Abstract

Jonsson, M. Wet Storage of Roundwood – Effects on wood properties and treatment of run-off water. Doctoral dissertation.
ISSN 1401-6230, ISBN 91-576-6703-9.

Wet storage (sprinkling) of wood offers valuable protection against drying out and biological attack, but at the same time there are disadvantages to be considered. Negative effects in the forms of reduction in wood quality and the environmental impact of log yard run-off must be minimised in order to make wet storage effective. In the work underlying this thesis, the effect of different sprinkling water qualities on changes in wood properties during storage was studied. A new method for treating log yard run-off by using it to irrigate soil-plant systems was also evaluated. Sprinkling experiments were conducted both indoors and outdoors in which the effects of sprinkling on the wood quality of Norway spruce (*Picea abies*) pulpwood piles were examined. Soil-plant systems with willows (*Salix schwerinii x Salix viminalis*), alder (*Alnus glutinosa*) and couchgrass (*Elymus repens*) were irrigated with Norway spruce log yard run-off and evaluated both in lysimeters and in the field (couchgrass) for their purification capacity.

Sprinkling water quality, in terms of salinity, did not affect the inorganic content of wood during storage. Brackish waters can be used without increasing the risk for raising the inorganic contents. Neither did sprinkling with fresh or recycled water affect wood brightness. Factors other than those studied determine the optimal wet storage regime.

The composition of different log yard run-offs is very different, but they are all rich in oxygen-consuming organic material. Irrigation of soil-plant systems purifies log yard run-off even at very high irrigation intensities and is a convenient method for practical use. The irrigation intensity, rather than the soil type or plant species, is the major factor for the efficiency since lower intensities lead to both better purification and greater possibilities for long-term sustainability.

Keywords: sprinkling, water quality, *Picea abies*, log yard run-off, inorganic content, discolouration, purification, retention, lysimeters.

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Appendix

Papers I-IV

This thesis is based on the following papers, which will be referred to by the corresponding Roman numerals:

I. Jonsson, M. & Persson, E. 2004. Sprinkling wood using brackish water – effects on the inorganic content of wood. *Nordic Pulp and Paper Research Journal,* 19(3):366-371.

II. Jonsson, M., Lind, T., Elowson, T. & Lönnberg, B. Wet storage of Norway spruce (*Picea abies*) pulpwood with fresh and recycled water – Effects on wood and water quality. (Submitted)

III. Jonsson, M., Dimitriou, I., Aronsson, P. & Elowson, T. Effects of soil type, irrigation volume and plant species on treatment of log yard run-off in lysimeters. *Water Research*, 38(16):3634-3642.

IV. Jonsson, M., Dimitriou, I., Aronsson, P. & Elowson, T. Treatment of log yard run-off by irrigation of grass and willows. (Submitted)

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Introduction

All industrial production in a market economy must be profitable in the long term in order to be viable. If not, it will have to be stopped sooner or later. However, in judging an industry and its prerequisites for survival today there are other values that have to be considered as well, *e.g.* social, health, and environmental values. Even if the production is profitable, it will not be sustainably justified if it has strong negative side effects, even if they may be difficult to foresee over the short-term. This can be exemplified by the Swedish pulp industry and the bleaching methods it used until the 1980's and 1990's. Chlorine had been used for effective pulp bleaching since the beginning of the twentieth century without any major consideration of its very ecologically harmful effects. The industry appeared to think that it had already done enough for the environment. Not until the environmental movement made the public aware of the problem, resulting in demands for chlorine-free products, was the issue made a priority for the industry. Environmentalists in Germany, representing Sweden's largest export market for pulp, essentially blacklisted Swedish pulp and paper. This forced the pulp industry to develop new, totally or partially chlorine-free processes and products. This development was successful, but in retrospect it seems that the industry should not have been forced to make these changes by the environmental movement. It would have been in the industry's own interest to combine high quality products and profitability with environmental concern in order to safeguard the future production.

A major theme of this thesis is to highlight the need to combine high product quality, and thus high profitability, with high environmental awareness in the forest industry in order to maintain sustainable production. (The more detailed objectives of the studies in this thesis can be found on page 20.)

From forest to industry

The forest industry has long been an important sector of the Swedish society. Today, products from the forest are omnipresent, despite the introduction of new materials. As consumers, we daily use products from this industry, maybe reading a newspaper sitting at a wooden table while drinking coffee from a paper cup. We continuously make higher and higher demands on these and coming products at the same time as the industry streamlines and rationalises its production. In addition, over the years environmental concern has grown stronger and stronger, leading to further restrictions on the industry. These demands and restrictions have resulted in extensive technical developments of the industrial processes to fulfil the environmental requirements. Today, in order to optimise the end products even further it is important to focus on the raw material before it enters industrial process streams and the overall environmental impact of the product.

The raw material

The quality of the raw material, the wood, determines the quality of the completed product reaching the consumer. This quality depends, in turn, on where and how the trees have grown as quality varies amongst different stands and forests. At the time of felling the quality and wood properties are given. However, despite these variations, differing consumer requirements can be fulfilled simply by dividing the wood into appropriate assortments.

With improved methods for controlling the logistics all the way from the stand in the forest to the mill at the right time, the potential for ensuring that more suitable raw material enters industrial process streams increases. New wireless communication techniques in combination with Global Positioning Systems (GPS) and Geographic Information Systems (GIS) help the logistics to be planned much more efficiently than before (Johansson, 1997). However, it is important to ensure that the desirable wood qualities from the intended stand are retained when entering the industrial processes, and not lost on the way from the forest to the mill.

Wood is a natural, ageing product, like milk or bread. This means that wood, like milk, has a “best before date”. How far in the future this “best before date” is, or how quickly it will be reached, depends on what the wood will be used for and how important different quality parameters are for the particular product. It also depends on how the wood has been handled earlier in the chain from forest to mill since earlier quality losses are difficult to rectify.

Five activities from forest to industry

On its way from the forest to the industrial process streams, the wood passes through five main activities described by Liukko (1997). These include: harvesting/felling, off-road transportation, storage at roadside, long distance transportation, and finally storage at the mill. In order to deliver wood of good quality, or fresh wood, to the industry, it is important that the freshness remains close to original during all of these activities. (Wood freshness is often considered to be closely related to the moisture content (MC), *i.e.* the weight of the water in the wood divided by the total weight of the wood.) This roundwood management chain can take several weeks, throughout which the wood is, to varying extents, losing freshness. During this handling from felling to industry the wood is very vulnerable to various sorts of damage such as drying out and attack by fungi and insects, which reduce its freshness. The large volumes and values involved can be described by the fact that at the end of 2003, 5.2 million m^3 wood was stored at roadside, terminals, or industrial sites in Sweden (Backe, 2004).

During harvesting/felling and the following handling in the forest, the wood is exposed to bark damage and losses, which cause problems since the bark efficiently prevents the wood from drying out. Bark losses are often worse during the spring and early summer since bark-wood bonding strength is relatively weak then (Wästerlund, 1985). This coincides with the most active period for insects, and the spring is also the time when drying is fastest due to relatively high temperatures and low humidity. This intensifies the problems with wood damage before the wood has left the forest. When the trees are felled and spread at the clearfelling they are highly exposed to wind, sun, and biological attack. It is also at this stage that supervision and control of the wood is most difficult. When the wood is forwarded and stored at the roadside it suddenly becomes significantly easier to control and protect it. The logs are stored in piles and are protected by each other from wind, sun, insects, and fungi. The location of the piles at the roadside is of importance, and the simple measure of placing the piles in the shade has been shown to decrease the drying considerably (Persson, Filipsson & Elowson, 2002).

After the long distance transportation from the forest the wood reaches the industry and final storage at the mill. Ideally, of course, no final storage at the industrial site would be needed. The felling and transports could be adjusted to the demands of each mill and a Just-In-Time (JIT) approach could be used for planning the logistics in order to deliver the wood at the exactly right time. This will not, however, be a reality in the foreseeable future due to seasonal variations in fellings and transportation, in combination with the very high costs for the industry associated with wood shortages compared to the storage costs (Hägg, 1991). The need for storage at the mill seems unavoidable and therefore the best techniques available must be applied to maintain freshness of the wood until it is used, and a storage regime must be developed that make it possible to control every pile in order to avoid overshooting the "best before date".

It is when the wood enters the log yards of the mills for storage that the prerequisites for large scale and efficient active protective measures for preserving the quality and freshness of the wood arise. The high concentrations of wood at the mills (or large terminals for later transport to them) provide practical and cost-effective possibilities for protective measures to be applied. In Sweden today, the most common active method for protecting stored wood and maintaining the original quality of both pulpwood and timber is water sprinkling (wet storage) of woodpiles at the log yards. It can also be mentioned that snow storage, where the woodpiles are embedded in snow and wood chips, resulting in a freezing effect, is practiced on a smaller, experimental scale.

It is very important to limit the time from felling to protected storage as much as possible since this is when the wood is most exposed to drying out and the MC will fall. It has been shown that it is very difficult to increase the MC once it has decreased. Not even water sprinkling can fully compensate for losses in MC prior to the sprinkling (Liese & Peek, 1984; Liukko & Elowson, 1999).

Wet storage

This thesis is focused on wet storage, defined as sprinkling water on stored wood on-land to protect it (Fig. 1). Wet storage can be performed in various ways, but the important and common objectives are to prevent the wood from drying out and protect it from biological attack. Wet storage is here distinguished from water storage, *i.e.* ponding or submerging the wood in water. Ponding as a protective measure has more or less ceased due to its negative impact on the water as well as deterioration of wood quality.

Fig. 1. Wet storage of timber.

According to the last nationwide Sawmill Inventory, for year 2000, 84% of Swedish sawmills producing over 100,000 m^3/year protect their timber with wet storage (Staland, Navrén & Nylinder, 2002). It can be roughly assumed that the remaining 16% of the sawmills do not take any wood protective measures during storage. Corresponding data for the pulp industry are not available. However, there is a growing practice to sprinkle pulpwood. Wood for mechanical pulping is almost as sensitive as timber and has since long been sprinkled to a similar extent. Variations in wood quality have not previously been of any great concern for the chemical pulping industry, but because of increased demands related to pulp quality, chemical pulpmills are also starting to show interest in sprinkling pulpwood. In 1999, Jansson reported the successful introduction of wet storage at sulphate pulpmills in southern Sweden.

Wet storage is also used to store huge volumes of unintentionally fallen timber caused by heavy storms or fires. There are, for example, records of wet storage, sometimes for several years, after the storms in Germany and Denmark in 1967, 1972, and 1990 (Moltesen, 1977; Liese & Peek, 1984; Bues & Läufer, 1993), and in the UK in 1987 (Webber & Gibbs, 1996). A heavy fire in 1989 at a pine plantation in South Africa was also followed by successful wet storage (von dem Bussche, 1993).

Open and closed systems

Wet storage of wood in log yards can be done with either an open system or a closed water system with re-use of the water. In an open system only fresh water is used. In closed systems, on the other hand, the sprinkling water is recycled, no water is discharged and new water is only added to compensate for evaporative losses from the wet woodpiles and the log yard. Of the 84% of Swedish sawmills that use wet storage, 61% use open sprinkling systems without recycling of the water and 39% use closed recycling systems (Staland, Navrén & Nylinder, 2002).

Climate-adapted sprinkling

In order to minimise the sprinkling intensity and water consumption while safeguarding the wood quality, a method for climate-adapted sprinkling was developed in the 1990's (Elowson & Liukko, 1995; Liukko & Elowson, 1995; Liukko & Elowson, 1997). The method is based on a theoretical model for estimating evaporation from timber piles related to the prevailing weather. To the theoretical evaporation a safety margin is added to ensure good wood protection.

Coastal locations

Because of the earlier importance of rivers as transportation systems for logs and the advantages of transporting finished products by boat, many sawmills and pulpmills are located by the big rivers and on the coast of Sweden. Consequently, a lot of wet storage today is conducted with brackish water. The salinity varies between 0.8-1.4% in the Baltic Sea, and between 2.0 and 3.4% in coastal waters in western Sweden, decreasing closer to land after dilution with fresh water (Bydén, Larsson & Olsson, 2003). The importance of these differences in salinity when sprinkling wood has been sparsely studied. In a study from 2001, Persson & Lindeberg suspected that their results, regarding changes in Fe, Mn, and Ca content in pulpwood due to wet storage, could have been influenced by the salinity in the sprinkling water used.

Salt and wood have been examined in a few studies such as the one by Firestone (1950), where it was reported that wood transported in saltwater picked up considerable amounts of salt, while Jasnowska (1962), and Johnson, Ibach & Baker (1992) showed that repeated wet/dry cycles with brackish water causes wood degradation.

Moisture content

Wet storage of wood protects the wood by keeping the MC of the wood at a high level and creating a protective water film on the wood surface. This prevents drying out and limits biological attack. The MC in standing trees varies over the year, over the day, between trees, and within trees. It is the MC of the sapwood that is crucial and Tamminen (1964) reported the outer sapwood of Norway spruce (*Picea abies*) to have an MC of around 60%. Regarding wood and the risk for damage in storage, there are three critical MC levels (Liukko, 1997; Persson *et al.*, 2002a). If the MC drops below 50%, fungi such as blue stain fungi more easily attack the wood. Decay fungi such as brown, white and soft rot fungi can also cause quality losses at MC values below 50%. Below 40%, debarking of pulpwood becomes more difficult and energy consuming. At MC values below 23%, *i.e.* the fibre saturation point where all free water in the wood has evaporated, the wood starts to shrink, tensions arise and cracks form.

The oxygen deficient conditions caused by higher MC values inhibit undesirable biological activities in wood. In addition, the water sprinkling has a cooling effect that decreases the biological activity (Björkhem *et al.*, 1977). This cooling effect comes from energy losses due to evaporation of the sprinkling water from the wood surface and also, sometimes, from the water temperature being lower than the wood temperature.

Wood properties

Wet storage has valuable wood-protecting qualities, as described above, but if the sprinkling proceeds for too long or is misapplied it can also affect the wood properties negatively (Persson & Elowson, 2001). Lower sprinkling intensities, attained with climate-adapted sprinkling, decrease the problems (Persson & Elowson, 2001; Persson *et al.,* 2002a), but still there are important and costly side effects to address at the log yards. Two main problems connected with wet storage and wood properties are bacterial damage and discolouration, both leading to undesirable quality losses in roundwood and products.

Bacterial damage

Bacteria of different kinds are early colonisers of wood in wet environments (Eaton & Hale, 1993a). The role of bacteria in wood decay is quite minor compared to fungal decay (Eaton & Hale, 1993a) but they still cause problems, of importance mainly for the saw industry. The wood-living bacteria destroy ray cells, resin canals and pits (Daniel *et al*., 1993), thereby increasing permeability. Increased and uneven permeability is a severe problem when finishing sawn wood products. Bacterially damaged parts of the wood absorb more of the finishing agent and the result is an uneven and stained surface (Daniel *et al*., 1993) (Fig. 2). Bacterial damage eventually increases with higher sprinkling intensities (Weslien, 1992a) and the use of recycled sprinkling water in closed systems increases bacterial growth both in the sprinkling water and the stored wood (Weslien, 1992b). Bacterial attack has also been found in connection with discolouration of wood (Tighe, 1973; von Aufseß, von Pechmann & Lippemeier, 1974). Bacterial attacks on pulpwood may cause uneven MC, via the permeability changes, which could be a problem in optimising pulping processes.

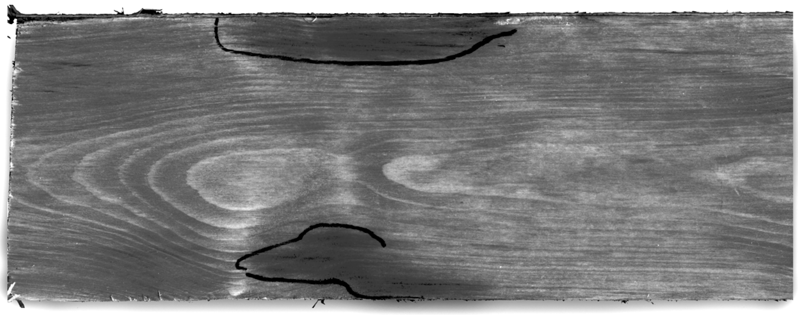


Fig. 2. Increased permeability (marked with lines) caused by bacteria on a piece of wood, visible after glaze painting.

Discolouration

Discolouration of coniferous wood during wet storage is mainly due to blue stain and/or tannin impregnation. The blue or dark discolouration of blue stain is caused by the growth of a variety of fungi in the sapwood. The colour is actually caused by the brown fungal hyphae that grow into the wood; the blue colour being caused by light diffraction when the wood is extensively infected by the fungi (Eaton & Hale, 1993b). Blue stain fungi do not degrade the cell walls, and therefore the wood's strength is not affected. Instead the fungi feed on freely available carbohydrates in ray cells and cell lumina (Eaton & Hale, 1993b). The problem is the wood discolouration, which affects the quality of the end-product. The risk for blue staining increases when the sprinkling intensity is too low to keep the MC of the wood above 50% (Liese & Peek, 1984; Liukko 1997; Persson *et al.*, 2002b). Climate-adapted sprinkling with an intensity corresponding to 100% of the evaporation was not sufficient to prevent blue stain developing in stored spruce pulpwood in a study by Persson & Elowson (2001), whereas sprinkling corresponding to 200% proved to be sufficient to prevent the infestation. If the sprinkling is insufficient it may lead to the reverse of the desired effect, and optimal living conditions for the fungi may arise. In the study by Persson & Elowson (2001), lightly sprinkled logs were attacked more seriously by blue stain fungi than dry stored logs. Therefore, as mentioned above, a safety margin must be applied when sprinkling wood in order to achieve good wood protection. Otherwise a blue stain attack can damage the sapwood to a large extent in a few weeks.

The spores of the blue stain fungus are spread by air or by insects such as bark beetles. This ability to spread blue stain spores is the main problem concerning insects when storing wood. Insects can also cause damage by boring in the wood, but this is of minor economic significance in Sweden. Insects are prevented from infecting the wood both by the unfavourably high MC and by the water film on the wood surface created by the sprinkling (Richmond & Nijholt, 1972).

Discolouration due to tannin impregnation is caused by the migration of tannin agents from the bark into the wood as a consequence of water or wet storage (Adler, 1951). Tannins migrating into the wood react with lignin and daylight, forming the dark colour (Adler, 1951; Lorås, 1974). This well-known phenomenon is also known as bark stain and has for example been reported in spruce wood by Adler (1951), Tydén (1956) and Gjerdrum (1976a). Tannin damage on wood impairs bleaching processes in the pulp industry (Adler, 1951; Tydén, 1956; Lorås, 1974) and is therefore of great economic concern. The extent of tannin impregnation during storage is correlated to water temperature, time, and the presence of bark (Tydén, 1956; Gjerdrum, 1976a). Wood stored for up to 45 days at a water temperature below 10 ˚C will not be damaged (Tydén, 1956). The importance of bark occurrence is shown by Lorås (1974), who reported water-stored spruce pulpwood without bark to have better bleaching responses than tannin-damaged logs with bark. When wet stored, the sprinkling intensity is also of importance for the development of tannin impregnation in wood. Persson and Elowson (2001) showed that discolorations after 12 weeks of wet storage were around 2.5 mm deep after storage with high-intensity sprinkling (200% of the evaporation) compared to around 1 mm after sprinkling at a lower intensity (100% of the evaporation). Closed systems with recycled water for wet storage may further increase the problems since recycling increases bacterial growth, and bacteria are found in association with tannin damage and discolouration (Tighe, 1973; von Aufseß, von Pechmann & Lippemeier, 1974). The increased permeability caused by bacteria may facilitate the migration of tannins into the wood.

Metals

Other substances migrating from bark to wood during storage can be undesirable too. Metals, for example, are much more abundant, by factors up to 5 or 10, in the bark than in the wood (Hakkila, 1989). Fossum, Hartler & Libert (1972) found concentrations of Ca, Mg, and Mn to be much higher in the cambium than in both outer bark and sapwood. Different metals cause different problems such as corrosion and bleaching difficulties in the pulping industry if they enter a mill with the wood (Dick & Andrews, 1965; Read, Eade & Slingsby, 1968; Gupta, 1970; Ulmgren, 1997). In order to confirm practical observations suggesting that wet storage leads to increased concentrations of Fe and Mn in pulpwood, Persson & Lindeberg (2001) performed a storage study on changes in metal concentrations in pulpwood. However, their results did not support the suggestions of increased metal concentrations, although wet storage increased the content of the studied elements in the wood to a very limited extent. No major differences between the effects of high and low sprinkling intensities were detected in their study. Persson & Lindeberg (2001) pointed out the need for further studies with a wider range of elements studied, and with different sprinkling water qualities. This thesis addresses these issues.

Environmental aspects

In addition to the negative effects on wood quality described above, there are also important environmental aspects of wet storage, which are mainly connected to water, both consumption of fresh water and quality of run-off water. Problems arise when the huge volumes of wood are concentrated in the log yards.

Fresh water consumption

In order to accomplish wet storage at a specific site, access to sufficient amounts of water for the sprinkling operation is essential. This water can originate from rivers, brooks and lakes or from the sea. The combination of high demands for sprinkling water for a large log yard and, sometimes, access only to a small watercourse such as a brook is of course a source of problems concerning the water supply. The water volumes used for sprinkling must be adapted to existing conditions. The larger the watercourse, the lesser the water supply problem. To limit the need for sprinkling water volumes of a given log yard or wood volume, the method of climate-adapted sprinkling (Elowson & Liukko, 1995; Liukko & Elowson, 1995; Liukko & Elowson, 1997) has been adopted by many of the bigger sawmills in Sweden. The sprinkling intensities and hence the water volumes required at the log yard can be decreased with this method by between 31% and 97% over a 24-h period (Liukko & Elowson, 1995).

The use of closed sprinkling systems with recycling of the water is another method for minimising the fresh water consumption since the need for new, fresh, water in these systems is limited to compensation for evaporation losses. But with this method there are problems with increased wood damage caused by bacteria as mentioned above. The working environment is also negatively affected with recycled sprinkling water due to bad smells and increased growth of bacteria in the water. These disadvantages make it desirable to find a good way of managing open systems as a better alternative to closed systems.

Log yard run-off

However, the main environmental problem with wet storage of wood is the large amount of log yard run-off water originating from open sprinkling systems (Fig. 3). Even though climate-adaption of the sprinkling limits the run-off volumes, the run-off is not completely eliminated due to safety margins and maintenance pressures in the sprinkling systems. A normal Swedish log yard with climate-adapted sprinkling in an open system can use around 100,000 m^3 water for sprinkling during a season (May to September in central Sweden). During this period, the amount of log yard run-off may be as high as 70,000 m^3. Most log yards in Sweden today are asphalted and, therefore, the run-off is drained in a controllable way and can easily be collected unlike, for example, the run-off from gravel yards. Log yard run-off does not only originate from sprinkling activities, it can also result from rain, snowmelt or applications of water for dust and fire control (Orban *et al.*, 2002).

Fig. 3. Log yard run-off from an open sprinkling system (to the right) and tap water for comparison.

The quality of log yard run-off has been examined in several studies, with varying findings (Gjerdrum, 1976b; Björkhem *et al.,* 1977; Beyer, 1983; Hammes, 1989; Peek, 1989; Borgå, Elowson & Liukko, 1996a,b; Webber & Gibbs, 1996; deHoop *et al.*, 1998; McDougall, 2002; Zenaitis & Duff, 2002; Zenaitis, Sandhu & Duff, 2002). The varying results are probably due to the highly variable log yard conditions with differences in the tree species stored, weather, sizes, and sprinkling systems (where used). A feature that most of the studies have in common is that they measured the biochemical or chemical oxygen demand (BOD or COD) in the run-off as an indirect measure of the organic material in the water. Some studies have found COD levels to be over 8,000 mg/l (Zenaitis & Duff, 2002; Zenaitis, Sandhu & Duff, 2002). Since organic material is mainly degraded aerobically, these high amounts can cause oxygen deficiency in the receiving watercourse. Oxygen deficiency is a serious problem that adversely affects living conditions, both directly and indirectly, for water-living organisms (Kalff, 2002).

Toxicity of log yard run-offs and similar waters, also caused by factors other than oxygen deficiency, has been reported in several studies. Bailey *et al.* (1999b) reported log yard run-off to be toxic to rainbow trout. Peters *et al.* (1976) found leachate from western red cedar to be moderately toxic and Taylor, Goudey & Carmichael (1996) reported aspen leachate to be toxic to aquatic life. The toxicity of log yard run-off, according to Microtox tests, is closely connected to the amount of organic material in the water (Borgå, Elowson & Liukko, 1996b). Phenolic compounds, such as tannins and lignins, and resin acids have been noted in the literature as potential sources of toxicity (Borgå, 1994; Taylor, Goudey & Carmichael, 1996; Bailey *et al.*, 1999b). Phenols can also easily react with chlorine and the resulting chlorophenols are all very toxic (Borgå, 1994). According to the study by Bailey *et al.* (1999b), the toxicity of log yard run-offs is mainly attributable to Zn (probably originating from buildings in the log yard). In addition, extracts of bark from various species are reported to be toxic to living organisms (Frei & Dodson, 1972; Krogstad & Solbraa, 1975; Buchanan & Tate, 1976). Other studies suggest, on the contrary, that log yard run-off does not pose any threat to the surroundings (Gjerdrum, 1976b; Webber & Gibbs, 1996; deHoop *et al.*, 1998).

Log yard run-off can also contain increased levels of potassium and phosphorus (Gjerdrum, 1976b; Björkhem *et al.*, 1977; Borgå, Elowson & Liukko, 1996a,b). Phosphorus is a nutrient and not actually a toxic element, but it does contribute to eutrophication of watercourses. Concentrations of nitrogen, on the other hand, are not increased in these waters. Woodpiles and log yards can rather be considered as nitrogen sinks, due to the consumption of nitrogen by microbes on the logs and pile foundations (Borgå, Elowson & Liukko, 1996a). Borgå, Elowson & Liukko (1996a) also showed that woodpiles could act, in the same way, as sinks for sulphates and minerals. The microbial community growing in the piles is essential for this degradation, and the microbes establish more rapidly if the sprinkling water is eutrophic rather than oligotrophic. This microbial activity is actually of significance for the run-off quality. (Borgå, Elowson & Liukko, 1996b.) In fact, bark and lignins can be used for the purification of metal-contaminated industrial wastewaters (Seki, Saito & Aoyama, 1997; Gaballah & Kilbertus, 1998; Bailey *et al.*, 1999a; Palma, Freer & Baeza, 2003) and a similar purifying effect may also possibly be found in woodpiles.

Handling log yard run-off

In the USA and Canada, several methods have been suggested for handling log yard run-off, such as biological treatment, ozone treatment, settling basins or infiltration basins (WDOE, 1995; Zenaitis & Duff, 2002; Zenaitis, Sandhu & Duff, 2002). In Sweden, no ready to use methods have been developed, and no clear guiding principles from the authorities have been issued. Therefore the companies are obliged to find satisfactory ways of purifying their run-off with little more to guide them than trial and error. However, there is knowledge, and experience, in Sweden of treating surface water, municipal wastewater, and landfill leachate with different biological methods such as willow (*Salix* sp.) plantations and wetlands (Krantz & Hjerpe, 2000; Hasselgren, 2003). Using similar systems, maybe modified, for log yard run-off seems most convenient.

Today, a majority of the Swedish log yards are asphalted to facilitate transport and cleaning. But traditionally they were covered only with gravel. The log yard run-off then mostly infiltrated through the gravel and was thus partly purified, and not as concentrated and visible as it is today. In addition, the awareness of environmental threats has increased latterly. Therefore, the extent of the log yard run-off problem today can be seen, in a way, as a quite new problem even if the source of the problem, the wet storage, is much older.

Wood concentration

Both the wood protection advantages of wet storage, and the disadvantages, in the form of environmental problems, are results of the large concentrations of wood that occur at log yards. Without this concentration the protection would be too costly and the water use and log yard run-off would be very limited. Since the advantages of wet storage outweigh the drawbacks we have to accept the disadvantages of the wood concentration and try to minimise them as effectively as possible. By finding ways for doing this, production can be made more efficient and the end product more valuable both for the industry and the consumer.

Earlier theses from SLU

This thesis is a continuation of earlier research at SLU (Swedish University of Agricultural Sciences) that in the last ten years has resulted in several doctoral theses discussing different aspects of the roundwood management chain from the forest to the mill, with storage and wet storage in particular foci. This is as a consequence of the growing interest in the industry in roundwood management issues. Liukko (1997) developed a new technique for wet storage, climate-adaption, which considered the current climate and evaporation at the log yard, and could thus optimise the irrigation intensity during the wet storage. This leads to better wood quality and less water consumption. Borgå (1994) studied, among other things, run-off water from wet storage, the impact of climate-adaption and differences between open and closed water systems. Persson (2001) evaluated effects of storage and climate-adapted wet storage on pulpwood quality.

Still, there are aspects of this roundwood management chain that need further investigation: for instance the influence of brackish water on pulpwood when wet stored has been poorly studied, although it is common in Sweden. Measures for limiting the environmental impact of the run-off water, even though the volumes are limited with climate-adapted sprinkling, also require further attention.

Objectives

In order to optimise the wood handling from the forest to industrial process streams, the two main problems associated with wet storage that need to be addressed are its effects on wood quality and its environmental impact. These two problems have to be considered simultaneously in the management regime.

In this thesis I examine some relatively neglected aspects of wet storage and define some limits for the practice with respect to the suitability of different types of water for sprinkling of wood. Since many sawmills and pulpmills are located near the coast the effects of brackish water are interesting, and changes in inorganic content in pulpwood due to sprinkling with brackish and salt water are discussed here. The effects of fresh and recycled sprinkling water on wood brightness as well as run-off water quality are also considered. This thesis further focuses on a new method for handling log yard run-off water. Even with climate-adapted wet storage considerable amounts of potentially harmful run-off arises from the log yards. Different soil-plant systems for purification of the log yard run-off are considered in attempts to find a simple and cost efficient way of treating this water.

This thesis will contribute to the knowledge base related to the wood handling chain from the forest to the mill and will hopefully give some practical guidance on how to perform wet storage the best way in terms of both wood quality and its environmental impact.

Materials and methods

In this section I briefly describe the materials and methods used in the studies described in detail in Papers I-IV appended to this thesis. The text is limited to information that is necessary for understanding the following results and discussion. More detailed information is found in the cited papers.

Sprinkling wood using brackish water – effects on the inorganic content of wood (Paper I)

To study the effects of sprinkling pulpwood with brackish and salt water on the inorganic contents of wood, three small Norway spruce (*Picea abies*) piles, 1000×400×400 mm, were placed in separate vats and intermittently sprinkled with 0%, 1%, and 3% salinity, respectively. The sprinkling proceeded for nine weeks at a controlled warm (30 ˚C) and humid (80–90%) climate with 12 h day and 12 h night cycles. Wood and bark samples for the determination of Ba, Ca, Fe, Mg, Mn, Na, and P contents were taken before and after the nine weeks of sprinkling. Water samples for the determination of Ba, Ca, Cl, Fe, Mg, Mn, N, Na, and P contents were taken before, during and after the experimental sprinkling. Changes in concentrations before and after sprinkling were studied.

Wet storage of Norway spruce (*Picea abies*) pulpwood with fresh and recycled water – Effects on wood and water quality (Paper II)

Four 3-m high and 15-m long Norway spruce (*Picea abies*) pulpwood piles were set up at a log yard in Borlänge, central Sweden. Three of the piles were sprinkled in accordance with ordinary high-intensity climate-adapted sprinkling at the log yard; the fourth pile received a lower intensity sprinkling. Two of the piles with high intensity sprinkling were sprinkled with recycled log yard run-off, and the other two piles with fresh lake water. To determine wood quality changes with respect to MC and brightness caused by the sprinkling regime during 14 weeks of storage (from the end of June to September) wood samples were taken throughout the experimental period. For determination of run-off water quality from the differently sprinkled piles, water samples were taken under the piles and analyzed for Total Organic Carbon (TOC), phenols, phosphorus, and nitrogen.

Wood from the same storage set-up was also used for laboratory pulping trials at Åbo Akademi University, Finland. Fibre dimensions, acetone-soluble substances, extractives, MC, tear index, tensile strength, brightness, light absorption, fibre length, and bleaching response were determined on mechanically ground pulp and handsheets. A paper in preparation (Lind *et al.*) presenting this study is not included in this thesis. However, the most important findings from this study are briefly presented in the *Results and discussion* section of this thesis, see page 26.

Effects of soil type, irrigation volume and plant species on treatment of log yard run-off in lysimeters (Paper III)

At a lysimeter station in Uppsala, central Sweden, eight lysimeters with clay soil and eight with sandy soil (volume 1200 l, diameter 1.3 m) were irrigated with two intensities, 10 mm/d and 20 mm/d, of log yard run-off from a closed log yard sprinkling system throughout one summer. Eight of the lysimeters were planted with willow (*Salix schwerinii x Salix viminalis*) and eight with alder (*Alnus glutinosa*). The drainage water from the lysimeters was analysed for TOC, phenols, phosphorus, and nitrogen in order to determine the purification efficiency in the different soil-plant systems in the lysimeters. The retentions in the lysimeters were calculated, based on concentration differences between the irrigation water and drainage water multiplied by the difference between the irrigation and drainage water volumes.

Treatment of log yard run-off by irrigation of grass and willows (Paper IV)

A couchgrass (*Elymus repens*) field in Heby, central Sweden, were irrigated (approx. 66 mm/d) with log yard run-off from a nearby log yard with an open sprinkling system. Four pairs of groundwater pipes were installed inside and outside the irrigated grass area for sampling groundwater, the depth varied between 1.2 and 3.1 m. Furthermore, four small lysimeters (volume 68 l, diameter 0.3 m) with couchgrass or willow (*Salix schwerinii x Salix viminalis*) were irrigated (49 mm/d) with log yard run-off from the same log yard as used for the couchgrass irrigation. Both groundwater samples and drainage water from the lysimeters were analysed for TOC, phenols, phosphorus, and nitrogen in order to evaluate the log yard purification efficiency both at the lysimeter scale and the field scale. Retentions in the lysimeters were calculated as in Paper III, and the retentions in the grass field were estimated using irrigation and groundwater data, assuming negligible transpiration and uniform mixing in the groundwater.

Results and discussion

To summarise the results of this work, it was found that, for the wood properties studied, the influence of the sprinkling water quality (*i.e.* its salinity level and whether or not it was recycled) used for wet storage of wood was small. It was further found that irrigating soil-plant systems with log yard run-off is a promising method for purifying log yard run-off originating from spruce roundwood.

Effects of wet storage on wood properties

Wet storage can be conducted in many ways with different water qualities that may affect the stored wood in different ways. As mentioned earlier, recycled sprinkling water increases bacterial attack (Weslien, 1992b). Other aspects of sprinkling water quality have been poorly studied. The potential changes in wood quality are, however, of importance for the industrial processes and the final products, and thus can have major economic effects. Here, some further quality aspects will be discussed.

Inorganic content in the wood

The different salinities of the water used for wet storage of wood in the studies described in Paper I did not seem to be of any major importance regarding changes in the levels of the analysed elements in the wood during storage, except for clear increases in Na and Cl contents in wood sprinkled with brackish and salt water. Wet storage itself seemed to result in some increases in inorganic content in the wood, but this increase did not seem to be larger when using brackish water. Start levels and changes of analysed elements in the wood sprinkled with fresh and brackish water studied in Paper I can be seen in Table 1.

Table 1. *Contents of analysed elements (mg/kg) in the wood before the sprinkled storage and absolute changes in contents during the nine weeks of sprinkled storage with fresh water (0% salinity) and brackish water (1% salinity). Negative change values show decreases. p=probability: only significant values ($p<0.05$) are presented, higher values are excluded (n.s.). n=18 for the fresh water treatment and n=16 for the brackish water treatment*

	Fresh water			Brackish water		
	Before	Change	p	Before	Change	p
Ba	9.5	-0.6	n.s.	10	0.5	n.s.
Ca	958	-124	n.s.	1027	-28	n.s.
Fe	3.0	1.1	0.002	3.4	0.3	n.s.
Mg	102	-13	n.s.	99	-6.9	n.s.
Mn	64	3.1	0.009	60	12	0.030
N	527	-5.8	n.s.	501	16	n.s.
P	47	3.5	0.033	38	0.9	n.s.
Cl	<0.01	<0.01	-	<0.01	0.1	0.000
Na	38	256	0.000	40	1430	0.000

Comparable changes in contents of Fe, Mn, and Ca in pulpwood due to different storage alternatives from two different studies can be seen in Table 2, the figures originate from Paper I and from the storage study by Persson & Lindeberg (2001). The figures are not exactly concordant between the two studies, especially regarding Ca, and the differences in experimental setup and conditions must be considered. The extreme storage conditions presented in Paper I could have enhanced the microbial activity and thus changed microbial processes in the wood. Bacterial or fungal activities that may have caused changes in inorganic content were not studied, but could have been considerable under the prevailing climate.

Table 2. *Changes in contents of Fe, Mn, and Ca in wood, mg/kg, after 9 or 12 weeks of different kinds of storage*

	Fe	Mn	Ca
Dry storage[a]	-3.5	+0.6	-23
Low sprinkling, brackish water[a]	+0.0	+6.7	+31
High sprinkling with bark, brackish water[a]	-1.5	+7.5	+76
High sprinkling without bark, brackish water[a]	+8.8	+3.9	-11
Sprinkling with 0% salinity[b]	+1.1	+3.1	-124
Sprinkling with 1% salinity[b]	+0.3	+12	-28
Sprinkling with 3% salinity[b]	+2.9	+9.3	-26

[a] Persson & Lindeberg, 2001, modified. Twelve weeks of storage.

[b] Paper I. Nine weeks of storage.

The common practice of wet storage with Swedish coastal waters should not increase the content of undesired inorganic elements in the wood (except for Na and Cl) more than using fresh waters according to the findings presented in Paper I. However, the increased content of Cl should be considered since Cl is known to cause plugging in recovery boilers in chemical pulpmills (Ulmgren, 1977). The increases in Fe and Mn that were seen independently of sprinkling water salinity may also cause problems since they can reduce the bleaching effect in pulping processes (Dick & Andrews, 1965; Read, Eade & Slingsby, 1968; Gupta, 1970; Ulmgren, 1977). If these problems are severe enough they may affect the choice between wet and dry storage alternatives at pulpmills. On the other hand, apart from its protective qualities, wet storage leads to advantages for the pulping industry such as higher and more homogenous MC and better debarking properties compared to dry storage of wood.

Wood properties such as inorganic content are obviously of importance for the pulp industry, but not directly for the saw industry. Changes in inorganic contents of wood do not affect the sawmill processing or the sawn product. Nevertheless, the wood properties of the raw material supplied to the saw industry do affect the pulp industry via the large amounts of sawmill chips entering a pulpmill. In year 2000, Swedish sawmills produced 11.7 million m^3 of chips, most of which were delivered directly to the pulp industry (Staland, Navrén & Nylinder, 2002). This is about 30% of the total wood volume entering the sawmills. This implies that changes in wood quality are of importance in both the pulpmill and the sawmill, even if it is easier to see the direct connection between pulpwood and pulp than between timber and pulp.

Fresh or recycled sprinkling water

The comparative study with fresh and recycled water used for wet storage (Paper II) showed that the water quality and intensity were of minor importance for changes in pulpwood brightness and MC. Both sprinkling intensities used, 70% and 140% of the measured evaporation, proved to be sufficient to keep the MC above 50%, the critical level for wood protection (see above). An intensity of 70% is usually considered much too low to protect the wood sufficiently, but for the prerequisites in this study, it proved to be enough. Normal climate-adapted sprinkling intensities lie between *ca.* 150% and 200% of the evaporation. If the protection requirements are fulfilled, a lower sprinkling intensity is preferable since the water use and sprinkling activity are reduced.

Choosing between open or closed sprinkling systems (fresh or recycled sprinkling water) for wet storage should not be determined by their effects on wood brightness according to Paper II. The brightness after wet storage in this study was not affected by the sprinkling water quality, instead storage time was more important. The slight, unexpected increase (see Fig. 4) in brightness observed over time in wood stored with both fresh and recycled water conflicts with the results of other studies that found discolouration and decreased brightness of pulpwood after wet storage (Krenn & Brandstätter, 1991; Persson & Elowson, 2001; Persson *et al.*, 2002a). The lack of decrease in brightness presented in Paper II could be partly due to partial bark losses during felling and handling of the logs. Less bark leads to less tannin migration (Lorås, 1974; Gjerdrum, 1976a), and subsequently less brightness losses. An alternative explanation to the increased brightness is the delayed transport from the log yard to the laboratory of the first set of wood samples from the first sampling date. This might have led to decreased brightness, due for example to blue stain, in this set of samples compared to the later wood samples with shorter transport times. However, no blue stain was observed, and no plausible reasons for any reduction in brightness in this first set of samples were discovered.

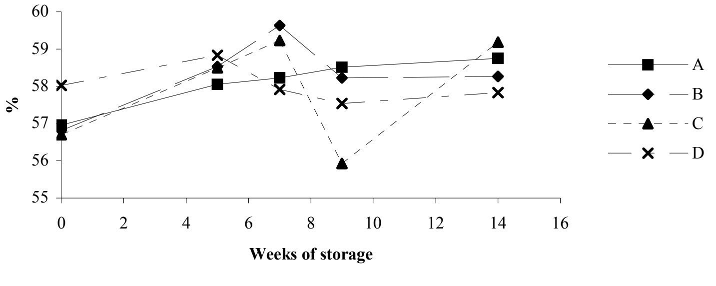


Fig. 4. Changes in brightness in the experimental wood from the four differently sprinkled piles (A-D) during the storage experiment presented in Paper II. A = fresh water sprinkling with high intensity (140% of evaporation), B = fresh water sprinkling with low intensity (70% of evaporation), C and D = recycled water sprinkling with high intensity.

Discolouration of stored wood

Discolouration and changes in brightness of stored coniferous wood are due, above all, to either blue stain or tannin impregnation from the bark. However, these two factors have conflicting responses to wet storage. Blue stain is increased by insufficient sprinkling, while tannin impregnation is known to increase with heavy sprinkling (Persson & Elowson, 2001). The optimum sprinkling intensity for minimising the total discolouration is somewhere between too high and too low, and is also dependent on the abundance of bark on the logs since the bark prevents attack by blue stain but increases the tannin impregnation. The best sprinkling intensity may depend on the purpose. For the pulp industry, the tannin impregnation is worse (in terms of bleaching) than blue stain (Persson *et al.*, 2002a), which means that the pulp industry can lower the sprinkling intensity. For the saw industry, which does not directly use the outer tannin-discoloured wood, the blue stain is a worse problem, and the companies concerned might want to use a higher sprinkling intensity to avoid the blue stain.

Bacterial damage

The increased risk for bacterial attack on wood when sprinkled with recycled water must be considered when discussing the total effect of sprinkling water quality on wood quality. Bacterial damage was not studied in the investigations underlying this thesis, but there is reason to believe that the recycled sprinkling waters (Papers I and II) caused greater bacterial damage to the wood. In Paper II, the bacterial attack of the wood may have been of greater importance for the total changes in wood quality than the actually studied brightness since bacteria flourish in recycled water and the infestation is accelerated (Weslien, 1992b).

Mechanical pulp properties

Mechanical pulp properties and corresponding handsheets made from the wood sprinkled with fresh and recycled water presented in Paper II were tested and analysed at Åbo Akademi University, Finland, and will be presented in a coming paper in preparation (Lind *et al.*) that is not included in this thesis. The results from these analyses showed only small differences between pulps made from the differently sprinkled wood. Some of the pulp properties (fibre length, long fibre fraction and strength properties) were, however, slightly better in pulp made from wood sprinkled with the lower intensity (70% of the calculated evaporation). The variation in sprinkling intensity proved to have greater effect on the pulp properties than the long storage time of 14 weeks. The bleachability of the pulps decreased slightly during the storage period.

Log yard run-off

The quality of a log yard run-off depends on the log yard conditions, *i.e.* tree species stored, weather, size, and sprinkling system. In all, 10 different log yard run-offs with varying concentrations of TOC, phenols, P, and N could be distinguished from each other in the four papers (I-IV) included in this thesis.

They differed in quality, but all originated from Norway spruce pulpwood or timber wet stored under different conditions.

The log yard run-offs considered in Papers I-IV were quite distinct from each other in composition (see Table 3). For example, the organic material in the run-offs varied between 56 and 864 mg TOC/l and the phosphorus concentrations varied between 0.8 and 5.2 mg/l. The large variation between the run-offs was probably dependent on the very different sprinkling conditions in the studies. The first three run-offs in Table 3 were collected directly beneath the piles, which probably explained the high concentrations of TOC and nitrogen. The water sampled directly beneath piles is not diluted in any way. Beyer (1983) has also shown run-off collected inside piles to have higher concentrations than the actual log yard run-off. The last three waters in the table were not strictly run-offs; they were recycled water used for indoor pulpwood sprinkling for nine weeks. The conditions during this sprinkling regime were extreme, with relatively small volumes of recycled water in a warm and humid climate. This might, for example, have favoured degradation of phenols, since the concentrations of these compounds are lower than in the other run-offs. Phenolic substances can be quite rapidly degraded under certain circumstances since some bacteria use them for respiratory purposes (Knoll & Winter, 1989).

Table 3. *Mean contents (mg/l) of TOC, phenols, phosphorus, and nitrogen of different log yard run-offs discussed in Papers I-IV*

	TOC	Phenols	P	N
High sprinkling, fresh water (Paper II)[a]	864	0.32	2.6	4.3
Low sprinkling, fresh water (Paper II)[a]	682	0.25	1.8	3.2
High sprinkling, recycled water (Paper II)[a]	739	0.32	2.6	4.0
Recycled run-off water (Paper II)[b]	180	0.11	1.1	2.2
Recycled run-off water (Paper III)[b,c]	191	0.13	3.9	2.7
Run-off from an open system (Paper IV)[c,d]	56	0.18	0.8	1.0
Run-off from an open system (Paper IV)[d]	112	0.12	1.4	1.3
Recycled water, 0% salinity (Paper I)[e]	427	0.01	1.0	6.9
Recycled water, 1% salinity (Paper I)[e]	264	0.06	1.2	4.5
Recycled water, 3% salinity (Paper I)[e]	375	0.06	5.2	3.9

[a] Run-off collected directly beneath the piles
[b] From Kvarnsveden log yard with closed sprinkling system
[c] Sampling after transport to lysimeter station
[d] From Heby log yard with open sprinkling system
[e] After nine weeks of extreme indoor sprinkling

However, in the investigations described in Paper II, where the intention was to create different sprinkling conditions (high and low intensity with fresh and recycled water) at the same log yard, the variation in the run-offs from differently irrigated piles was quite small. No major differences in concentrations of TOC, phenols, phosphorus, and nitrogen were seen between piles sprinkled with fresh and recycled water, or between higher or lower sprinkling intensities. This highlights the importance of the wood itself, and the microbial degradation processes in the piles affecting the run-off quality (Borgå, Elowson & Liukko, 1996a,b). Borgå, Elowson & Liukko (1996b) have shown clear differences in run-off quality from Norway spruce and Scots pine, with more heavily polluted run-off from spruce. Artificial mechanical pulping effluents from different Canadian coniferous species and aspen have also proven to be toxic to varying extents depending on the species (O'Connor, Kovacs & Voss, 1992).

Higher initial concentrations in log yard run-off during the first weeks of sprinkling are described in the literature (Björkhem *et al.*, 1977; Gjerdrum, 1976b; Borgå, Elowson & Liukko, 1996a,b). Similar patterns could be seen for TOC and phenols in Paper II. An observed tendency for leaching of Ba, Fe, Mn, and P from wood to water to be higher in initial stages (the first three weeks) of recycled sprinkling in the salinity study (Paper I) also supports this finding. Borgå, Elowson & Liukko (1996a,b) attribute the higher initial concentrations and subsequent decrease in leaching after a couple of weeks to an increase in microbial biomass in the piles, which gradually degrades and absorbs progressively more substances from the water. Björkhem *et al.* (1977), on the other hand, explain this decrease as being due to water absorption in the bark of the dry logs at the start of wet storage, which could decrease the run-off water volumes; resulting in higher concentrations of different substances in the run-off. This is, however, unlikely to be the only explanation since the bark can hardly absorb such large volumes of water during such extended periods.

A "trickling effect"

An interesting finding was the difference (significant for TOC, P, and N) between the run-offs collected directly beneath the piles described in Paper II and the corresponding recycled run-off water from the pump station (see Table 3, lines 1-3 and 4, respectively). Technically it was the same water, except that the latter had moved from beneath the piles over the ground, through the drainage system and into the pump station. Since the concentrations of TOC, phenols, phosphorus, and nitrogen were generally lower in the recycled run-off water than in the run-off from under the piles, this implies that some kind of purification occurs between the piles and the pump station. Degradation of some kind on the ground surface as the water trickles over the asphalt is one possible explanation. Degradation is probably more likely to occur in water on the ground surface in the presence of air and sunlight than in the drainage system or pump basin where the conditions are almost anaerobic.

Both the "trickling effect" on the water quality as it flows over the log yard surface and the increased degradation capacity in the piles during the first weeks of wet storage help reduce pollution of the log yard run-off. Concerning the "trickling effect", the best storage practice would be to place the wet stored piles as far away from the ditches or wells as possible at the log yard in order to increase the trickling distance and time. In order to optimise the degradation in the piles, the same piles should be sprinkled for a longer period while newly delivered wood enters the industry processing stream directly. This could work as long as the wet stored wood did not lose quality due to the storage time being too long. The maximum time of storage must then be based upon the loss of quality that is acceptable. Of course, the need for effective handling and sorting of the logs on the log yards must also be considered and might conflict with this approach.

Low nitrogen levels

Nitrogen levels in the log yard run-offs are relatively low, comparable to eutrophicated Swedish lakes (Bydén, Larsson & Olsson, 2003) and normally no surplus nitrogen is added to the watercourse as a consequence of wet storage of wood. Although it is useful to have some data on N concentrations, to contribute to the eutrophication debate, there is little point in spending much money or effort on assessing N-levels in log yard run-off. Organic material and phosphorus are of more concern. However, there is one area where it could be interesting to discuss nitrogen concentrations and this is when thinking of adding nitrogen to log yard run-off to increase biological degradation. Both nitrogen and phosphorus are often added at pulpmills to optimise the purification of process wastewater from the mills (Hynninen, 1998). Adding nitrogen to the log yard run-off before irrigation of the soil-plant systems described in Papers III and IV might increase the efficiency and sustainability of these systems.

Treatment of log yard run-off

Irrigation of soil-plant systems with log yard run-off for purification purposes seems to be a promising approach. Purification rates of up to 98% were recorded in the study presented in Paper III. A summary of the relative retentions (calculated as percentages) found in the different systems studied in Papers III and IV can be seen in Table 4. More information about actual concentrations of TOC, phenols, P, and N in both the drainage water from studied lysimeters and the groundwater in the studied couchgrass field can be found in Papers III and IV.

Table 4. *Relative retentions for soil-plant systems irrigated with log yard run-off described in Papers III and IV. The figures are based on the mean values (n=8 for the two treatments described in paper III, n=4 for lysimeters described in paper IV, and n=1 for the estimated field retention presented in paper IV) for the different treatments described in the papers*

	Irrigation (mm/d)	Retention (%) TOC	Phenols	P	N
Large lysimeters (Paper III)	10	84 – 93	31 – 76	59 – 98	-44 – 76
Large lysimeters (Paper III)	20	72 – 88	53 – 65	52 – 94	11 – 73
Small lysimeters (Paper IV)	49	35 – 46	68 – 80	73 – 76	-17 – -7
Couchgrass field (Paper IV)	66	63	82	96	0

Irrigation intensity

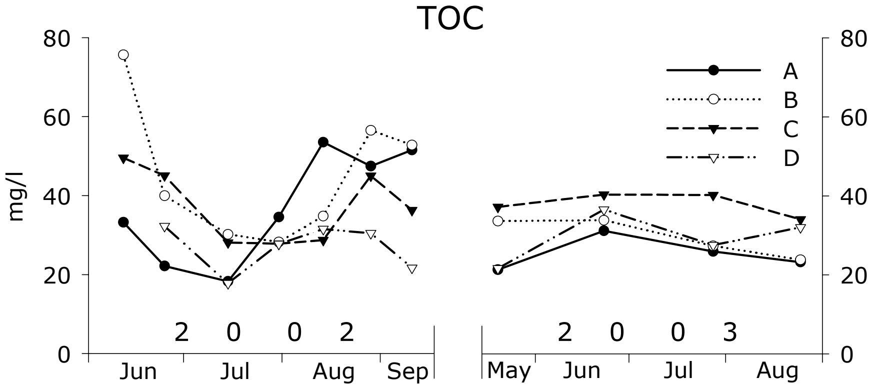
The purification efficiencies of the systems depended neither on the plant species nor the soil type used. Instead, the key factor was the irrigation intensity. The retention of TOC and phosphorus in lysimeters irrigated with between 10 and 49 mm/d was higher at the lower irrigation intensity. Phenols, on the other hand, were surprisingly retained most strongly at the highest irrigation, 66 mm/d. The couchgrass field study is, however, somewhat difficult to compare with the other studies since it involves a full-scale system and the retentions are estimated in a different way (see Paper IV for details). Nevertheless, the retention values from Paper IV do show that this kind of purification system probably is transferable from experimental lysimeters to full scale without losses in efficiency, even if the comparison of exact retention figures between lysimeters and field may be somewhat uncertain.

The irrigation intensities used in the studies, especially Paper IV, were extremely high. Corresponding systems for treatment of municipal wastewater have irrigation levels of around 5 mm/d compared to the 49 and 66 mm/d in Paper IV. The comparison with municipal wastewater concerning irrigation intensities is not entirely valid since municipal wastewater is quite different from log yard run-off and contains much more nitrogen. The high irrigation intensities used mean that the purification efficiency of the log yard run-off systems studied is probably not optimal. Lower irrigation intensities would most likely lead to even better retention and purification. High intensities are used for practical and economic reasons, and to minimise land use. It would be of great value to determine the optimal irrigation intensity with respect to both log yard run-off purification and economic/land use parameters.

The high irrigation load in the study on the irrigated couchgrass field (Paper IV) also resulted in increased groundwater levels beneath the irrigated area. The rise was seen immediately after the irrigation began and the groundwater level also decreased quickly after the irrigation had ceased. Similar rises in groundwater levels beneath sprinkled gravel log yards have been seen earlier in Sweden (Björkhem *et al.*, 1977; Beyer, 1983). The increased groundwater level reported by Beyer (1983), caused by intermittent sprinkling 24 hours a day, was restricted to the immediate surroundings of the irrigated area. The sprinkling intensities in Björkhem *et al.* (1977) were 25 to 50 mm/d.

Sustainability of the systems

Due to the high irrigation intensities in the studied systems (Papers III and IV), the total load of the substances in the water on the soil-plant system was very high. In Paper IV the total loads over one season were up to 5,000 kg TOC/ha and 100 kg P/ha. This gives rise to questions about the sustainability of the systems, since the soil may become saturated or clogged and the purification efficiency drastically reduced. The couchgrass field described in Paper IV has so far been irrigated with log yard run-off for three seasons, the second of which is documented in Paper IV. Additional groundwater analyses from the third season suggest that the system was continuing to work in the same way as it did in the previous, second season. Concentrations of TOC and phosphorus in the groundwater pipes for seasons two



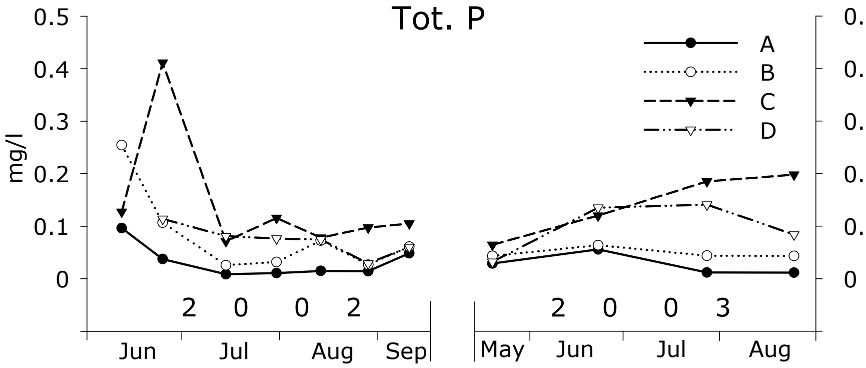


Fig. 5. Mean concentrations (n=2) of TOC and phosphorus in groundwater sampled within (A-B) and downhill of (C-D) the couchgrass field that was intensively irrigated (66 mm/d) with log yard run-off during the two seasons 2002 and 2003.

and three (years 2002 and 2003) are presented in Fig. 5. How the system will continue to work after several more seasons of irrigation is not yet known.

Hasselgren (2003) calculated for example the phosphorus need of a fully established willow (*Salix* sp.) plantation to be 10-15 kg/ha and year. Compared to the abovementioned 100 kg P/ha and year this gives an indication of the possible sustainability problems for the system.

If more normal irrigation intensities were used on similar systems as those described in Papers III and IV, the appropriate areas for irrigation would be dramatically increased. The couchgrass field described in Paper IV was irrigated with approximately 66 mm/d. If all log yard run-off from the adjacent log yard was used for irrigating a field with 10 mm/d, the area needed would be around five hectares, or about eight football fields. It is probably not easy to find 5-ha grass fields in the vicinity of most saw or pulpmills, but the sustainability of the system would most likely be much higher. The seasonal load of TOC and phosphorus would be 750 kg/ha and 15 kg/ha, respectively, compared to the 5,000 kg/ha and

100 kg/ha recorded in Paper IV. Maybe an irrigation intensity of 30 mm/d giving a required area of 1.7 ha would be more reasonable. The ambition must be to find the right intensity, or some kind of rotation, that is simultaneously ecologically sustainable, economically acceptable and practicable for the industry.

Conclusions

The main conclusion to be drawn from the results presented in this thesis is that a more optimised wet storage of spruce wood and log yard run-off handling should be managed with the following findings in mind:

- The salinity of the sprinkling water does not affect the inorganic content of stored wood. Swedish brackish waters are safe to use.
- The use of fresh or recycled sprinkling water does not affect the brightness of the wood.
- Irrigation of soil-plant systems with log yard run-off is a promising method for purification of the run-off. The method is simple and practicable for the industry.
- Irrigation intensity of soil-plant systems for run-off purification determines the purification efficiency more than the choice of plants or soil type. The irrigation intensity should be as low as practically possible.

By adapting the wood handling practices at log yards in accordance with the above conclusions and those of other studies, the wood industry can develop handling practices that both ensure the wood quality and minimise the environmental impact. By doing this, the roundwood handling chain with wet storage will be justified and sustainable in a long-term perspective. This should avoid a scenario like the late and forced bleaching development in the Swedish pulp industry after heavy pressure from the environmental movement.

Further research

Although the findings in this thesis contribute to our overall knowledge of wet storage and wood handling at log yards, there is still a need for further studies. The most interesting areas for future studies are listed below:

- Further studies regarding brackish and salt water sprinkling of stored wood are needed to ensure that there are no negative side effects compared to fresh water sprinkling. For example, the extent of bacterial or fungal attack on the wood, and methods to handle brackish log yard run-off for purification need to be researched. Ordinary soil-plant systems may not work.
- The tendency of brightness to increase during wet storage seen in Paper II should be followed up.
- The “trickling effect” for purification of log yard run-off on the ground surface should be further studied. If it proves to be of any importance, it could be a very simple and cheap way of handling log yard run-off.
- The sustainability of the soil-plant systems for purifying log yard run-off must be studied over a longer period of time before it can be stated with certainty that they work. How is the soil affected?
- The function and sustainability of the soil-plant systems if irrigated with maybe as little as 5 mm/d would be very interesting to study in order to optimise the purification efficiency. Adding nitrogen to the systems might

also increase their efficiency and would be exciting to study. In deciding the optimal irrigation intensity for soil-plant systems, efficiency, sustainability, and economic possibilities for the industry should all be considered.

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Acknowledgements

Many, many times I have had doubts about this work. But thanks to a large number of people I am finally here, writing the acknowledgements.

My first thanks goes to Torbjörn Elowson, my main supervisor. Without his knowledge and continuously encouraging discussions it would have been impossible to accomplish this work. I am also very grateful for all the valuable help and support I have received from my other supervisor, Pär Aronsson. Without all the help from Ioannis Dimitriou I would have been very lost, and Richard Childs, Hans Fryk, and Cecilia Åstrand also always know what to do. Ioannis and Hans have also professionally helped me with figures and photos. I wish to acknowledge my co-authors Erik Persson and Tom Lind for their collaboration. Thank you all.

I am most fortunate to have my dear husband Isak at home, who understands what it is to write a thesis and also knows what to do when my computer goes mad. Thank you for your patience with my mood changes and many silly questions. I am also grateful to my parents, who have been satisfied, throughout the last four years, with my answer “doing some research” to the question “What are you really doing at work?”. They also early gave me the best foundation for later studies. Thank you both!

Anna-Karin, who gives me perspectives on being a doctoral student at SLU, and the rest of my friends are also warmly thanked. And of course, all the people at SPM, how boring these years would have been without you!

Finally, I would like to express my gratitude to Heby sawmill and Stora Enso Kvarnsveden for valuable cooperation and support.