

Expected Pollutant Pathway Differences between Snow Deposits and a Permeable Snow Cooling Plant

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ABSTRACT

Urban snow is often considered an inconvenience but can instead be an environmental alternative for different cooling purposes. In many towns snow is removed from roads and placed into an above ground snow deposit (AGSD). Alternatively, a town's removed snow can be put into a snow cooling plant (SCP) to help meet summer cooling demands. A SCP works by transporting chilled water out of an embanked snow deposit through pipes, returning luke-warm water for recirculation or rejection. An impermeable liner-equipped snow cooling plant built in Sundsvall, Sweden worked well, but the initial investment was high. If a snow cooling plant is built without a liner this cost would be significantly reduced. Since urban snow is polluted, and a permeable snow cooling plant (PSCP) allows percolation, the pollutant loads leaving a PSCP and an AGSD must be compared. The common contaminants in urban snow are metals, nutrients, and suspended solids. Standard values for snowmelt contaminant concentrations in dissolved and particulate phase are not available making local studies necessary. Dissolved contaminants migrate with water, while particulate migration is dependent on surface water velocity. For an AGSD meltwater infiltration rates depend on soil parameters and melt rate, melt in excess of the infiltration capacity becomes surface runoff. A PSCP blocks the surface runoff pathway cutting off particulate flow. With low soil hydraulic conductivity, infiltration and percolation is low while surface runoff is high allowing a large particulate migration from an AGSD and more control of pollutants through filtering and treatment of PSCP reject water.

Keywords: snow deposit; urban snow; snow pollutants; dissolved metals; snowmelt; alternative energy

INTRODUCTION

Most northern towns have to remove snow from roads to increase traffic safety. In many towns this removed snow is placed in an above ground snow deposit (AGSD). Lately, demands for cooling capacity during summer seasons, have occurred with rising energy prices and a public call for cleaner energy. It is natural to consider the possibility of using deposited snow to meet many of these purposes. Along with increased cooling demand there has also been an increased awareness of the pollutants within urban snow.

Snow cooling uses the transfer of heat energy which occurs from the phase change of solid to liquid water. A snow cooling plant (SCP) is a snow deposit where the meltwater is transported through pipes for different cooling purposes. This melt water can be filtered or treated before being recirculated through the snow deposit or rejected. In 1999 Skogsberg and Nordell (2001),

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presented a liner-equipped snow cooling plant (LSCP) constructed with wood chips to reduce the melt rate and impermeable asphalt sides and bottom to prevent the uncontrolled spread of the melt water (Figure 1). A permeable snow cooling plant (PSCP) will work the same as a LSCP system with the exception that groundwater can flow in or out of the PSCP through the bottom and sides. This will result in a PSCP having less control than an LSCP over dissolved pollutants.

Although it is obvious that an LSCP will give the operator greater control of pollutant migration and allow a cleaner environment, building the liner is expensive making this system to costly for many municipalities. This is why a majority of the discussion will focus on comparing an AGSD to a PSCP.

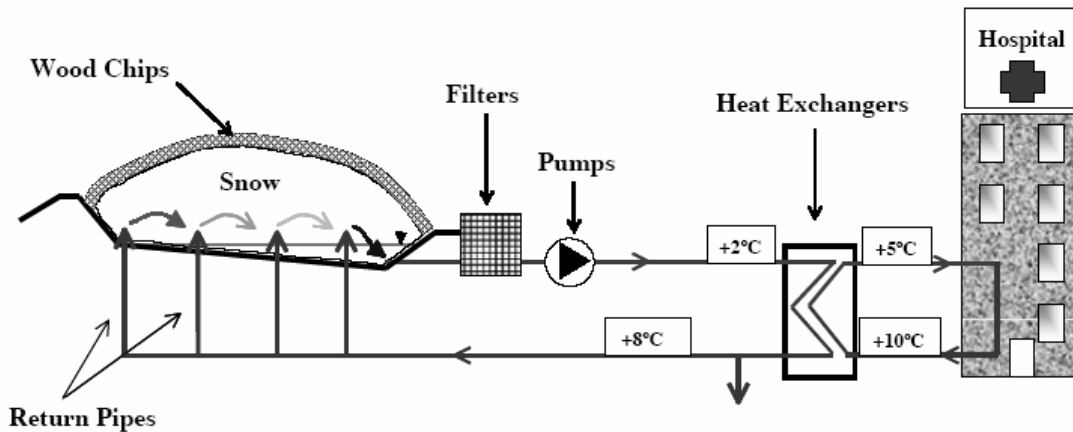


Figure 1. The Sundsvall liner-equipped snow cooling plant system with water temperatures indicated by the red and blue colors (Skogsberg, 2005).

The major contaminants in urban snow are metals, nutrients, salt, and hydrocarbons (Viklander, 1996 and 1997b). The anthropogenic sources for urban snow contamination, in order of importance are; traffic, anti-skid material, factories and litter. Contaminant concentrations will increase with time, making them depend on the speed of snow removal operations (Skogsberg, 2005; Viklander, 1997c; Westerlund et al., 2003).

Pollutant and nutrient concentration along with mass estimates are needed to determine the total load of contaminants in a snow deposit. The dissolved and particle bound proportions of these pollutant and nutrient loads are very important when considering potential pollutant pathways. The main pollution transports for a snow deposit are; snowpack elusion, infiltration, and/or surface runoff (Oberts et al., 2000). The dissolved pollutants can be transported through groundwater flow, while it is assumed that most of the substances attached to suspended solids (SS) will be filtered in the unsaturated zone before making it to the groundwater table (Viklander, 1996). In surface water runoff, mostly dissolved and some particle bound pollutants can be transported (Viklander, 1997). The amount and size of SS in surface runoff is dependent on the flow velocity (Reinosdotter, 2007).

Most environmental changes between a PSCP and an AGSD are due to changes in the pollutant pathways. A PSCP blocks the surface water flow that would contribute (polluted) meltwater to a local surface water recipient while being more likely to contribute meltwater to a groundwater recipient. An AGSD on the other hand might produce surface water flux carrying SS to surface water bodies while also having a groundwater recipient.

The expected contaminant proportions in dissolved and particulate phase are one of the most important factors in the planning of a snow deposit (Reinosdotter and Viklander, 2005). Any water not infiltrated in an AGSD will become surface water runoff. The ability of surface runoff to carry contaminants in the particulate form will therefore create most of the difference between the PSCP and AGSD.

According to Reinosdotter et al. (2007), the mobility of contaminants in groundwater depends on: soil texture, humus content, water quality and to some extent other geochemical factors. Soil texture describes grain size distribution and the way in which soil particles fit together and interact (Freeze and Cherry, 1979). This controls the properties that govern water velocities through soil. Reactions within the soil can slow contaminant movement through sorption and desorption (sometimes referred to as filtering). Sorption is when a water carried substance (e.g. a pollutant) interacts with the soil material in such a way that the pollutant bonds to the soil and desorption is when these bonds become untied. This process is pH dependent, for example, if the pH in a soil decreases the bonding sites available for contaminants with positive surface charges decreases allowing more dissolved particles to pass through the soil. This may also lead to a soil releasing adsorbed ions back to the dissolved phase. However, in this report all contaminants are considered conservative, and filtering is neglected since it will not decrease contaminant loads and is only a temporary reaction. Considering all the contaminants to be conservative also allows a calculation for the fastest (worst case) contaminant migration.

Environmental impacts of urban snowmelt are mostly due to the snowmelt properties such as; contaminant concentration and/or total load, flow volume, and temperature along with the sensitivity of the recipient (Westerlund and Viklander, 2007). Most of the environmental effects are non-lethal. For example plants may have reduced biomass and/or changes in dominant species. Changes in amount or type of flora in an area can then result in a species shift in fauna. Some sublethal effects are seen at low contaminant concentrations (Oberts, 1994; Oberts et al. 2000). Sublethal effects can also occur in humans (Oberts et al. 2000). With more than ¼ of the world and ½ of the US population relying on aquifers for drinking (Fitts, 2002), potential groundwater resources should in general be kept clean.

Polluted urban snow when deposited on a low permeability soil in a traditional above ground snow deposit (AGSD) is likely to pollute nearby surface water recipients with the meltwater surface flux transporting suspended solids from the deposit. If the snow is instead utilized for cooling purposes with a permeable snow cooling plant (PSCP), the pollutant pathways would be changed. The aims of this study are to:

1. Conduct a literature review on the common pollutants in urban snow.
2. Point out factors that alter the volume of meltwater (with nutrients and metals) flowing through the pollutant pathways of a PSCP or an AGSD in either
 - surface runoff (carrying mainly particulate matter)
 - groundwater percolation (carrying mainly dissolved matter)
3. Conduct a sensitivity analysis for the parameters involved in conservative groundwater contaminant transport in till.
4. Determine if and during what conditions turning an AGSD into a PSCP would reduce the total pollutant loads.

BACKGROUND

Urban snow contaminants in meltwater

Contaminants are most mobile (bioavailable) in the dissolved/soluble state, while bioavailability in the solid phase decreases as the size of the particle increases. The proportions of particulate and dissolved contaminants in urban snow are affected by the SS concentration. High SS concentrations are caused by sand spread on roads, road wear and dust. The SS in urban snow increases alkalinity, resulting in a higher pH than natural snow (Westerlund, 2007). The high pH in urban snow leads to a high percentage of contaminants binding to particles and fewer dissolved contaminants in the meltwater compared to snow melt from rural areas (Viklander, 1999;

Reinosdotter, 2003; Westerlund et al., 2007). The SS concentrations in urban snow depend on traffic, weather and snow handling strategies.

Traffic: Pollution in snow varies with traffic load, the more traffic the more pollution can be expected (Viklander, 1997b). Contrary to this, the percentage of dissolved metals decreases as traffic loads increase (Reinosdotter, 2007). This is due in part to an increase in SS with traffic load. Also, a higher proportion of metals tend to bind to smaller particles as traffic intensity increases (Reinosdotter and Viklander, 2006).

Weather and Snow Handling: There is a strong correlation between the amount of snow that falls in one year and the amount of snow deposited (Reinosdotter et al., 2007). However, even if the same amount of snow should fall in two separate years, the deposited snow amounts and contaminant concentrations can differ (Skogsberg, 2005). Lower contaminant concentrations would be present for a year that has fewer, but higher intensity snowfall events compared to a year with many lower accumulation snowfall events. This is due to higher intensity snowfall events forcing municipalities to remove the snow quickly (Viklander, 1997b). Snow handling practices determine; the time it takes snow to be cleared from streets, allowable height of snowbanks (Reinosdotter, 2007) and which anti-skid material (salt, chemicals or grit/sand) will be used on the streets (Viklander, 1997b). Urban snow deposits from areas using salt as a de-icer were found to have higher dissolved metals than if sand was used. Salt treated roads have less SS, resulting in lower alkalinity and pH, than if grit was used as the anti-skid material (Reinosdotter, 2007).

Pollutants in urban snow

A brief review of ecological effects expected from pollutants and nutrients in urban snow follows below; a more detailed review is planned (manuscript titled Environmental effects on soil and recipient waters from a permeable snow cooling pond is in preparation for submission to the Journal of Environmental Engineering). Reviews of environmental effects from a single contaminant e.g. the effects of deicing salts in soils by Cunningham et al. (2008) are available. Also reviews describing the most common contaminants in urban snow can be found in papers such as Viklander, 1997b or Glenn and Sansalone, 2002.

Urban ecosystems

Snow deposits have higher total pollutant and nutrient loads than undisturbed snow since polluted urban snow is concentrated in the snow deposits (Viklander, 1997). Viklander (1997a) studying a pilot snow deposits found that, the H⁺ and SS release into meltwater was almost constant through time. Most of the SS deposits on the soil surface under the AGSD (Westerlund and Viklander, 2007). However, the transport of SS is a function of flow and availability of materials (Westerlund and Viklander, 2006). Rain on snow events will increase the meltwater flow which in turn increases the transport capacity of the surface flow allowing more SS to leave the deposit (Oberts et al., 2000; Westerlund and Viklander, 2006).

The pollutant problems in urban snow are mostly due to high lead (Pb), zinc (Zn) and copper (Cu) levels (Viklander, 1997b) and often immeasurable amounts of cadmium (Cd) (Viklander, 1996). Urban snow also normally has; high nutrient loads of phosphorus (P) and nitrogen (N), salt (NaCl), organic material (such as oil), sulphate, high amounts of SS and high chemical oxygen demand (COD) (Viklander, 1996).

Metals: Metal concentrations in the saturated zone are assumed small due to their low solubility at pH's in natural water (Hill, 2004; Janssen et al., 2003; Pitt et al., 1999; Ruby et al., 1999). Many snow studies have found metals to be associated with the smallest fraction of particles (i.e. Reinosdotter and Viklander, 2007). Trace metals can cause severe health problems for humans and other animals higher up in the food chain at relatively low concentrations, due to metal accumulation in the body (Dominico and Schwartz, 1998; Hill, 2004; Janssen et al., 2003; Ruby et al., 1999).

Phosphorus (P): P has low solubility, often undergoing P-fixation, resulting in secondary mineral formation, or precipitation as it migrates through the unsaturated zone (Pitt et al., 1999). This makes surface runoff the main transport for P in surface water recipients. Primary production in most surface water bodies is P limited. An increase in the primary production of a recipient will make the recipient more eutrophic resulting in cloudier waters, and an increased capacity for fish biomass (Jeppesen et al., 2005).

Nitrogen (N): N is highly soluble and will stay in the aqueous form in soil. However, aqueous N concentrations are usually low resulting in low groundwater contamination potential (Pitt et al., 1999). There is also a constant natural nitrogen flow into lakes by rivers and streams, limiting the effect of changes in nitrogen (Jeppesen et al., 2005).

Sodium Chloride (NaCl): Both Na and Cl are very soluble and can cause many environmental effects in urban snowmelt. Too much Cl in groundwater makes it unfit for drinking, and if used for irrigation it can be detrimental to plant growth. Salt treated roads with low pH meltwater cause soil structures to change when Na is involved in cation exchange reactions (Monteith, 2007; Oberts, 1994; Oberts et al., 2000; Pitt et al., 1999). High salt content can also cause a stable stratification of lakes, leading to oxygen deficiency in non-circulating strata (Oberts, 1994; Oberts et al., 2000).

Organic contaminants: The main organic contaminants in urban snow are petroleum hydrocarbons, which are extremely soluble in water. Many of the solvents used in fuels, have higher densities than water making them sink to the bottom of the saturated zone, which makes them hard to remediate (Dominico and Schwartz 1998; Hill, 2004; Pitt et al., 1999).

The mobility of these pollutants in surface water is assumed to be the same, while there is a large difference in the mobility of soluble or insoluble pollutants in the groundwater.

Pollutant pathways of an AGSD and PSCP

An AGSD contributes melt water through groundwater infiltration and surface runoff. Infiltration rates for snow deposits vary from 0-100% depending on soil properties and the initial water content if the soil freezes before snow is placed in the AGSD (Oberts et al., 2000) (Figure 2). Snowmelt will flow through the groundwater pollutant pathway until the soil under the deposit nears saturation, at which point surface runoff volumes increase according to Oberts et al., (2000); however if the melt rate is high and the infiltration capacity of the soil is low the main snowmelt pollutant pathway should be on the soil surface. Low runoff flows carry fine SS, while high runoff flows can carry larger particles and thus also larger amounts of SS. However, most SS will be deposited as sediment on the soil surface below the deposit (Oberts, 1994; Oberts et al., 2000; Westerström, 1984; Westerlund et al., 2003).

A permeable snow cooling plant (PSCP) will trap SS by cutting off the surface water flow, having banks higher than the surrounding ground (Figure 2). A PSCP can also filter or treat contaminated water in the piping system before being rejected or recirculated through the snow deposit. The water levels inside and outside the PSCP will control the flow direction through the PSCP sides (Skogsberg, 2005)(Figure 3).

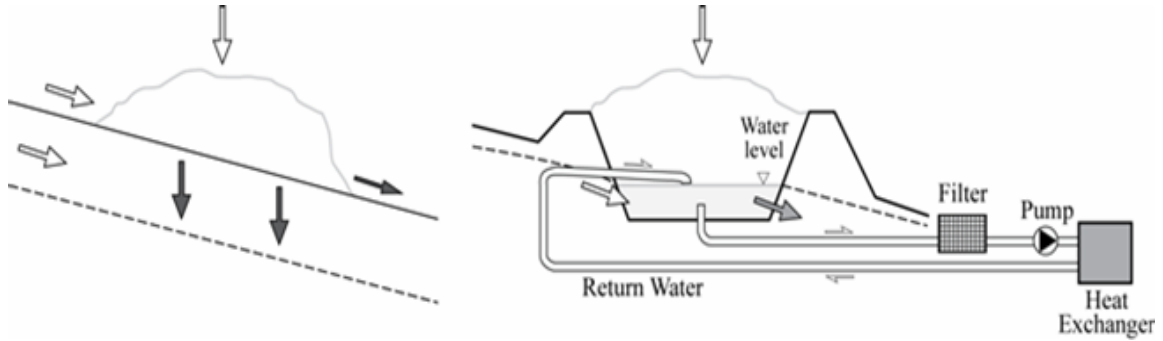


Figure 2. Pollutant pathways for an AGSD located above a sloping groundwater level (to the left) and for a PSCP located under a sloping groundwater level (equipped with filter, pump and heat exchanger (to the right)). The hatched line is the groundwater level, light arrows are clean water, dark arrows are polluted water, and the gray arrow is moderately polluted water.

The ideal site for a PSCP is a level area with a constant year round water table near the ground surface. This would allow water to flow into a PSCP, rather than a contaminated water flow out (Figure 3a). If percolation or the groundwater flow rate through a snow cooling plant (SCP) is high a liner-equipped snow cooling plant will be necessary (Skogsberg, 2005).

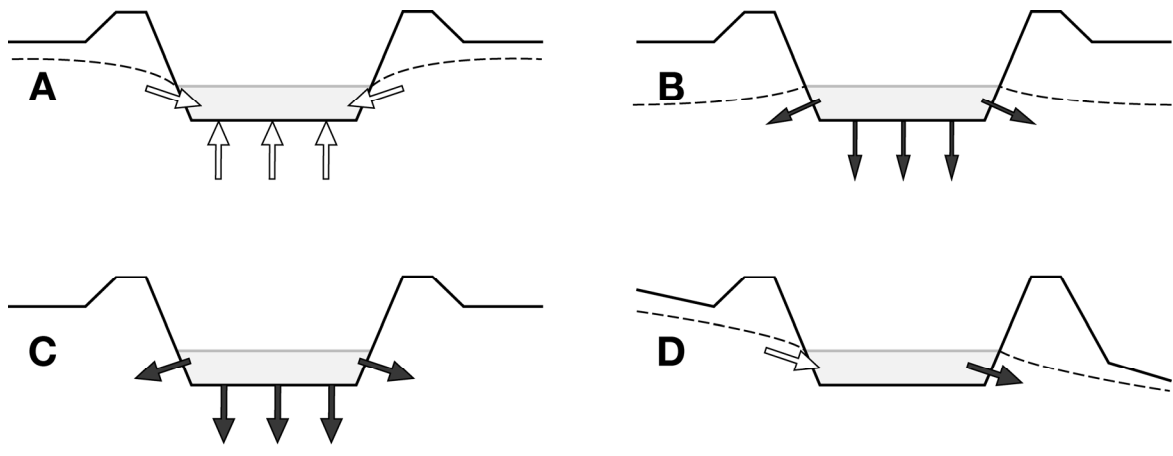


Figure 3. Examples of different groundwater configurations in conjunction with PSCPs: A) Groundwater above the plant (pond) water level; groundwater flowing into the PSCP (ideal case), B) Groundwater level below the plant (pond) water level but above the base of the PSCP C), Groundwater level is below the bottom of the PSCP (worst case), and D) Groundwater level is intersecting the PSCP at an angle with some groundwater flowing through the sides.

Proposed PSCP details

The proposed PSCP is designed to hold 200,000 m³ of snow. It will be 10 m deep having a bottom 6 m under the ground level and banks built 4 m above the (current) ground level. The dimensions of the snow cooling plant are 40 m X 80 m on the bottom with banks rising at a 1:4 slope having a top area of 120 m X 160 m. When in operation the water level should be maintained at 4 m above the bottom of the PSCP. The area of the pond water level is 8000 m², and the groundwater level for the calculations is assumed to be well below the PSCP base.

THEORY

Below are the steps to estimate snow melt contamination load, concentrations and pollutant pathways for two different types of snow deposits in an area with rather impermeable soil; an existing AGSD and a proposed PSCP located above the groundwater level. Both the existing and the proposed deposit are located in Luleå, Sweden and urban snow typical for the area and soil characteristics typical for cold climate areas that experienced glacial recession during the Holocene are used for the calculations. The general method should be applicable for any snow deposit; however, as mentioned in the preceding review, differences in climate, traffic, snow handling procedures, soil properties and distance to a surface water recipient, must be adopted to the specific site. First the total mass of SS, Cl, N, P and metals, along with the fraction of metals in dissolved and particulate form in the snow deposit has to be estimated. Melt water (and pollution) pathways depend on the design of the deposit, the expected melt rate, and the soil at the location, (primarily its hydraulic conductivity), therefore melt rates and infiltration capacities are estimated for a couple of different snow deposit designs and soils.

Melt water is a cooling resource so the possible loss of water through the base of the PSCP, located above the groundwater level, should also be determined to assure that this loss is small compared to the total melt water mass. Finally a sensitivity analysis of the pollutants vertical and horizontal transport times (assuming the pollutants to be conservative) using a combination of hydraulic conductivities, effective porosities and hydraulic gradients representative for the area is performed.

Calculating contaminant load

The total pollutant load *Pollutant mass (kg)* for a snow deposit can be estimated by multiplying the pollutant concentration in the melt water $Conc_{DP}$ (kg, m^{-3}) by the volume of the deposit $Volume_{DP}$ (m^3) and the ratio between snow ρ_{Snow} ($kg m^{-3}$) and water density ρ_{Water} ($kg m^{-3}$).

$$Pollutant\ mass = Conc_{DP} * Volume_{DP} \frac{\rho_{Snow}}{\rho_{Water}} \quad (1)$$

The estimates of total pollutant load from Eq. (1) require the concentration of pollutants in urban snow melt. The best source for contaminant concentrations would be samples from the actual snow deposit. However, the snow in a deposit is very packed, contains grit and sand and is several meters thick. Such samples are therefore very difficult to take, and do not appear to be available from any study. Road runoff concentrations values determined from rainfall are easier to find, but these concentrations can not be assumed to be the same as snow concentrations. Sometimes regional snowmelt runoff concentrations values are available, but these tend to show large variations in the metal content (dissolved and particulate) over the same winter season (Reinosdotter, 2007); therefore the use of such values is difficult to justify.

However, if snow samples, taken from road banks with different traffic loads for the city in question are accessible or can be taken, the average concentration of pollutants in the snow deposit can be estimated based on the fractions of roads with different traffic loads (i.e. Viklander, 1997; Reinosdotter, 2007). If the total mass of metals and their dissolved mass are calculated, then the fraction of particulate and dissolved contaminants can also be estimated.

If snow samples from the actual city cannot be taken, snow samples from a location with similar traffic loads, snow handling, and climate may be used, with caution.

Melt water pathways for an AGSD and water loss through the base of a PSCP

This study only aims to determine the order of magnitude of water fluxes since details of plant design and soil characteristics are not known. Therefore, rather crude assumptions are made regarding the water flux.

As mentioned earlier, surface runoff can carry suspended matter while groundwater does not, therefore separation of melt-water into infiltrated (percolated) water and surface flux becomes important for an AGSD. For an AGSD the snow normally melts in about 150 days (before the

next winter season begins). When such a deposit is located on a low-permeable soil the melt rate will be higher than the infiltration capacity resulting in surface runoff. Therefore the melt rates as well as the infiltration capacity of the soil are needed to separate the flow paths and the pollution transport.

The *snowmelt* rate (m/day) can be determined from the melted snow mass m_{snow} (kg), the area of the deposit or pond A (m²) and the number of *days* (-) in which the snow in the plant or in the deposit is melted.

$$\text{snowmelt} = \frac{m_{\text{snow}}}{A \cdot \text{days}}, \quad (2)$$

Snowmelt in excess of the infiltration capacity can be assumed to contribute to surface runoff. In this way the fraction of surface runoff can be determined as a function of deposit area, soil hydraulic conductivity and expected melt time.

A rough estimate of the snowmelt infiltration capacity ic (m/day) can be based on Darcy law used in the vertical direction if a number of simplifications are made:

$$ic = k \left(-\frac{dh}{dz} \right), \quad (3)$$

where k is the hydraulic conductivity (m/day) and dh/dz is the hydraulic gradient (m/m). The following simplifications are made: The soil is assumed homogenous and isotropic, the effect of frozen pore space is disregarded, the infiltration is assumed to take place only through the base area of the plant/deposit and only vertical flux is assumed. The hydraulic gradient is assumed one (1), and the saturated hydraulic conductivity is used even if the soil initially is unsaturated (when located above the groundwater); hydraulic conductivity values determined for normal groundwater temperatures are used even if we are dealing with near freezing water. The fraction of initially water filled pores in the unsaturated zone is disregarded. Influence of possible difference in water density due to high content of salt or other pollutants is also disregarded.

The maximum infiltration flux Q_z (m³/day) can then be estimated by:

$$Q_z = ic \cdot A. \quad (4)$$

The vertical water (pollutant) front advancement velocity $v_{\text{pollutant}}$ (m/day) can be determined by:

$$v_{\text{pollutant}} = k \left(-\frac{dh}{dz \cdot n_{\text{eff}}} \right), \quad (5)$$

where n_{eff} (-) is the effective porosity of the soil.

The loss of water through the base of a PSCP located above the groundwater and the vertical advancement of the wetting front under a PSCP can be calculated with Eqs. (3-5) using the same assumptions as for an AGSD. Here the flux area is assumed to be equal to the area of the PSCP at the water level (A_{pond}). Ponding is also neglected even though the water level in the pond will be about 4 m above the base of the pond.

Horizontal pollution transport

Conservative pollutants, i.e. pollutants that do not interact with the soil, travel with the same average velocity as the water in the soil. For very low water velocities and very high pollutant concentration gradients diffusion transport may also have to be considered. However, for water velocities in glacial till and the calculated concentration gradients the advection transport can be assumed dominant and diffusion has been neglected. Dispersion does not influence the average transport velocity, and the entire pollutant mass is here assumed to move with piston flow. The water and the advancement of the pollutant front can then be determined by Darcy law Eqs. (3) to (5) applied in the horizontal direction where dh/dz is replaced by dh/dx .

METHODS

The pollutant concentrations and the fractions of dissolved and particulate matter in the snow melt were based on snow samples taken from roads, with both high and low traffic loads, collected in Luleå shown in Table 1 (combined from Reinosdotter and Viklander, 2006; Viklander, 1993; 1997). The snow in the deposit was assumed to come from 50% high and 50% low traffic streets in Luleå city. The density of the snow transported to the deposit is about 500 kg/m³ and the storage volume is around 200,000 m³.

The total mass of particulate and dissolved phase of metals and P was first determined for the snow deposit. From this, the proportions of particulate and dissolved phase, along with the parts per billion (PPB) for contaminants in the dissolved phase were estimated.

Table 1. Measured pH, SS, N, Cl and concentrations for metals, in snow melt (with standard deviations) from roads with high and low traffic load in Luleå city (combined from Reinosdotter and Viklander, 2006; Viklander, 1993; 1997).

Traffic Load		Low	High
pH		7.3 ± 0.38	8.3 ± 0.36
SS	mg/l	4471 ± 3144	7889 ± 6744
N tot	mg/l	3.8 ± 1.1	3.8 ± 1.1
Cl	mg/l	4.4 ± 2.8	20 ± 15
Cu tot	µg/l	310 ± 245	1022 ± 1089
Cu dis	µg/l	4.5 ± 2.45	7.0 ± 5.3
Pb tot	µg/l	119 ± 87	217 ± 232
Pb dis	µg/l	0.3 ± 0.6	0.08 ± 0.03
Zn tot	µg/l	931 ± 659	2233 ± 2308
Zn dis	µg/l	7.1 ± 6.7	1.5 ± 1.0
P tot	mg/l	1.265 ± 0.6	2.039 ± 1.22
P dis	µg/l	15 ± 17	6 ± 1.4

The Luleå site is located on till (moraine), a soil type with low porosity and low hydraulic conductivity. The porosity of moraines is at most 17%, the average effective porosity is usually below 5% and hydraulic conductivity is poor, between 10⁻⁷ and 10⁻⁹ ms⁻¹ according to Salonen et al. (2002) as cited by Mälkki, (2006). In the area there is also some sandy till so a hydraulic conductivity of 2·10⁻⁵ was used for the highest expected water transport velocity calculations.

Estimates for infiltration capacity and water front advancement from the AGSD were therefore made for two different hydraulic conductivities (dense moraine and a sandy till) assuming the same effective porosity. The effect of variances in effective porosity were disregarded since these variations are much smaller than the variations in hydraulic conductivity. The snow in the deposit was assumed to melt out in 150 days and the melt rates needed for this were determined for two different AGSD base areas: 40,000 and 20,000 m². These melt rates were compared to the infiltration capacities to obtain snowmelt fractions for surface runoff and infiltration.

Possible water losses through the bottom of a PSCP, located above a groundwater table were estimated assuming that the snow in the deposit lasted all year. The estimate was made for an infiltration (water level) area of 8000 m² for both dense and sandy till.

The horizontal advection transport velocities (neglecting dispersion) and the time it would take for the pollutants to travel a distance of 100 m for a number of different combinations of soil parameters (k , n_{eff} , dh/dx) was made in order to illustrate the importance of the different variables. A reference velocity is calculated for realistic combinations of k (10⁻⁸ m/s), n_{eff} , (8%) and dh/dx (1/100).

A combination of k (10⁻⁵ m/s), n_{eff} , (10%) and dh/dx (1/10) values causing very high velocities (denoted max velocities) and a combination of k (10⁻⁹ m/s), n_{eff} , (5%) and dh/dx (1/1000) values causing low velocities (denoted min velocities) were also calculated. Finally the effect of variation

in just one of the variables was illustrated by using the reference values and altering one parameter at a time.

RESULTS

Snow contamination

The snow deposit mass, based on a snow density of 500 kg/m³ and the storage volume of 200,000 m³ resulted in a snow storage mass of 100,000 tons. Using 50% high and 50% low traffic street ratio for snow contribution to the deposit results in an estimated pH of 7.8 (± 0.37) and the estimated contaminant total mass for suspended solids, metals, chloride and nutrients (with standard deviations) listed in Table 2. The total mass load of pollutants in the deposit indicates a high concentration of SS and a slightly basic pH. Most of the metal contaminant should be in particulate form (table 3).

Melt water pathways for an AGSD

Estimated infiltration capacities, vertical advancement of the water front and infiltration fluxes for two AGSD with different base areas are shown in table 4. The influence of the hydraulic conductivity is, as can be expected huge.

Table 2. Calculated total mass load of SS Cl, N and metals (with standard deviations) in Luleå snow deposit (100,000 tons).

Substance		mass	stdev
SS	(tons)	620	490
Cl	(kg)	1,200	890
N tot	(kg)	380	110
Cu tot	(kg)	67	67
Cu dis	(g)	580	390
Pb tot	(kg)	17	16
Pb dis	(g)	19	32
Zn tot	(kg)	160	150
Zn dis	(g)	430	390
P tot	(kg)	170	91
P dis	(kg)	1.1	0.92

Table 3. Estimated proportions of metal and P in dissolved and particulate form along with dissolved PPB for the Luleå snow deposit.

Pollutant metal	Dissolved form (%)	Particulate form (%)	Dissolved PPB
Cu	1.07	98.93	5.8
Pb	0.14	99.86	0.19
Zn	0.41	99.59	4.3
P	0.74	99.26	11

Table 4. Calculated infiltration capacities, vertical advancement and infiltration fluxes for a PSCP and an AGSD with different infiltration areas and hydraulic conductivities. The snow in the PSCP is expected to last all year while the snow in the AGSD is assumed to melt out in 150 days. The estimates are based on an effective porosity of 8% and conductivities for a dense moraine and sandy till.

Hydraulic conductivity (m, sec ⁻¹)	1.0×10^{-8}	2×10^{-5}
Hydraulic conductivity (m,day ⁻¹)	8.6×10^{-4}	1.73
Infiltration capacity <i>ic</i> (mm/day)	0.86	1730
Vertical advancement wetting front (mm/day)	10.8	21,600
Infiltration AGSD with A = 40,000 m ² (m ³ , 150 day ⁻¹)	5.2×10^3	1.0×10^7
Infiltration AGSD with A = 20,000 m ² (m ³ , 150 day ⁻¹)	2.6×10^3	5.2×10^6
Infiltration loss; PSCP with A = 8000 m ² (m ³ , year ⁻¹)	2.5×10^3	5.0×10^6

The calculated melt rates needed to melt a snow mass of 100,000 tons in 150 days for an AGSD with different base areas are shown in Table 5. For a “normal” base area of around 20,000 to 40,000 m² the melt rate is about 20 to 30 (mm, day⁻¹) and the infiltration capacity for the dense moraine is roughly 1 mm per day so more than 90 percent of the snowmelt can be expected to become surface runoff on a dense moraine. For the “permeable” sandy moraine the infiltration capacity is almost 2000 mm per day so all melt water should infiltrate into the soil (unless the saturated groundwater level rises to slow infiltration).

Water loss through the base of a PSCP above the groundwater level

The infiltration capacity for a PSCP is the same as for the AGSD but the snow is assumed to last all year in a PSCP (Table 5). For an infiltration area of 8000 m² (as for the planned PSCP) the water loss through the base, if located above the groundwater level, will be around 2.5×10^3 m³ year⁻¹ or 2.5×10^6 kg, year⁻¹ on a dense moraine (Table 5). This constitutes about 2.5% of the total stored snow mass (100,000 tons). For a PSCP located above the groundwater level on a sandy till the entire stored snow volume might initially (until the groundwater level is raised to the base) percolate to the groundwater (Table 5).

Table 5. Melt rates required to melt a snow mass of 10⁵ tons in 150 days for an AGSD with different base areas along with infiltration capacities for a dense ($k = 10^{-8}$ m, sec⁻¹) and the sandy moraine ($k = 2 \times 10^{-5}$ m, sec⁻¹) with separation of melt water into surface runoff and groundwater percolation.

Area (m ²)	Melt rate (mm, day ⁻¹)	k (m, s ⁻¹)	Infiltration capacity (mm, day ⁻¹)	Surface runoff (%)	Infiltration (%)
20,000	33	10^{-8}	0.86	97.4	2.6
40,000	17	10^{-8}	0.86	94.8	5.2
800,000	1	10^{-8}	0.86	0.0	100
400 to 20,000	33 to 1667	2×10^{-5}	1728	0.0	100

Horizontal pollution transport

The horizontal transport velocities and the time it would take for the pollutants to travel 100 m for a number of different combinations of possible *k*, *n_{eff}*, *dh/dx* are shown in Table 6. For the reference Darcy velocity (0.009 mm per day) calculated with realistic combinations of *k* (10^{-8} m/s), *n_{eff}*, (8%) and *dh/dx* (1/100) a pollutant would travel 100 m in about 2000 years. For the max Darcy velocity (86 mm per day) calculated with a combination of *k* (10^{-5} m/s), *n_{eff}*, (10%) and *dh/dx* (1/10) values causing high velocities a pollutant would travel 100 m within a couple of months. For the min Darcy velocity (0.00009 mm per day) calculated with a combination of values *k* (10^{-9} m/s), *n_{eff}*, (5%) and *dh/dx* (1/1000) causing low velocities it would take a pollutant

more than 100,000 years to travel 100 m. The effect of variation in just one of the variables is illustrated by using the reference values and altering one single parameter (Table 6).

Table 6. The influence of the hydraulic conductivity, K , the effective porosity n_{eff} and the hydraulic gradient, dh/dx on the Darcy velocity, the average pollutant transport velocity and the time it will take for a pollutant to travel 100 m (assuming only advective transport and neglecting dispersivity).

	k		n_{eff}	dh/dx	Distance (m)	v_{darcy}	$v_{pollutant}$	Time (years)
	(m/s)	(m/day)	(-)	(-)		(m/day)	(m/day)	
Ref	10^{-8}	$8.6*10^{-4}$	0.08	0.010	100	$8.6*10^{-6}$	$1.08*10^{-4}$	2537
Max velocities*	10^{-5}	$8.6*10^{-1}$	0.10	0.100	100	$8.6*10^{-3}$	$8.64*10^{-1}$	0.32
Min velocities**	10^{-9}	$8.6*10^{-5}$	0.05	0.001	100	$8.6*10^{-7}$	$1.73*10^{-6}$	158,549
Ref, but low K	10^{-6}	$8.6*10^{-2}$	0.08	0.010	100	$8.6*10^{-4}$	$1.08*10^{-2}$	25
Ref, but high K	10^{-9}	$8.6*10^{-5}$	0.08	0.010	100	$8.6*10^{-7}$	$1.08*10^{-5}$	25,368
Ref, but high dh/dx	10^{-8}	$8.6*10^{-4}$	0.08	0.100	100	$8.6*10^{-6}$	$1.08*10^{-3}$	254
Ref, but high n_{eff}	10^{-8}	$8.6*10^{-4}$	0.17	0.010	100	$8.6*10^{-6}$	$5.08*10^{-5}$	5391

*Combination of k , n_{eff} , and dh/dx causing high velocities

**Combination of k , n_{eff} , and dh/dx causing low velocities

DISCUSSION

The main environmental differences between a permeable snow cooling plant (PSCP) and an above ground storage deposit (AGSD) are caused by changes in pollutant pathways. The PSCP traps all SS within its walls, while an AGSD will have mostly small, with some larger suspended solids (SS) flowing downstream of the deposit during periods of intense melt. Over 98% of the heavy metal pollutants are in the particulate phase, leaving less than 2% of the metals in the dissolved form. The migration of the majority of metals, 98% in the particulate form, will depend on surface flow velocities.

The metal masses and concentrations in the urban snow seem small compared to other sources of metals in the environment. The total yearly mass of Zn in the deposit is about 160 kg and the suspended part that is likely to travel with surface runoff is less than half a kilo. This can be compared with the reported leakage of Zn from the Blaiken mine into the nearby river and lake both named Juktan that is reported to be about 200 kg per day (Svenska Dagbladet, May 30, 2008)! The suspended Cu concentration in the urban snow is about 5 $\mu\text{g/l}$ which can be compared to Cu concentrations found in an open pit mine that ranges around 40 $\mu\text{g/l}$ (Frandsen, 2007).

Depending on climate, soil characteristics, and depth to the saturated zone, groundwater contaminant contributions from an AGSD and a PSCP system may be very similar or different. Oberts et al. (2000) stated that snowmelt (from an AGSD) would first go to groundwater infiltration while excess water increasing as saturation nears contributes to surface water runoff. As seen in the calculations above, the higher the infiltration capacity, the lower the surface water flow will be.

In the pollutant pathway calculations, evaporation and rainfall were neglected. Evaporation takes place from the snow deposits reducing the mass of meltwater and increasing the pollutant concentration in the remaining snow. On the other hand rainfall would add water to the snow, thus diluting the pollutant concentration in meltwater while increasing the amount of infiltrated water. The melt rates are also assumed to be the same every day; in reality melt rates will vary from day to day which will increase the fraction of melt water moving as surface runoff allowing greater transport of SS from an AGSD. Also neglected in the calculations is the efficiency to which filters and other pollutant/nutrient technologies work to reduce meltwater pollutant concentrations when water is piped through the snow cooling system.

The calculations for infiltration were all completed assuming a water table level staying well below the plant/deposit allowing a high infiltration rate. However, infiltration and percolation from an AGSD can be slowed by saturation of the ground below a deposit (Oberts et al., 2000).

This is also true for the amount of water leaving a PSCP system located above the groundwater when the groundwater table over time is rising towards the infiltrating water source.

The infiltration rate can also be decreased if pore spaces within the soil are filled with ice (Oberts, 1994). This is only a concern for AGSD's, as it is assumed the water in a PSCP will be kept ice free year round. However due to snow insulation, it is assumed insignificant also for an AGSD in most locations and was not included in the calculations.

The infiltration and percolation rates through the soil were calculated using the saturated hydraulic conductivity. This neglects the initial condition of soil under the deposit as it would be unsaturated so a lower unsaturated hydraulic conductivity should be used. This is caused by unsaturated soil having a wetting front that progresses slower due to gas pressure within the pores. For more detailed estimates the fraction of water filled pores can be taken into account by calculating the water front advancement using the Green-Ampt method (Green and Ampt, 1911).

However, initially soil under a deposit would be unsaturated with a wetting front and gas pressures within pores causing a lower unsaturated hydraulic conductivity. This condition should not persist, and can thus be ignored. We also assumed a homogenous and isotropic soil condition: Vertical conductivity is often lower than the horizontal conductivity for soils formed in layers; thin layers with low conductivity will reduce the vertical flux considerably. Such effects are not taken into account in this study and will reduce infiltration.

The infiltration calculations are also simplified since constant surface areas (AGSD base area, and PSCP area at pond water level) were used and only vertical flux was considered: In reality water will move sideways due to differences in soil moisture contents so the real infiltration cross section area will be larger than the ones used here.

For the AGSD the surface area of the deposit is used for the separation of surface water flux and groundwater infiltration, but the area down stream of the deposit is also likely to act as infiltration area when surface water is flowing across it.

In the calculation of the infiltration capacity and the wetting front advancement the hydraulic gradient was assumed to be one, also for the PSCP with ponding water present thus underpredicting the infiltration rate and the velocity.

The migration of the contaminant was calculated neglecting retardation due to sorption and desorption. This will not effect the total contaminant loads since retardation does not reduce the amount of contaminants, it only slows down the spread. However neglecting retardation could have consequences during site remediation as retardation could turn a short term concern into a long term problem.

Any meltwater or rainfall in excess of the infiltration capacity was assumed to be surface flux, both Oberts (1994) and Westerlund (2003) cautioned about rain on snow events having the ability to have high potential energy flows. These rain on snow events can carry a much higher than normal volume of particulates away from an AGSD. This make a majority of the difference in pollution loads to a surface water recipient between an AGSD and a PSCP system.

Differences in contaminant flux to an aquifer are a bit more complicated. However, building a PSCP will result in higher contaminant vulnerability to potential aquifers due to a reduction in the height between the groundwater level and the bottom of the PSCP. This will reduce the filtering capacity and sorption sites in the soil levels between the PSCP and the groundwater table. This reduced filtering of contaminants increases the risk of N, Cl, organic contaminants and metals polluting a groundwater recipient when compared to an AGSD.

The pollutant and nutrient pathway from a snow deposit has a large influence on the net biomass production in a surface water recipient, since primary production is P-limited. Due to the low solubility of P, (Dominico and Schwartz, 1998; Pitt et al., 1999) an AGSD should contribute more nutrients to a recipient than a PSCP. The reduction in primary production will usually take 10 to 15 years due to internal loading of P (Jeppesen et al., 2005). Therefore, if an AGSD is closed or replaced by a PSCP the aquatic ecosystem and quality of water in a surface water recipient is directly effected.

It would be interesting to further investigate the relationship between particle size, metal attachment and surface flow velocity in conjunction with AGSDs and PSCPs. Reinosdotter and Viklander (2006; 2007) and Westerlund et al. (2007) have made studies on the contaminant

particle sizes found in snow and could serve as base for such a study. However, the above studies on urban snow pollution concentrated on road runoff rather than stream flow characteristics from an above ground snow deposit.

CONCLUSIONS

It is difficult to draw any categorical conclusions regarding differences in pollutant pathways and spread from above ground snow deposits (AGSDs) and from permeable snow cooling plants (PSCPs) since the spread depends on many factors. The soil hydraulic conductivity and the location of the groundwater table being the most important parameters.

When located under the groundwater table PSCPs are more likely to spread soluble contaminants to groundwater aquifers than AGSDs since the polluted melt water will be in direct contact with the aquifer.

However, when located on low permeable soils AGSDs will spread suspended solids (with pollutants) to nearby surface water recipients through the surface water pathway since the melt (and rain) rates will be larger than the infiltration capacity. On the other hand, with a low hydraulic conductivity, a PSCP will reduce pollutant mobility and increase pollutant control by cutting off the surface water pollutant pathway while also having a low groundwater flux resulting in the reject water becoming the main pollutant pathway.

The PSCP design gains a noticeable advantage in reducing environmental impacts through the filtering of circulated and reject water when compared to the uncontrolled surface water runoff of an AGSD. The PSCP reject water pollutant concentration levels are only restricted by the filtering technology employed. With a PSCP there is also control over where the reject water is released. This makes it easier to reduce expected pollutant concentrations and environmental impacts in recipients justifying the building of a PSCP.

However, the potential harm of pollution in the two different types of recipients (surface water and groundwater) has to be judged at each local site.

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