Nordic Hydrology, 29 (4/5), 1998, 285-302

Modelling Snowmelt Induced Waste Water Inflows

Paper presented at the 11th Northern Res. Basins Symposium/Workshop
(Prudhoe Bay to Fairbanks, Alaska, USA – Aug. 18-22, 1997

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Impacts of urbanisation on hydrological processes are different for snowmelt and rainfall events. Furthermore, snowmelt and runoff generation differ between rural and urban areas. Within an urban area, melt intensities are increased at some sites; hence, the volume of water early in thaw can be greater than in rural areas. However, shading can reduce melt in other areas so that the melt period is extended. Many surfaces are at least seasonally impervious and generate overland flow – there is an apparent increase in the area contributing to quickflow as normally permeable surfaces become saturated or frozen or both. Water infiltrating permeable soil causes saturation and groundwater recharge so that water can seep into sewers. Regardless of whether water enters via inlets or sewer infiltration, drainage networks ensure swift delivery of melt water to outlets.

Snowmelt induced runoff reaching the Uddebo Waste Water Treatment Plant in Luleå, Sweden, is investigated and a model of urban snowmelt and meltwater routing is proposed. The role of surface type (permeable and impervious) and snow cover characteristics (snow-free, undisturbed, compacted and piled) upon model output is studied. Results are encouraging and provide a good platform for further research.

Introduction

Snow plays an important, seasonal role in the lives of people living in Nordic communities. Snow brightens up the winter darkness, provides leisure and is an important resource for electricity generation following thaw. But snow can be a problem to both inhabitants and the surrounding environment. Pollutants held in the snow can damage property, soils, aquifers and vegetation; however, snow removal is costly and has its own associated environmental problems (*e.g.* Viklander 1997). Related to these problems is the unique role snow plays in urban hydrology. Indeed, many northern towns experience spring-time flooding.

Despite its importance, snow has been largely ignored by urban hydrologists. There has been some work on meltwater quality; however, design rainfalls and pipe flow routines tend to have received the most emphasis. Important exceptions include Bengtsson (1983), Westerström (1984), Bengtsson and Westerström (1992) in Sweden and Buttle and Xu (1988), Xu and Buttle (1987) and Buttle (1990) in Canada.

In general, urban hydrology is characterised by rapid runoff response times and responses to short-duration events. Runoff from impervious surfaces, such as roofs and asphalt, is exclusively in the form of overland flow and usually drains into a pipe network. Infiltration into soils can be lowered and, hence, overland flow may occur from these surfaces as well. During snowmelt the hydrological impacts of urbanisation are different in comparison to rainfall events. There is an apparent increase in the area contributing to quick flow as soil permeability decreases. Compacted soils, which are permeable in summer, can experience lowered infiltration capacities when frozen, resulting in overland flow or flow through cracks just below the surface during the melt period (Bengtsson 1982, a). In heterogeneous urban soils, water is likely to flow preferentially through macropores and back-fill material around buried pipes. Direct flow and sewer infiltration (or leakage) into pipe networks ensure swift delivery to outlets. Melt intensity, which at some urban locations is arguably greater than in rural environments (Buttle and Xu 1988; Semádeni-Davies and Bengtsson 1998), compounds the problems by increasing the volume of water released at any one time.

In northern Sweden, many centres experience melt-water flow, directly or indirectly, into sanitary sewers which causes at least a doubling of waste-water discharge during the snowmelt period and for several weeks after. Increased volumes of water, reduced concentration times and long flow durations lead to high waste-water system loads, in turn causing low residence times in treatment. Sludge containing bacteria vital to treatment can be flushed out of retention tanks so that the required sludge age is not reached. Moreover, cold water temperatures reduce both bacterial activity and heat recovery.

The problems caused by waste-water system overloading have led to the formulation of the research aims for this paper. There are two main thrusts: to discuss the literature concerning snow hydrology; and to investigate the feasibility of modelling snow accumulation, melt and melt water pathways to sewers as a tool for waste-water managers. Such a model would be helpful in the understanding of urban snow hydrology. A Swedish study (Hernebring 1996) is used as a guideline for model development. The sewer system is not specifically modelled. The research is limited by its dependence on existing data collected at Luleå, northern Sweden. Despite this, the model provides a preliminary indication of results possible in urban areas and a direction for future research and modelling.

Urban Snow Hydrology

Snowpack Energy Balance

The effects of urbanisation on the snowpack energy balance have been discussed, especially with respect to the radiative fluxes, by Xu and Buttle (1987), Todhunter *et al.* (1992) and Semádeni-Davies and Bengtsson (1998). The vertical surfaces of the urban canyon tend to trap radiation. The basic pattern is characterised by substantial enhancement in full sun – both due to multiple reflections (solar radiation) and warming of surrounding structures (longwave radiation) – and for reduction in shaded areas with solar radiation restricted to diffuse beam. In full sun conditions in Luleå, the average enhancement integrated over 10 metres from a two storey building can be up to 100 W m^{-2} (Bengtsson and Westerström 1992). Xu and Buttle (1987) measured the net radiation in the vicinity of two single-family dwellings; eight metres from buildings the net all-wave radiation, largely through longwave radiation, could be 1.5 times greater than that in open areas. The formation of motes of bare ground around buildings could be caused by enhanced longwave radiation (*ibid.*). Additionally, the albedo of both the snowpack and the urban surroundings is lower than in rural areas, causing increased solar energy absorption (Bengtsson and Westerström 1992; Takamura and Toritani 1994).

The turbulent exchanges of momentum, water vapour and heat depend on wind speed, humidity, air stability and air temperature. The urban barrier is likely to cause an overall reduction in wind speed, thereby decreasing the total latent and sensible heat loss. However, wind tunnelling and mixing due to greater surface roughness could cause localised increases. Turbulent exchanges within a sheltered forest are negligible (Hendrie and Price 1979); this has implications for urban sites where melt too can often be attributed to net all-wave radiation (Westerström 1981). Spatial variability is likely – Bengtsson and Westerström (1992) suggested that sheltered yards and parks may have lowered turbulent fluxes, but streets and roofs, which experience greater wind speeds, may experience increases in these fluxes.

Snowpack Areal Distribution

Prior to melt, the spatial distribution of urban snowpacks is uneven not only because of complex air flow patterns around buildings, but also due to snow clearance. Snow is ploughed from streets, yards, footpaths and carparks and is piled alongside these areas as snow banks or is removed to snow dumps. How much snow is removed from or piled on public areas depends on the available space, funding allocations (Bengtsson 1983) and the quantity of snow acceptable to city authorities. Private front yards can have increased snow depths as snow is shovelled from drives and footpaths (Buttle and Xu 1988).

Runoff Processes

The main difference in runoff generation between urban and rural catchments is the rapid response time. There is a shift from sub-surface pathways dominating stream flow generating processes to surface ones. Urban flow paths to outlets tend to be more direct and accelerated melt rates ensure that greater volumes of water are released early in the melt season. Buttle and Xu (1988) found that much of this water runs off as quick flow.

Infiltration – Snowmelt induced runoff can be rapid or slow depending on the physical characteristics of the soil. Porous ground frost occurs in dry soils with good aggregation and air-filled macropores – liquid water can coexist with ice crystals and infiltration is almost unrestricted. Concrete ground frost occurs in wet soils which have undergone rapid freezing and infiltration can be restricted under such conditions.

Bengtsson *et al.* (1991) and Buttle and Sami (1990) found that forested catchments typically have slow stream response and that both discharge and recharge consist of displaced pre-event water. Espeby (1990, a) notes the effect of macropores on melt water movement through frozen glacial deposits, stating that infiltration can be rapid. Conversely, melt water runoff from disturbed open fields displays diurnal fluctuations with runoff peaks from the first day of melt (Bengtsson 1982, a). Generally, when the soil cover is thick and permeable with macropores, such as in a forest, melt water does not leave even small catchments as runoff for several months. At the other end of the spectrum, runoff from the base of a wet snowpack over impervious surfaces can be equated to surface melt.

Urban catchments are highly heterogeneous and comprise a myriad of interspersed permeable (gardens, gravel, some paving stones) and impervious (asphalt, roofs) surfaces. Snowmelt induced runoff in urban environments is typically dominated by overland flow because of the imperviousness. Melt water reaching permeable surfaces can either infiltrate or flow overland depending on the soil's structure, moisture and thermal status. The infiltration capacity varies seasonally with normally permeable surfaces becoming impervious during the melt period. Urban soils during early spring can have concrete ground frost (Buttle and Xu 1988). Westerström (1984) and Bengtsson (1983) found that overland flow is more prevalent as the melt season progresses due to both saturation and freezing. Indeed, freezing caused normally permeable gravel and grass surfaces in Luleå to become virtually impervious while infiltration in a nearby forest remained relatively unaffected (Engelmark 1984). Aside from saturation and freezing, Buttle and Xu (1988) found that infiltration capacities of urban soils are reduced as they are compacted by heavy machinery and foot traffic and as natural soil horizons are disturbed during development.

Artificial Drainage – Drainage networks provide direct flow paths to outlets. For a waste-water treatment plant, inflow consists of a waste-water (grey and sewage water) component and a hydrological component. Flow peaks in sewer pipes typically exceed volumes which can be attributed to impervious areas, which implies that water can enter indirectly as well as draining directly through inlets. Indirect flow refers to sewer infiltration through pipe cracks and joints. While rainfall and snowmelt reaching pipes directly account for peaks seen at outlets, sewer infiltration can be likened to the slow component of the hydrograph. The causes of sewer infiltration are varied and include workmanship, materials, age and traffic passing overhead, and the volume of infiltration is related to the length of the pipes as well as the hydrologic characteristics of the soil.

In Sweden, older parts of towns generally have combined sewer systems. New areas or those which have been renovated have separate sewer systems. Despite this, Bäckman *et al.* (1993) showed how water from the storm-water drainage network can reach sanitary sewers and how melt water from gardens can leak into the sewer system. Similarly, water flowing preferentially through trench back-fill can leak into sewers, especially when soils become saturated following melt.

There can be significant sewer infiltration from groundwater if the water-table rises above the level of the sewer network. Aquifers can be affected by recharge outside of the town area, so even when snow in the town is removed, the piezometric levels beneath the town can rise causing a measureable response at treatment plants.

It is extremely difficult to separate waste water from the hydrological component of sewer flow. Waste water flow is usually equated to supply. However, continuous measurements of flow at supply sources are often few and far between, so engineers are forced to resort to long term average values. This approach, as well as removing diurnal variability, removes day to day and even seasonal usage patterns which can be influenced by events as diverse as changes in weather, televised sport and holidays. In a northern winter, when water is not used outdoors, daily waste water can probably be equated to the supply.

Study Site: the City of Luleå

Luleå (65°33') is a Swedish city on the Baltic coast approximately 100 km south of the Arctic Circle. Average annual precipitation is 615 mm, of which 39% is snow. Snow coverage is permanent during the winter months and partial melting during winter is rare. Melt usually occurs from mid April to early May. Soil is glacial till (1-1.5 m thick) overlying bedrock. Several urban snow hydrology investigations were undertaken in Luleå (Bengtsson 1983; Westerström 1984; Bengtsson and Westerström 1992). Their experience is drawn on throughout this study.

Snow Distribution

Bengtsson and Westerström (1992) estimated that during the winter of 1979, 22% of the total snow volume (92,000 m^3) was transported from central Luleå, while a further 54% was piled. A summary of snow distribution in residential and central Luleå for the winters of 1978 to 1980 from Bengtsson and Westerström is given in Table 1.

Table 1 – Percentage cover of different snow types. Luleå, 1978-1980.

Snow cover	Residential (%)	Central (%)
Undisturbed	50	6
Snow-free/cleared	25	83
Piles	15	11
Reduced or partially melted	10	

Even when snow is not transported away, redistribution, such as piling, results in snow-free areas. Such areas include sloped streets and roofs. Indeed, Westerström (1984) notes that these surfaces are usually snow-free at the onset of significant runoff. He found the cleared area in residential Luleå to be similar to the 1979 size during 1983. Redistribution implies that the impervious areas which normally contribute to flow in the stormwater pipes do not contribute to inflow after snowmelt. Instead, the more or less undisturbed snow covering permeable soils is responsible for the observed spring melt peaks.

Data

The study period is the winter of 1992 – 1993. Data available are somewhat piecemeal and come from two separate sources.

Daily waste-water inflow measurements are available for the entire period. The Uddebo Waste Water Treatment Plant in Luleå serves a population of approximately 62,000 (Hernebring 1996). The total catchment area is 28 km^2, but the area draining to the plant through the sewer system is approximately 8.25 km^2. Hernebring estimated that for snow-free periods the permeable and impervious areas are 7.60 km^2 and 0.65 km^2, respectively. The average water supply in Luleå is 0.247 m^3s^{-1}, which represents about 75% of the measured average annual flow (1984-1993) into the waste-water treatment plant. Although there is a strong diurnal pattern in inflow with greater rates during the day; the day to day variation in water usage cannot be separated from hydrological components.

Climatic data were obtained from SMHI (Swedish Meteorological and Hydrological Institute). The measurements were made at Kallax airport, some 5 km from the city centre. Hourly data were obtained only for January and the snowmelt period (April to June). These data included incoming global solar radiation, diffuse solar radiation, longwave radiation, temperature, precipitation, wind speed and relative humidity. Cloud readings were taken twice daily and snow depth daily. Daily precipitation and average temperature were available from June 1992 to summer 1993. To obtain values of outgoing solar radiation, snow albedo was set to 0.6, a value typical for undisturbed snow (US Corps of Engineers 1956).

The history of the snowpack is unknown. An investigation of the energy balance expected during winter led to the assumption that substantial melt would be unlikely prior to April, although some minor melt events – caused by a warm period in early February and several days of rain in mid-February and mid-March – did occur. The initial depth of the snowpack for the melt model was taken from SMHI snow depth measurements giving an initial snow water equivalent (SWE) of 120 mm with an assumed relative density of 0.3.

Modelling Routines

Snowmelt

The usual approach, and that used here, for determining whether precipitation falls as rain or snow is to set a threshold ambient temperature above which all precipitation is assumed to be rain and below which, snow. The threshold temperature was set at 0°C; however, as the temperature was taken at the airport, there is a possibility that inside the urban area there were both warmer temperatures and less snowfall.

Temperature index snowmelt models are preferred to energy balance approaches in the absence of detailed knowledge of the spatial changes in energy fluxes and snow characteristics, since the former rely only on daily air temperature measurements. This approach is considered to be better for modelling average conditions (Ferguson and Morris 1987). In contrast, energy balance snowmelt models attempt to physically calculate the energy fluxes into and out of the snow cover and are more accurate short-term predictive tools for points or small catchments. However, these models have a drawback in that they are both more data and calculation intensive.

Commercially available urban water routing models typically contain simple temperature indices. MOUSE NAM is such a model and a version modified to include refreezing of meltwater and snow-water storage was used to simulate inflow into the municipal waste-water system in several Swedish centres (Hernebring 1996). Air temperature used as input to the model was recorded at 7 a.m. Despite the reasonable results obtained by Hernebring, there were problems with the timing of snowmelt induced runoff peaks which were systematically delayed several days in many of the towns investigated, including Luleå. An explanation could be that a single temperature reading, particularly at this hour, cannot be considered representative of the daily average value. Modelled peak discharges were also often higher than those measured. This could reflect a lack of attention to snow cover heterogeneity or simply an overestimation of the snow water equivalence. The urban hydrology package used was designed for temperate Danish climates rather than polar regions and although snow is included, there is no option for specifying the spatial distribution – or outright clearance – of the snow cover.

Bengtsson (1984) showed that snowmelt from heterogeneous urban areas can not adequately be determined from temperature indices. Melt rates vary over the course of each day, whereas temperature indices usually have a one-day time step. For a temperature index to be justifiable, the runoff generated must be the result of several days of melt, such that, while the average runoff over several days is correct, daily melt totals are likely to be incorrect (*ibid.*). Urban catchments have rapid runoff responses to water inputs. Additionally, the degree day approach has a limited ability to explain the nature of urban snow hydrology. Thus, a surface energy balance model was applied here. Model calculations are made using an hourly time step. Model inputs are net radiation, air temperature, humidity and wind speed. Snow surface temperature is set to either the air temperature value when below freezing or 0°C.

The energy balance calculations for snowmelt here are the same as those detailed by Semádeni-Davies and Bengtsson (1998). Surface melt water can only leave the base of a snowpack after the cold content (the energy needed to make the pack isothermal at 0°C) is satisfied and after the irreducible water content (the maximum fraction of liquid water that a snowpack can hold without the water being released by gravitational forces) is reached. The time taken for melt-water release can be considerable if the pack is initially dry and nocturnal air temperatures are well below freezing. Retention and refreezing of liquid water within the pack were described by modelling their downwards propagation from the snow surface according to Bengtsson (1982, b). Water is allowed to refreeze to a certain depth according to the snow properties and the length of time that the snow surface temperature is sub-freezing. The irreducible liquid water content of the snowpack adopted here is 8% for fresh snow and 4% for refrozen snow.

Percolation through a wet snowpack is swift in comparison to lags caused by water retention (Kuusisto 1984). Bengtsson (1982, c) found that the time lag for a wet snowpack half a metre deep was in the order of one hour. Hence, after the snowpack is ripe, liquid water leaving the snowpack can be equated to the rain water and surface melt water for the same period.

The Transformation Sub-model

Not all the water reaching the Uddebo waste-water treatment plant through the sewer system can be attributed to waste water and flow from impervious areas – antecedent hydrological conditions also come into play. The situation is analogous to overland, inter- and base-flow components found in rural catchments; that is, a direct response (via pipe inlets) from impervious areas *versus* an indirect response (sewer infiltration) from permeable soils. The need to establish antecedent soil conditions meant that a simple two soil layer, bucket sub-model (Fig.1) was run from the end of the previous melt period (May 1992) until the winter of 1993.

Sewer infiltration can occur anywhere along the length of a pipe, particularly at joints. For this reason, it is difficult to say what the exact physical conditions are at the point of water entry, hence, sewer infiltration was modelled as occurring evenly from each surface type.

Parameters were calibrated for the summer and autumn hydrographs of the two years modelled (June – October). At this stage, routing is done on a daily basis. For each surface type, the flow can be summarised as

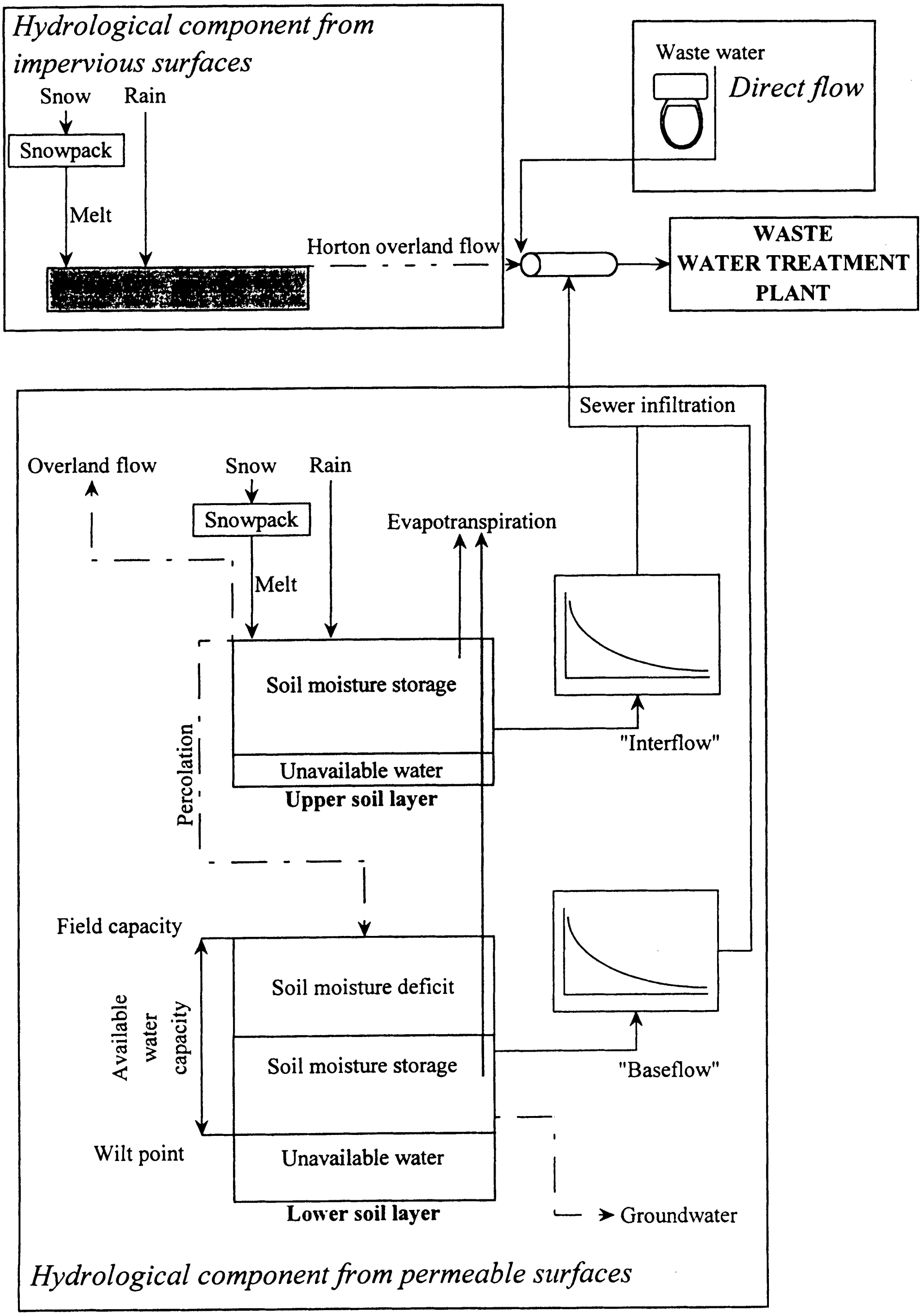

Fig. 1. Overview of the soil analogy water routing routine for the sewer system. Each of the sources modelled are boxed. Dashed lines refer to saturated conditions.

$$\frac{dSMS_u}{dt} = R + M - AET_u - OLF - L_u - Perc \tag{1}$$

$$\frac{dSMS_l}{dt} = Perc - AET_l - L_l - GW \tag{2}$$

where R is rainfall; M is melt water; SMS is soil moisture storage; AET is actual evapotranspiration; OLF is overland flow; L sewer infiltration; $Perc$ is percolation; and GW is groundwater recharge. The upper and lower soil layers are denoted by u and l, respectively.

Inputs are measured daily melt, rainfall, air temperature and potential evapotranspiration interpolated from the monthly values. Outputs are the soil moisture storage for each soil layer, the quick (overland flow) and slow flow components.

Rain and snowmelt are routed together and infiltrate unsaturated permeable surfaces. It is assumed that ground frost does not affect the soil infiltration rate; this is not obvious for urban soils which can be compacted with concrete ground frost.

The small volumes of rain falling in winter on cleared areas (impervious) were routed directly to the sewer system. Rain falling on snow prior to the melt period in April was assumed to be incorporated into the snowpack. These are generalisations: as stated, rain and short periods of non-freezing air temperatures combined to partially melt the snow cover at at least one point, affecting the hydrograph and possibly soil conditions.

The sub-model distributes soil water into upper and lower reservoirs or layers of 0.5 m and 1 m depth, respectively. Soil moisture storage is the independent variable in the assessment of actual evapotranspiration, inter- and base-flow. The size of the store is expressed in terms of the available water capacity (*AWC*), the difference between the soil's field capacity and wilting point. Glacial till is unsorted and highly heterogeneous; it can include macropores, clay, gravel and large boulders. Thus, the porosity and hydraulic conductivity are difficult to quantify and results of hydrological analyses of water movement are hard to interpret (Espeby 1990, a). *AWC* was taken as 17% by depth to reflect the clay component of till.

Actual evapotranspiration (*AET*) is estimated as a linear function of the potential rate (demand) and the soil moisture store (supply) and is calculated for each soil layer according to the respective storage and the ratio of layer depth to total depth.

When the upper soil layer reaches field capacity (SMS_u=AWC_u), surplus melt and rain water are routed either as overland flow, *OLF*, or as percolation, *Perc*, to the lower soil layer. The partition depends on a runoff coefficient, R_c, set to 0.2 (Gottchalk 1980). Overland flow from normally permeable surfaces is not routed to the treatment plant as it is unlikely that such surfaces would drain directly into sewer inlets

$$OLF = \mathrm{surplus} \times R_c \tag{3}$$

$$Perc = \text{surplus}(1 - R_c) \tag{4}$$

The saturated hydraulic conductivity for glacial till is low and has values spanning several orders of magnitude (10^{-5}-10^{-9} m/s, see Smith and Wheatcraft 1993; Espeby 1990, b). Interflow, or rather, sewer infiltration from the upper soil layer, L_u, is calculated according to the soil moisture store of both the upper and lower layer and a time recession coefficient, K_u.

$$L_u = K_u SMS_u \left(\frac{SMS_l}{AWC_l}\right) \tag{5}$$

The coefficient sets the maximum possible daily sewer infiltration and is parameterised at approximately 10^{-8} ms^{-1}.

Piezometric levels can rise as a consequence of melt both in and around town, however, it is extremely difficult to separate the sewer infiltration into pipes from the soil layers and that coming from groundwater (Westerström 1984). Hence, sewer infiltration was assumed to come only from the lower storage reservoir and is calculated as

$$L_l = K_l SMS_l \tag{6}$$

Surplus water after the lower soil reservoir reaches field capacity (SMS_l=AWC_l) is lost to the modelled system as groundwater recharge.

Model Runs

The routing model was run initially with a very simplistic spatial distribution of the snowpack which assumed that all impervious surfaces are snow-free and drain directly to the treatment plant and that all permeable surfaces are fully covered in undisturbed snow. Essentially, this run was similar in its distribution assumptions to Hernebring (1996); however, the earlier study assumed full snow cover for the entire urban area and routed all overland flow to the sewer conduits.

The second run used the findings of Bengtsson (1997, pers. comm.), Bengtsson and Westerström (1992) and Westerström (1984) as a basis for distributing the snowpack spatially. Actual surface locations were not modelled (recall that the points of sewer infiltration are not known). Instead, the snow cover was broken down into weighted areas according to snow characteristics and surface permeability (Table 2). Although no corroborating spatial information is available, the run can indicate the effect of including more specific snow conditions and distributions. In this way, it can be considered a test of model sensitivity.

Compacted, dirty snow had the same *SWE* as the undisturbed sites (0.12 m) but the albedo was lowered to 0.4 in accordance with Bengtsson and Westerström (1992), the relative density was raised to 0.4 and the irreducible water content set to the lower value of 4%. Piled snow was assumed to have characteristics similar to

Table 2 – Approximate area weighting of the snowpack according to surface type.

Snow cover	Permeable (%)	Impervious (%)
Undisturbed	70	0
Compacted and dirty	29.4	10
Snow-free/cleared	0	85
Piles	0.6	5

those observed in snow dumps near Luleå (Sundin 1997, pers. comm.) with increased relative density (0.6), lower irreducible water content (4%) and lower albedo (0.2). The *SWE* was increased from 0.12 m to 0.5 m based on volumes expected from piling 50% of the snow-cover from impervious surfaces onto the area covered by piles. Permeable surfaces with snow banks are mainly roadside verges.

Results and Discussion

The snowpack routines were tested against SMHI measured snow depths, converted to *SWE*, for the main snowmelt period (Fig. 2). The snow measurements are representative of an undisturbed rural snowpack. As stated, cost and the rarity of winter partial snowmelt outside the town, where the measurements were taken, meant that only the main melt period in April was modelled. Fit was very good over the period modelled and melt commenced and finished on the correct days.

The transformation routine was tested against the measured inflow at the treatment plant (Fig. 3). The modelled hydrological component of inflow during winter flow consisted only of water originating from autumn rain events as partial melt was not modelled. Hence, winter discharge peaks are not present in the modelled flow record despite the fact that partial melt episodes did cause small hydrograph peaks. The minimum flow curve (interflow and baseflow) for winter time appears to be correct. However, care must be taken in winter hydrograph interpretation; dips followed by peaks are typical of ice blockages within the sewer pipes. Hernebring (1996) was able to simulate some winter peaks using the degree day method. The fit for the calibration, summer/autumn periods (June-October, 1992 and 1993) was R^2=0.64 and flow was overestimated (2% of the total volume). Fit during spring melt (April-May, 1993) was R^2=0.87 and the total volume was underestimated by 5%. The rising limb of the generated hydrograph was too steep and the timing of the flow, including the peak, was slightly late. The peak height was similar as was the shape of the recession curve. It seems that the recession curve underestimates the hydrological component of waste-water inflow in winter and spring. The model is a soil routing analogy, in reality, much of the sewer infiltration comes from seasonal rise in groundwater which covers the pipes. It may be necessary to include piezometric levels in the model and then re-calibrate the model accordingly for better baseflow estimations.

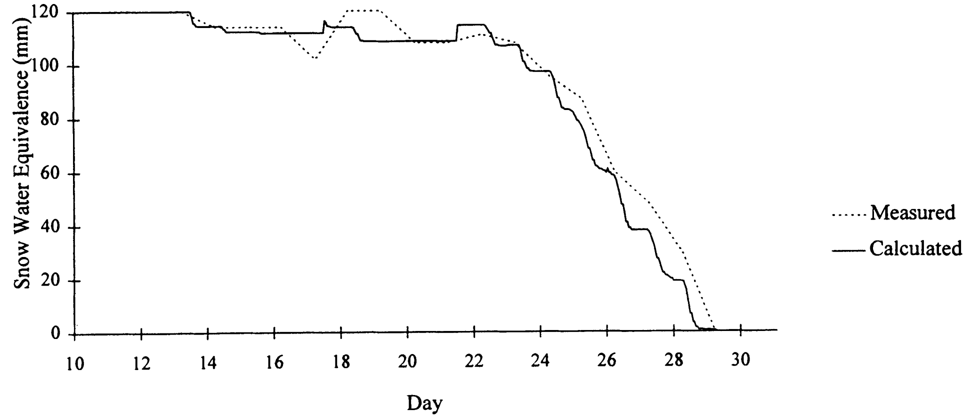

Fig. 2. Measured and calculated *SWE* for undisturbed snow at Kallax airport, 5 km from Luleå, April, 1993.

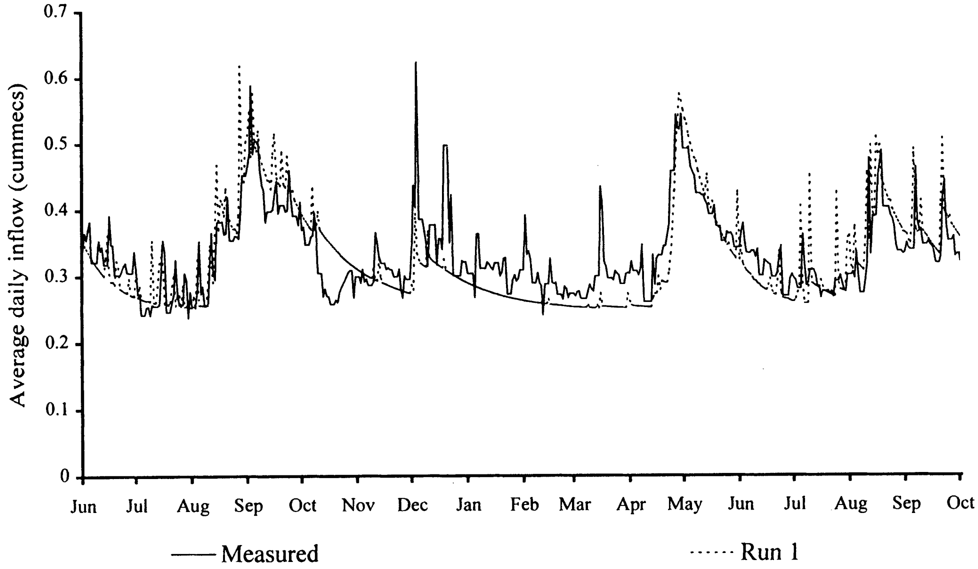

Fig. 3. Measured and calculated daily inflow into the Uddebo Waste Water Treatment Plant, June 1992 – December 1993. Run 1: undisturbed snow cover on permeable surfaces.

The assumed snow characteristics for the second run changed the computed rate of snowmelt significantly (Fig. 4). The modelled dirty compacted snow and piled snow melted more rapidly. However, the modelled melt season for the piled snow was longer by virtue of the increased *SWE*. Changing the distribution, or rather snow cover proportions in Table 2, improved the spring hydrograph fit (R^2= 0.95, overestimation = 2%), partly by increasing the snow covered area (and volume) and partly

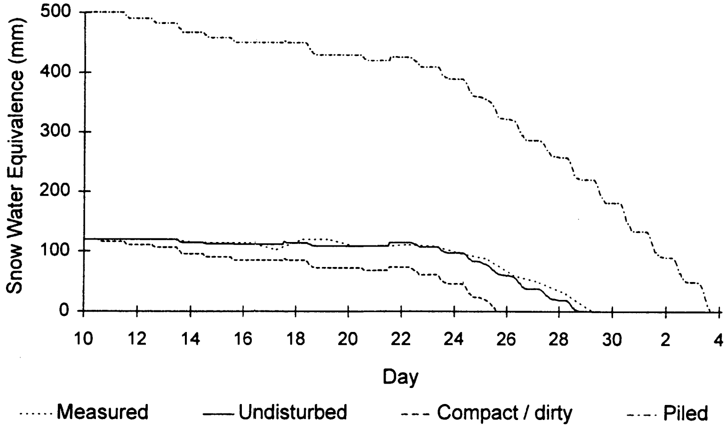

Fig. 4. Calculated *SWE* for the three snow types modelled against the measured values, April – May, 1993.

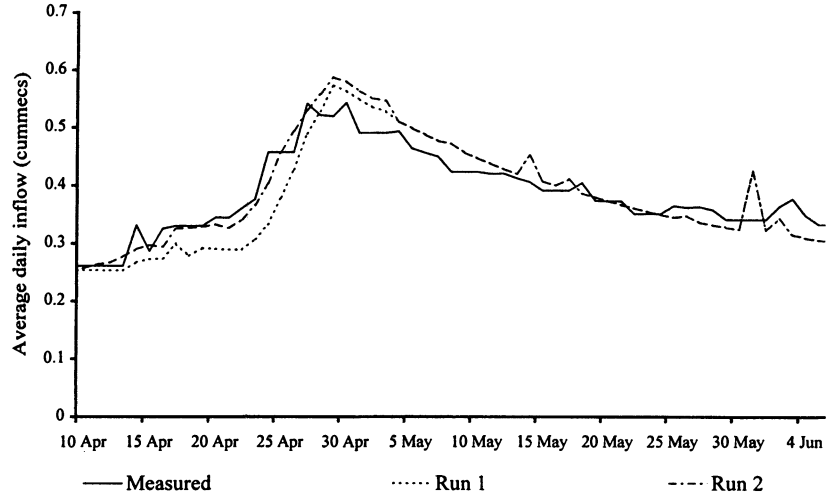

Fig. 5. Measured and calculated snowmelt induced daily runoff into the Uddebo Waste Water Treatment Plant, April – June, 1993. Run 1: undisturbed snow cover on permeable surfaces. Run 2: weighted snow cover distribution for three snow types.

by spreading out the season with melt water from compacted and piled snowpacks (Fig. 5). For instance, the timing and volume of the hydrograph rising limb is better modelled at the beginning of melt when melt water from dirty and compacted snow is able to flow through the sewer system. Peak flow is less well modelled; piled snow increases the peak discharge and extends the period of high flow. The recession curve after melt ceases is barely altered as the soil layers are saturated in both runs and indirect flow is governed solely by soil moisture storage.

The model was found to be sensitive to changes in snow cover distribution, with different hydrographs generated depending on the melt rate of the different snow types and the underlying surface. This prompted a number of other model runs, each with the same snow volume but different distributions. Modelling the total volume of piled snow on only impervious surfaces affected neither the rising limb nor recession but exaggerated the hydrograph peak. Conversely, modelling piled snow on only permeable surfaces lowered the hydrograph peak by removing the direct or overland flow component from the computed waste water. Again, the modelled soil was fully saturated so the computed recession was unchanged. Removing the compacted snow from the impervious surfaces had a negligible impact, lowering the volume delivered early in the melt season slightly. Increasing the ratio of dirty and compacted snow to undisturbed snow over the permeable surface from 3:7 to 1:1 raised the height of the computed rising limb improving fit somewhat.

Despite the sensitivity of the model to snow cover properties, the overall model fit was affected only to a relatively minor degree compared with the differences seen between the first and second model runs. Hence, even basic distribution assumptions can be worthwhile considering when modelling urban areas.

Aside from snow albedo, the effect of urbanisation on the energy balance components were not modelled. Changing albedo increases the energy available for melt. For instance, Conway *et al.* (1996) found that a decrease of 30% increased ablation by 50%. Semádeni-Davies and Bengtsson (1998) used the same energy balance snowmelt routine used here coupled with a radiation model in a series of sensitivity analyses to determine the effect radiation changes on snow. Near buildings, some areas have enhancement (south/full sun) and others reduction (north/shaded). It is conceivable that alterations to the energy balance at different locations could further spread out the melt period for the town as a whole. Since much of the sewer occurs in yards close to houses, such alterations to the radiative fluxes of the energy balance have implications for melt water delivery.

Conclusions

This paper reviewed some of the peculiarities of snowmelt modelling and water routing in urban areas and presented preliminary results from a model in development. A lack of research into snow hydrology in urban environments was acknowledged. The work can only be seen as an initial exercise in a much wider spatially distributed study. Suitable data, both for forcing and testing this kind of model, simply do not exist for Luleå township. However, improvements to predictions can be made by including several classes of snow cover and spatial weights given rudimentary assumptions based on past research and experience. Three types of snow and two surface permeabilities were included here, but other categories are possible.

For instance, increased snow depths around houses caused by snow sliding off sloped roofs could have an effect on inflow as much sewer infiltration occurs near houses. A more physically realistic study would require snow, melt, soil texture and moisture status, and climate data to be taken from several representative sites such as shaded and full sun sites, parkland and roadsides. Ground surveys or aerial photography or both could be used to determine the spatial distribution of the snowpacks.

Physically-based snowmelt models are better, more explanatory tools for research, but for practical purposes the degree-day approach, possibly with a number of melt factors for different snow types and locations, could be sufficient for operational use. The water routing model is conceptually simple, but would benefit from a more solid physical foundation. The results at this stage are encouraging and provide a good basis for further study.

Acknowledgements

The following people kindly helped me obtain data, Göran Lindström and Barbro Johansson of SMHI and Claes Hernebring of VBB Viak AB. Thanks are also due to Janusz Niemczynowicz, who helped me to better understand urban hydrology and Lars Bengtsson, my supervisor. The Per Westling Memorial Travel Fund helped finance my trip to Alaska to present this research at the 11th Northern Research Basins Symposium.

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Received: November, 1997
Accepted: April, 1998

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