 27 h. The dissolved oxygen content was measured with a portable oxygen meter in different parts and at different depths of the wetland on a few occasions in July 2007. The measured oxygen concentrations were as low as 0.4-1.7 mg/l and 3.7-17.3% at a temperature of approximately 15°C.

The hydraulic loading rate was, however, expected to be acceptable, because constructed wetland studies by Braskerud (2002, 2003) have shown good treatment effects for TP and SS at hydraulic loading rates as high as 0.7 to 2.0 m/d. The wetland in this study was constructed in a similar way as in the studies by Braskerud (2002, 2003), and the water streams from the different studies (log yard runoff and runoff from agricultural catchments, respectively) had roughly the same characteristics regarding a high content of TP and SS. Nevertheless, the log yard runoff was apparently so different that the same wetland design was not appropriate. It is likely that the high content of organic matter in the log yard runoff led to a very low oxygen content in the water, due to aerobic biodegradation processes, and this most likely resulted in a reduced treatment efficiency. It is also possible that the particles that are present in log yard runoff do not settle as fast as particles in the runoff from agricultural fields.

3.4 System Performance Outside the Sprinkling Season

Logs are generally stored on log yards all year round, but sprinkling normally only takes place when the temperature and evaporation rate is high and there is a risk of biological attack. Outside the sprinkling season the precipitation that falls on the logs create polluted log yard runoff, but the runoff from the log yard is normally reduced compared to when sprinkling takes place.

Sampling outside the sprinkling season was undertaken at the second infiltration site (the plots with different species of plants; Paper III) and in the treatment wetland (Paper V). The sampling was done to assess the treatment effect and investigate if previously captured pollutants were leaching out of the treatment systems during the colder months when the biological activity was lower.

3.4.1 Soil Infiltration System

Outside the sprinkling season the infiltration system only received the precipitation that was falling directly on the system. No water from the log yard was spread on the site during the winter months. The results for the infiltration system between October and December and between January and April can be seen in Table 3. The results show that leaching of previously captured contaminants did not take place during winter. The flow of water through the infiltration systems was lower during this season, and the corresponding concentrations of pollutants were lower or of the same magnitude as during the irrigation season.

Table 3. *Statistics for drainage water from the infiltration system during periods when no log yard runoff was released onto the plots.*

Sampling time	Statistics	pH	TC	TIC	TOC	TN	TP	SS
October-	Mean	6.8	35.8	22.0	13.7	4.1	0.64	149
December	Stdev	0.64	9.54	6.78	4.19	4.27	0.525	64.1
2005/7	n	22	16	16	22	22	14	14
January-	Mean	6.4	30.4	17.7	12.7	1.8	0.32	220
April	Stdev	0.63	6.94	3.48	5.23	1.47	0.312	107.4
2005/7	n	16	16	16	16	16	16	10

TC, total carbon (mg/l); TIC, total inorganic carbon (mg/l); TOC, total organic carbon (mg/l); TN, total nitrogen (mg/l); TP, total phosphorus (mg/l); SS suspended solids (mg/l); stdev, standard deviation; n, sample number

When no irrigation with log yard runoff is taking place on the infiltration system, the pore water in the soil that originates from irrigation is slowly replaced by water originating from precipitation. It is therefore expected that the concentrations of pollutants in the drainage water should be higher during autumn than during spring. The evaluation of the results is however made more complicated by the difference in decomposition rates and plant uptake during autumn, winter and spring.

In comparison to the periods when the system was irrigated with log yard runoff, the mean concentrations of TC and TOC were considerably lower in the drainage water when only the precipitation component was infiltrating (Table 3). The mean concentration of TP during autumn was similar to the concentration during the irrigation season, but the mean value during spring was much lower. This was also the case for pH. The TIC concentrations were similar regardless if log yard runoff was applied to the system or not. The TN and SS concentrations were highly variable both during and outside the sprinkling seasons, so no clear differences could be seen.

3.4.2 Treatment Wetland

The performance of the treatment wetland when no sprinkling was taking place on the log yard was investigated from October 2006 until early May 2007. The mean concentration of TOC and the pH of the runoff (Table 4) were roughly the same between the sprinkling seasons and during the sprinkling seasons 2006 and 2007 (May to end of September). The mean concentration of TP during the sprinkling season 2006 was unusually high (see section 3.5), but the values between the sprinkling seasons 2006 and 2007 were similar to the values during the sprinkling season 2007. The findings for concentrations and flow showed that the wetland did not function as a source of pollutants during the cold season. The flow of water was considerably lower between the sprinkling seasons (2,900 m^3) than during them (27,500 m^3 in 2007), and consequently the transport of TOC and TP was much smaller.

Table 4. *Results for log yard runoff sampled between the sprinkling seasons 2006 and 2007 in sampling point PT1, before the constructed surface flow wetland, and PT2, after the wetland. All samples are flow proportional composite samples.*

TOC	PT1	PT2
Mean	78.2	75.7
Stdev	32.70	39.81
n	3	3
TP	**PT1**	**PT2**
Mean	0.946	0.810
Stdev	0.372	0.459
n	3	3
pH	**PT1**	**PT2**
Mean	6.8	7.0
Stdev	0.27	0.46
n	3	3

TOC, total organic carbon (mg/l); TP, total phosphorus (mg/l); stdev=standard deviation; n=number of samples.

The treatment efficiency did not increase outside the sprinkling season although the hydraulic loading rate on the wetland was much smaller and the retention time consequently much higher, but this can at least partially be explained by the cold climate from October to May and the lack of oxygenation of the relatively still-standing water (Gualtieri and Gualtieri, 2003).

3.5 Consequences of Wet Storage of Aged Windthrown Logs

The studies of log yard runoff that are described in this thesis were taking place before, during and after storage of aged windthrown trees had to take place at the investigated sawmills. In Boxholm (the treatment wetland study site) windthrown logs were stored during 2006, and in Heby (the infiltration system study site) windthrown logs were stored in large amounts both during 2006 and 2007. This provided the opportunity to investigate if the runoff from aged logs differed from runoff created during storage of logs that have been felled more recently.

There was a clear increase of TP in the runoff when aged logs were stored on both log yards. In Boxholm (Paper V) the increase was observed for all sampling points except for the incoming sprinkling water, showing that the difference was not due to changes in the incoming water. The concentrations of TP were much higher than in previous years; i.e. as high as up to 9 mg/l compared to 1-2 mg/l for the other assessed years. The increase could not be attributed to disturbances from the construction of the treatment wetland, because the concentrations were elevated also upstream of the wetland and along the flow path from the part of the log yard that mainly stored *P. sylvestris* and that was not affected by the construction of the wetland. The incoming sprinkling water showed normal levels, which confirmed that the increase was not caused by contaminated sampling bottles or an error during analysis.

The storage of sprinkled logs in the yard considerably increased in 2006 compared to previous years to allow for processing of more windthrown logs before they became too damaged by insects or fungi. The height of the piles was increased from approximately 3 m to roughly between 4 and 5 m, and up to 45,000 m^3 of sprinkled logs were stored. This is a considerable increase compared to the normally permitted 24,000 m^3. This increase of storage volume is, however, not sufficient to explain the high TP concentration increase during 2006.

Figures 6a and 6b show the total phosphorus and total organic carbon concentrations, respectively, in the runoff water where it flows from the log yard into the upper end of the collection ditches (sampling points 1 and 2) in comparison to the sprinkling water and the concentration in the water that reaches the recipient (sampling point 11). In 2007, the concentrations were back to normal levels, as recorded in previous years (Figure 6a). Other parameters such as TOC (Figure 6b) did not show any clear increase.

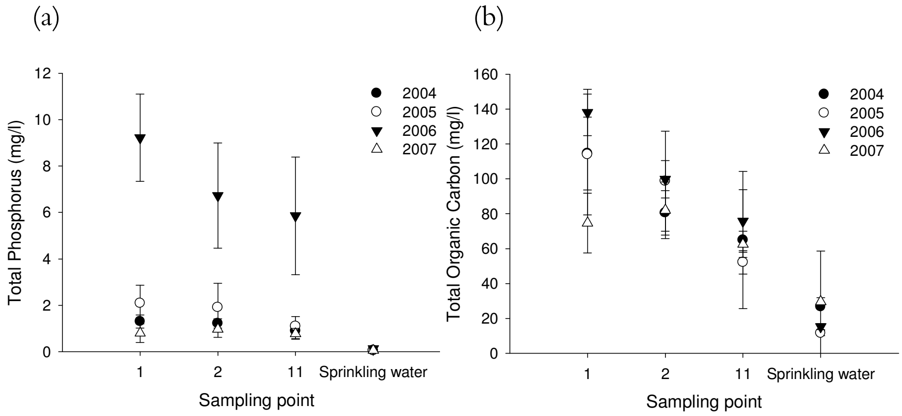


Figure 6. Concentration of (a) total phosphorus and (b) total organic carbon (mg/l) in log yard runoff from sampling points 1 and 2 (at the start of the collection ditches), 11 (at the outlet to the recipient) and in the incoming water before sprinkling during the sprinkling seasons 2004-2007. All samples are grab samples. n=7 in 2004; n=8 for 2005-2007.

A similar increase in concentration of TP was noted in the runoff at the sawmill in Heby (Paper III; Tables 1 and 5). At that sawmill there was also a clear increase in TOC concentration in the runoff.

It is probable that the increase in concentrations can be explained by storage and sprinkling of aged logs that were windthrown during the severe storm in January 2005. Logs that are left in the forest for a relatively long period of time after felling are more affected by biological decay and death of cells compared to fresh logs (Feist et al., 1971). The content of phosphorus in the stem wood of *P. abies* is between 9.2 and 47 mg/kg (Barrelet et al., 2006), and it is probable that a larger amount of TP and TOC will be released from aged logs that have started to degrade compared to logs that are fresher during sprinkling on the log yard.

The concentration of phosphorus has been found to increase in stem wood and inner bark towards the youngest tissues, from the pith (located in the centre of the stem) of *Pinus sylvestris* to the youngest annual rings (Helmisaari and Siltala, 1989). If this is also the case for *Picea abies*, it could explain why the concentration of TP in the runoff increased when aged logs were stored on the log yards. Trees that have aged after felling usually have lost more of the outer bark than freshly felled trees, and it is possible that the leaching of phosphorus is greater when water comes in direct contact with the inner bark. More research is, however, needed to test the validity of this hypothesis.

The increased concentration of phosphorus in runoff from aged logs has important consequences for the future storage requirements for logs that are windthrown. With increasing global warming, it is expected that extreme weather conditions will become more common (Blennow and Olofsson, 2008), and countries with a lot of forest should prepare for storing windthrown logs in a way that reduces the impact on receiving watercourses.

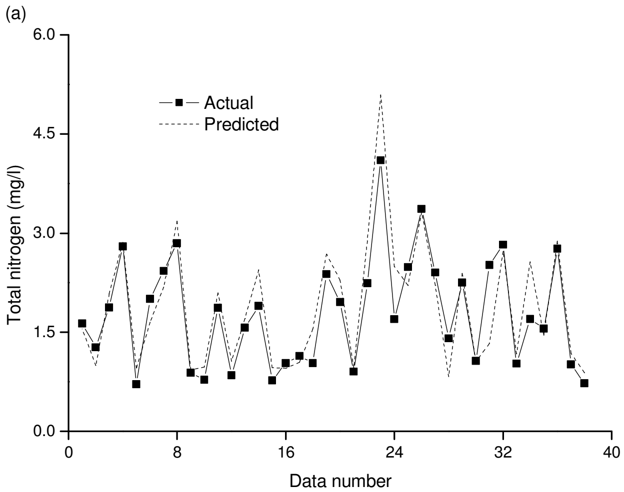
3.6 Application of Self-organising Map Modelling

The sampling and analysis of different water quality parameters can be quite time-consuming and costly, and therefore one of the research aims was to assess if a self-organizing map (SOM) model could be developed to predict expensive and time-consuming water quality variables with low-cost and easy-to-measure variables (Paper IV).

The results from the second infiltration study site (the plots with different species of plants) were used to develop the SOM model. Because all eight plots were relatively similar in terms of their treatment performance, the corresponding sets of drainage water quality parameters were combined into one large data set to identify the relationships between the effluent TN and TP concentrations with other water quality variables by applying the SOM model. In general, the input variables used for prediction should be more cost-effective in comparison to the target variables, and relatively highly correlated with them. Based on this consideration, pH, TOC and SS were selected as input variables to predict TN in the drainage water of the infiltration system, and TIC, TOC and SS were selected as input variables to predict TP.

The data set (n=148) was mixed in a random order and subsequently subdivided into two subsets to predict the TN and TP concentrations by applying the SOM model. The first subset was used as a training data set (n=110). In comparison, the second subset was used as a test data set (n=38). Each target variable was omitted from the test data set, implying that its entries were in fact missing values, to verify the prediction results with the test data set. After running the simulation, the predicted target variable values were subsequently compared with the actual values. The SOM modelling performance in terms of predicting the effluent TN and TP concentrations are shown in Figures 7a and b.

The predicted concentrations are in conformity with the actual concentrations. The correlation coefficients between the actual and predicted concentrations for TN and TP were 0.91 and 0.88, respectively. This showed that the SOM model performed very well in predicting the TN and TP concentrations, and that modelling can be used to reduce the cost for sampling and analysis of log yard runoff.



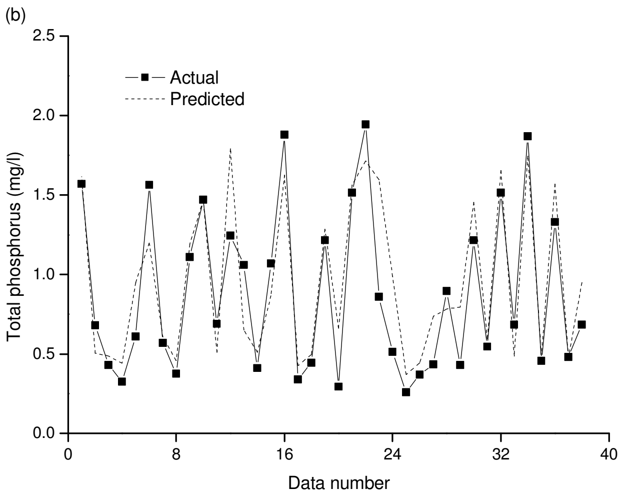


Figure 7. Comparison of the actual and predicted effluent concentrations (mg/l) for (a) total nitrogen and (b) total phosphorus.

4 Conclusions

The research shows that infiltration in planted soil systems can be used as an effective treatment method to reduce the concentrations of organic substances, TP and distillable phenols in log yard runoff. The systems were virtually maintenance free, which makes them cost-effective in comparison to more technologically advanced and engineered systems. The treatment efficiency was satisfactory even at very high irrigation intensities, which are, however, not recommended to maintain the long-term performance of the treatment system. At too high irrigation intensities, the loads of pollutants can exceed what the infiltration system can degrade and absorb, and leaching to groundwater can occur. The reduction of irrigation intensities that was implemented in one of the described studies did not improve the treatment efficiency, but seems to have reduced the increase in groundwater concentration of total phosphorus that was noted before the intensity was reduced.

The treatment results for SS did not show that infiltration led to reduced concentrations. It follows that infiltration cannot be recommended as a suitable method to reduce the amount of SS in log yard runoff. The results for pH and TN showed that runoff from log yards storing *Picea abies* does not cause acidification or harmful concentrations of TN in receiving watercourses, thereby confirming the conclusions of previous studies.

A large area of suitable land must be available in the vicinity of the log yard to apply treatment in planted soil infiltration systems. Consequently the cost-effectiveness of the system mainly depends on the price of land. The research indicates that, under similar boundary conditions (e.g. soil texture) as in the described infiltration studies, an area of approximately 0.5 ha of infiltration system would be required for every 10,000 m^3 of annual runoff from a log yard to achieve the same retention of contaminants.

The characteristics of log yard runoff in the described studies indicate that small-scale wetlands should be able to treat the runoff effectively. The high amount of organic matter and phosphorus and the relatively low content of dissolved species of these parameters should be suitable for treatment in wetlands, even if the nitrogen content is relatively low. However, the results from the study of the free surface flow constructed wetland ditch did not support that hypothesis. It is likely that the hydraulic loading rate for this wetland case study was too high, and that the concentration of oxygen in the runoff was too low for the biochemical processes in the wetland to succeed in reducing the concentrations of TP, TOC and SS. It also seems as if the particles in log yard runoff remain suspended for a long time and therefore have a low sedimentation rate.

The research indicates that it is not important what type of vegetation is used for planted soil infiltration systems when treating log yard runoff. The four different plant species that were used during the comparative study did not significantly affect the purification efficiency. There were also no significant differences between the treatment effects of the two species of trees compared to the two species of grass.

Despite a lower biological activity during the colder months of the year, there was no leaching of previously captured contaminants from the planted soil infiltration systems or the constructed treatment wetland between late October and late April. The flow of water through the systems was lower during this period of the year because the log yards are not sprinkled during the colder period, and the concentrations of pollutants after treatment were lower or of the same magnitude as during the warmer sprinkling season.

The application of SOM modelling that was performed on the results from the comparative infiltration study produced a promising outcome; the concentrations of TN and TP in log yard runoff that has been treated in a planted soil infiltration system can be accurately predicted by more cost-effective water quality variables such as pH, TOC and SS. It should be possible for log yard operators, who have access to a relatively large series of data, to perform SOM modelling with the aim to reduce the cost of sampling and analysis, but still retain the same level of data accuracy.

When aged windthrown logs were stored in the studied log yards there was a remarkable increase of TP in the corresponding runoff. This is an important finding that should influence how emergency storage sites are chosen and designed in the future. It is often essential to sprinkle windthrown logs after heavy storms and hurricanes to prevent large numbers of logs becoming unusable due to biological attack and cracking. If the felled logs have aged before the sprinkling starts, the log yard runoff can contain considerable amounts of phosphorus. Abatement techniques should therefore be applied at the storage sites (e.g. soil infiltration or treatment wetlands) to protect nearby watercourses from negative impact.

4.1 Further Recommended Research

This thesis and the appended papers support the reader in choosing a sustainable and cost-effective treatment technique for runoff from wood handling sites. However, no ultimate method that gives sufficient long-term removal of phosphorus was found. Further studies on sustainable treatment methods that can effectively remove phosphorus from runoff are therefore strongly recommended.

Different types of soil, e.g. silty clay and sandy loam, have different characteristics and therefore different capacity for successful soil infiltration. Further research on infiltration of log yard runoff in different types of soil would be necessary to be able to calculate the appropriate size of soil infiltration systems under different conditions. A series of pilot-scale soil infiltration systems at log yards with different types of soil would be useful to assess the land-use needed at each site. Long-term studies of infiltration systems are also recommended to assess the sustainability of the treatment, i.e. for how long at different loads the systems can be used before leaching of TP reduces the treatment efficiency.

The constructed wetland described in this thesis did not show any treatment efficiency for log yard runoff. Further studies on the possibility of using constructed wetlands to treat log yard runoff are recommended, and in these studies the hydraulic loading rate should be considerably reduced, the residence time in the treatment wetland should be longer, and oxygenation should be promoted. The oxygenation can be increased e.g. via mechanical stirring of the water or trickling of the water over shallow swales or thresholds either before the wetland or between the sedimentation zone and the wetland filter.

The lack of treatment efficiency in the wetland study might partly be explained by the particles in the runoff remaining suspended for a long period of time. A laboratory study of the sedimentation rate for particles in log yard runoff could therefore provide useful results and determine the potential for treatment of log yard runoff in free surface flow wetlands.

Further research on the 'real' whole life costs and tangible benefits of soil infiltration systems and wetland treatment systems compared with traditional wastewater treatment methods such as the activated sludge process and percolation filtration should be undertaken. Moreover, the modelling of infiltration system and wetland performance for highly dynamic (i.e. seasonal operation and fluctuating stock capacities) systems such as log yards remains a challenge.

No supporting or contradicting research studies on release of phosphorus and organic compounds from aged logs have been found in the scientific literature. More research would be needed to investigate the process of release of these pollutants from aged logs during sprinkling. It would be of interest to assess if the concentration of TP in the runoff from aged logs increases because these logs have lost more outer bark than fresh logs, and the more phosphorus-rich inner bark therefore has become more exposed to precipitation and sprinkling water.

It is common that sprinkling water for a log yard is abstracted from a watercourse close to the yard, and in small watercourses the abstraction in combination with the subsequent release of polluted water can have negative effects both on the biology and the chemistry of the watercourse. No research on this aspect of the wood handling industry's environmental impact can be found in the public domain, and more information would be beneficial for the abstraction licensing process.

The environmental impact from each separate log yard and wood handling site can be relatively small, but cumulatively, the overall environmental impact from the storage and handling of wood is likely to be of high significance in terms of the pollution load in a forest-rich country such as Sweden. This hypothesis needs to be tested in future research studies, and the results should influence the policies of lawmakers and environmental authorities.

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Acknowledgements

I had no plans to do a PhD before I met Torbjörn Elowson at a sawmill. He managed to convince me that research can make life more interesting even for a hardened and confirmed environmental regulator, and he subsequently became my main supervisor. Thank you Torbjörn for your support!

Thank you also to Pär Aronsson, Maria Jonsson and Karin Tonderski, my co-supervisors who all have been vital for the progression of the work and my peace of mind. Pär has provided necessary critical discussions and guidance, Maria has given me a lot of practical help and useful suggestions, and Karin has always been enthusiastic and convinced that all problems can be solved.

The work in Heby would not have been possible without Richard Childs who did the field work for many years in rain and in sunshine, and sometimes even in snow. Gunnar Torstensson provided the necessary technical expertise to set up the automatic sampling system and provided support when the technology was acting up.

I owe my former colleagues at Länsstyrelsen Östergötland a lot for the very enjoyable eight years I spent with them, the two last years of which I was allowed to work half-time to be able to do my PhD work. I miss you a lot and wish you could come and work in Scotland with me!

My thanks also go to my present employer, the Scottish Environment Protection Agency, for hiring a Swede to work full time with sheep dip inspections, emissions trading and finally air policy at the same time as doing a PhD on log yard runoff in Sweden. My focus has sometimes been a bit split, but you have all been very friendly to me anyway.

This work would not have been possible without the support and friendly cooperation of Rörvik Timber Boxholm AB and Setra Trävaror AB in Heby. Special thanks to Tommy Halldin, Dan Fritz, Kjell Karlsson and Olle Modin. Karl-Erik Önnsejös stiftelse för vetenskaplig forskning och utveckling also provided financial support.

A big thank you to Ivan Hedmark and Gudrun Spieshöfer for always being very supportive and even assisting with the field work on a few occasions.

Last but not least, thank you Miklas for being so lovely, as well as being energetic in a way that is just on the verge of what I can stand without losing my sanity. I look forward to less work and more fun!