Modelling sediment transport during snowmelt- and rainfall-induced road runoff

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ABSTRACT

In this paper, a simple conceptual model is presented to describe the dynamics of total suspended solid (TSS) transport during snowmelt- and rainfall-induced road runoff from a small urban runoff plot in northern Sweden. The study period (28 March to 28 May 2000) included both snowmelt and rainfall. A temperature-index method is used to describe snowmelt and the accumulation and transport of TSS is described by a linear build-up function and a wash-off model. The model was verified through measurements taken from 22 March to 22 May 2001. The simulation results showed that the simple model concept was capable of describing the dynamics of road runoff and TSS well, based on the continuous course of events for the whole modelling period. However, if the model was used for simulating a snowmelt period, or single events during snowmelt, the model approach would be too simple.

Key words | modelling, road runoff, sediment, snowmelt, total suspended solids

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INTRODUCTION

Runoff from urbanised watersheds is often contaminated and should be treated to protect both human health and safety and the quality of receiving waters. The physical, chemical, biological and combined effects that runoff has on receiving waters are different, depending on the climatic conditions, but they seem to be particularly severe during snowmelt and rain-on-snow in cold, alpine and some temperate climates (Marsalek *et al.* 2003). The reason for this difference is that precipitation in cold climates can accumulate and stay as snow on the ground for several months, depending on the weather conditions. During this time, the snowpack will store chemicals, solids and other pollutants that also have a higher release during winter months compared to the rest of the year due to, for example, the heating of houses, burning of fuels, starting of cold engines, wearing of tires, wearing of roads due to studded tires and use of anti-skid control agents (Viklander 1997; Marsalek *et al.* 1999).

Today, there are a number of operational models used for urban areas which includes routines for snowmelt and pollutant build-up and transport, e.g. SWMM and MOUSE. As well, there are models initially intended for snowmelt in rural areas, such as the HBV model, which has been used in urban areas (Sand 1990; Matheussen 2004). A model specially designed for urban snowmelt processes, taking anthropogenic activities into account, was recently developed in Norway (Matheussen 2004). However, this model is too sophisticated for operational use. The fact that urban snowmelt was not accurately represented in urban hydrology models was pointed out at such meetings as the Third International Conference on Urban Storm Drainage in Gothenburg in 1984 (Bengtsson 1984), at the Symposium in

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Budapest on the topic "Modelling snowmelt-induced processes" (Bengtsson 1986) and the Inter national Conference on Urban Hydrology under Wintry Conditions in Narvik 1990 (Buttle *et al.* 1990). The differences between snowmelt in urban and rural areas and for different runoff conditions during snowmelt- and rainfall-induced runoff were discussed thoroughly by Bengtsson (1984, 1986, 1990) and Semadeni-Davies & Bengtsson (2000). It was further pointed out by Semadeni-Davies (2000) and Valeo & Ho (2004) that the different temporal and spatial scales in urban and rural areas makes the temperature-index model unsuited for urban response. However, temperature-index models are commonly included in many software packages used in urban areas today and are considered to provide melt rates with sufficient accuracy for most practical purposes.

In cold climates where traction sand is used for slipperiness control, the loads of total suspended solids (TSS) to receiving water bodies can be extensive and might cause problems for stream health and aquatic life. High TSS concentrations of up to 5000 mg/l during a snowmelt period were reported by Westerlund *et al.* (2003). The concentrations of TSS during snowmelt were reported to be five-fold higher compared to rainfall runoff and the concentrations of particle-bound metals were found to be influenced by the concentration of suspended solids (Daub *et al.* 1994). The modelling of the snowmelt quality is not as developed as the snowmelt quantity modelling (Marsalek *et al.* 2000). Attempts to model urban snowmelt quality dates back to the early 1970s and progress has been made in conjunction with, for example, the US EPA Stormwater Management Model (Hubert and Dickinson 1992) and in the form of independent model algorithms (Bartosova & Novotny 1999). To decrease impacts from road runoff in cold regions, it is important to understand the dynamics of pollutants and then use this knowledge in models to predict and prevent environmental damage.

OBJECTIVES

The objective of this study is to test an existing model concept included in urban drainage software (MOUSE RDII and MOUSE TRAP) commonly used primarily for the dynamics of total suspended-solids (TSS), and consequently the dynamics of road runoff, within a small urban runoff plot. The reason for this is to see if the applications included in the software model are capable of describing the TSS transport accurately during snowmelt- and rainfall-induced runoff.

RUNOFF PLOT DESCRIPTION

The small runoff plot is situated at Södra Hamnleden in the central urban areas of Luleå, consisting of a road with two traffic lanes and a grassed verge besides the road (Figure 1). The impermeable road and the permeable grassed area besides the road have physical areas of 6 × 72 m, respectively. The traffic intensity of the road is about 7400 vehicles/d. The runoff was drained via a gutter to a gully pot which is connected to a separate stormwater pipe that conducts runoff to a nearby recipient. Traction sand, 4–8 mm, is used as an anti-skid material, but no de-icing salts are used in the central parts of Luleå.

SAMPLING

From 28 March to 28 May 2000, flow measurements were performed for snowmelt (28 March to 16 April) and rainfall events (17 April to 28 May). Throughout the period 22 March to 22 May 2001, flow measurements used to verify the model were performed for snowmelt (22 March to 8 April) and rainfall events (9 April to 22 May). The gully pot

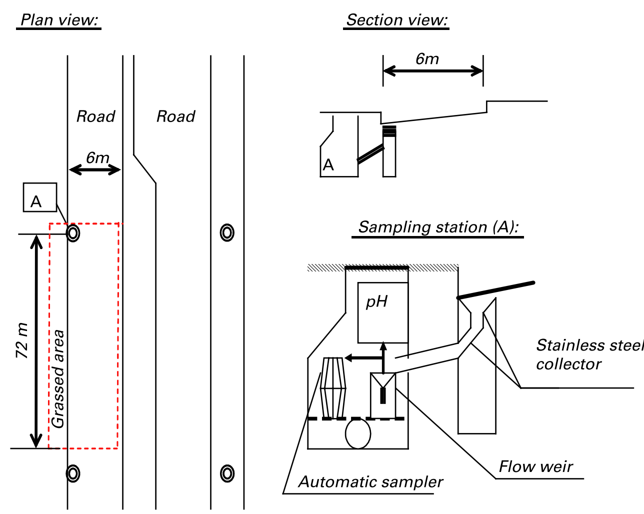

Figure 1 | Plan and section view of the runoff plot (broken lines) and the sampling station.

at the road surface was connected to a v-notch flow weir and a submersible pressure transducer, logged every two minutes during runoff, and an automatic water sampler (EPIC 1011), designed to take flow-weighted samples. The weir was calibrated in the laboratory using a flow rating test. For every 100 or 200 litres of runoff to the gully pot, a sample was taken for laboratory analyses. Precipitation data (measured every 12 h) were obtained from the nearest meteorological station (Kallax Airport), about seven kilometres from the runoff plot due to equipment problems at the site. The temperature was logged every 48 min (factory set) within the runoff plot. Measured and discussed parameters in this paper were flow and TSS concentrations. The TSS concentrations were measured in accordance with the standard method SS 02 81 12 (Swedish Standards Institute 1996).

MODEL DESCRIPTION

The model of the runoff plot is defined by two different surfaces: the road surface and the grassed area beside the road. When runoff is dominated by snowmelt, only the grassed surface, by assumption, contributes to flow because precipitation that falls as snow on the runoff plot will be ploughed off the road surface onto the grassed surface. When the runoff is dominated by rainfall, only the road surface contributes, as the contribution from the grassed area is deemed to be negligible due to an assumption of permeability. The model consists of two parts: one describing the dynamics of the road runoff and the other describing the dynamics of TSS. The dynamics for the snowmelt and rain runoff were simulated in an Excel spreadsheet and later in the MOUSE RDII software (DHI 2003*b*) because some calibration parameters are not available to the user for manipulation in MOUSE RDII. The dynamics of the TSS transport were simulated in MOUSE TRAP (DHI 2003*a*). All MOUSE software belongs to DHI, Water, Environment and Health, Denmark.

Runoff

The snow-melting process in the model is based upon a simple temperature-index method where the quantity of snowmelt runoff is proportional to the number of positive degree-days. To calculate the growth and melting of the snow cover, temperature data are used. Precipitation, together with a negative air temperature, implies an addition of precipitation to the snow cover while a positive temperature starts the snow-melting process. The time step of the simulations is 5 min which is disaggregated data from the Kallax precipitation data and the field site temperature data. In the simplest form, the temperature-index method can be expressed as follows:

$$Q = C_{melt} \cdot (T_a - T_m)$$

where Q = melt rate (mm/Δtime), T_m = threshold melt temperature (°C), C_{melt} = melt rate factor (mm/°C/Δtime) and T_a = air temperature (°C).

However, a modification of the temperature-index method was done (Bengtsson 1982; Hernebring 1996), where consideration is given to the capability of the snow pack to retain water, i.e. the water retaining capacity (H_2Ocap). The water retaining capacity was reported by the US Corps of Engineers (1956) to be approximately 4% by weight for “ripe” snow with an approximate density of 0.4–0.45 and 8% by weight for snow with an approximate density of 0.55–0.6. The water retaining capacity of 8% by weight is used in the model. The snow storage is divided into two parts: a liquid part (SN_{lq}) and a frozen part (SN_{fr}). During thaw, the liquid part is first filled up until it reaches 8% of the frozen part. The runoff from the snow storage will not start until the melting has satisfied the liquid water fraction.

A description of refreezing of the snow storage is also included in the modification. The equation for refreezing comes from equations used for describing the freezing of lakes. In the same manner as the snowmelt, the ice growth was calculated by a temperature-index method where the thickness of the ice h was calculated by the following formula:

$$h = C_{fr}\sqrt{S}$$

where C_{fr} is the refreezing constant and S is the number of negative degree-days (Bengtsson and Eneris 1977). In the model, 5 min is used instead of a daily time step. A description of the model concept, implemented in MOUSE RDII, can be seen in Figure 2. The surface runoff is routed with a simple linear time-area method and the concentration time set to 10 min. The rationale behind the set concentration time was

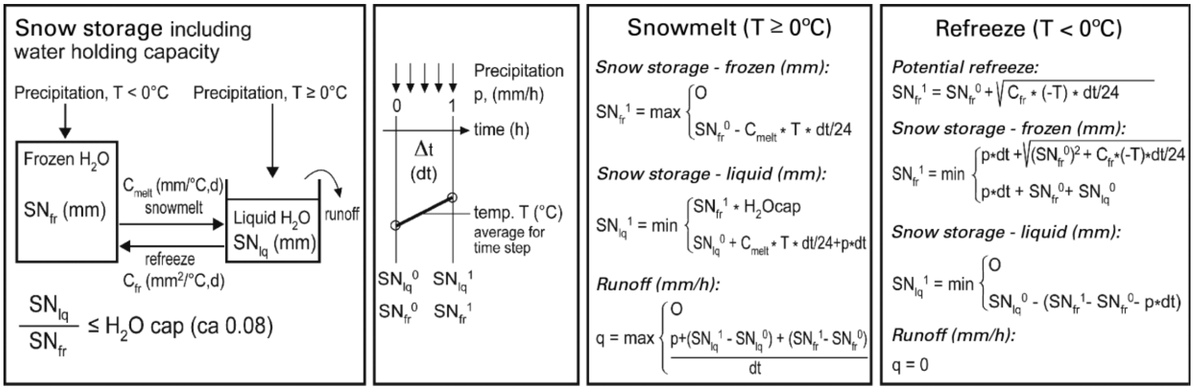

Figure 2 | Details of the model concept for runoff - modified temperature-index method (Hernebring 1996).

that a certain inertia is needed to compensate for the digital resolution of the rain data. The verification was done by loading the model with the precipitation data. When the shape of the hydrograph was produced correctly as compared to the measured hydrograph, it was considered verified. The runoff velocities for snowmelt events are very low, and consequently a 10 min concentration time is accurate for both rainfall- and snowmelt-induced runoff.

The parameters used for calibration in the Excel spreadsheet are the water retaining capacity, the starting depth of the snow cover (i.e. the start depths of the liquid and frozen parts), the coefficients for melting and refreezing (C_{melt} and C_{fr}) and the threshold melt temperature (T_m), which is used to compensate for such factors as closeness to buildings or other factors which will cause a change in temperature.

Total suspended-solids

The qualitative part of the model is based upon Svensson (1987). The model consists of the accumulation of particles, described by a linear build-up function, and the wash-off of particles from the surface of the runoff plot. The wash-off of particles is described in the model by raindrop erosion, Equations (1) and (2), and is separated into the transport of fine and coarse particles:

$$QS_{fine} \propto dr \cdot \left(\frac{ir}{id}\right)^{rp} \cdot \text{Area} \cdot k_{fine} \qquad (1)$$

$$QS_{coarse} \propto dr \cdot \left(\frac{ir}{id}\right)^{rp} \cdot \text{Area} \cdot k_{coarse} \qquad (2)$$

where QS = mass transport of (fine or coarse) sediments (g/s), dr = detachment rate (m/s), ir = rainfall intensity (μm/s), id = rainfall intensity constant (μm/s), rp = rain power = 2 (numerical exponent), $Area$ = area of surface (m^2), k_{fine} = porosity constant (fine particles) (dimensionless) and k_{coarse} = porosity constant (coarse particles) (dimensionless).

The fine particles are independent of particle diameter and will be transported according to Equation (1) as long as there are fine particles available at the surface to be washed off, while the amount of coarse particles is infinite in the model so the transport is only limited by the transport capacity of the overland flow. This maximum transport capacity of the coarse fraction is calculated by the Van Rijn formula (DHI 2003). The geometric means of the fine and coarse particle diameters are 10 μm and 1 mm, respectively.

RESULTS

The climatological input data used for the calibration and the verification are shown in Figure 3. The calibration period stretched from 28 March to 28 May 2000 and the verification period from 22 March to 22 May 2001.

As seen in Figure 4, for certain events there were large runoff contributions associated with small TSS fluxes, while the opposite also occurred. Thus, there is no linear relationship between accumulated runoff and accumulated loads of TSS. The model concept was used to describe this dynamic of road runoff and TSS transport. It should be noted that there were instances when runoff was measured but no TSS analyses were performed, and subsequently

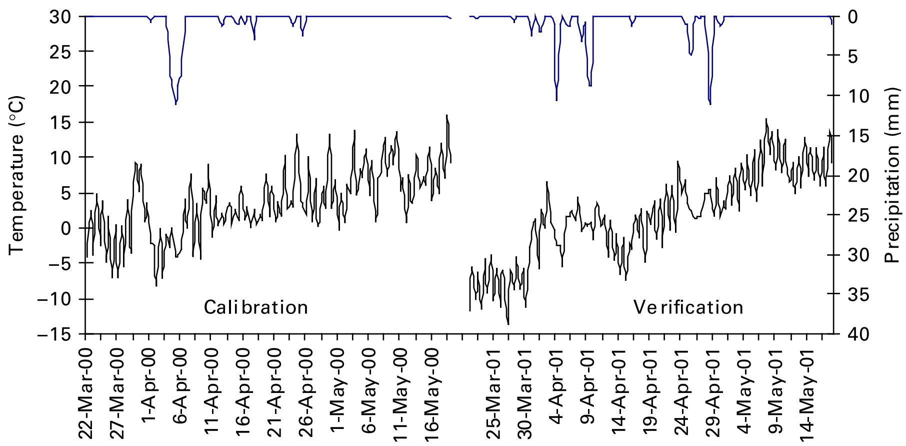

Figure 3 | Climatological data for the calibration (2000) and verification (2001) periods, respectively (average temperature and precipitation data per 12 h intervals).

discrepancies between measured and modelled loads of TSS can therefore be partly attributed to this.

Runoff calibration

During rainfall, the contributing road area was verified with on-site flow measurements and precipitation observations logged during rainfall events at the end of May and June 2001. The modelled contributing road area was estimated to be about 0.06 ha by these measurements. The verification gave a good agreement between modelled and measured series ($R^2 = 0.885$ and 0.830), respectively (Figure 5).

Unfortunately, no documentation of the snowpack was made, so indirect estimations were made based on the water balance and on temporal variations of the snowmelt runoff. The first step was to reproduce the growth and melting of the snow cover (i.e. the total snow storage (mm)) by estimating and adding the amount of frozen and liquid H_2O according to the model concept in Figure 1. Precipitation data from Kallax airport and the logged temperature data from the runoff plot were used. To calculate the frozen and liquid H_2O, the melt-rate factor together with the water retaining capacity were calibrating factors. The melt-rate factor was calibrated to 4 mm/°C/d and the water retaining capacity to 0.08. These values were then kept constant for the whole simulation period. The freezing rate is set to a fixed value of 10 mm^2/ °C/d, due to the difficulty of using it as a calibrating parameter (Hernebring 1996). The initial

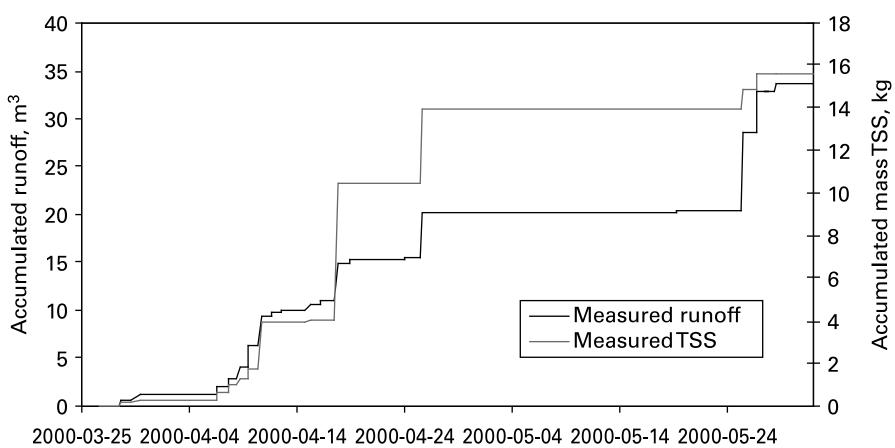

Figure 4 | Measured accumulated runoff (m^3) and mass of total suspended solids (kg).

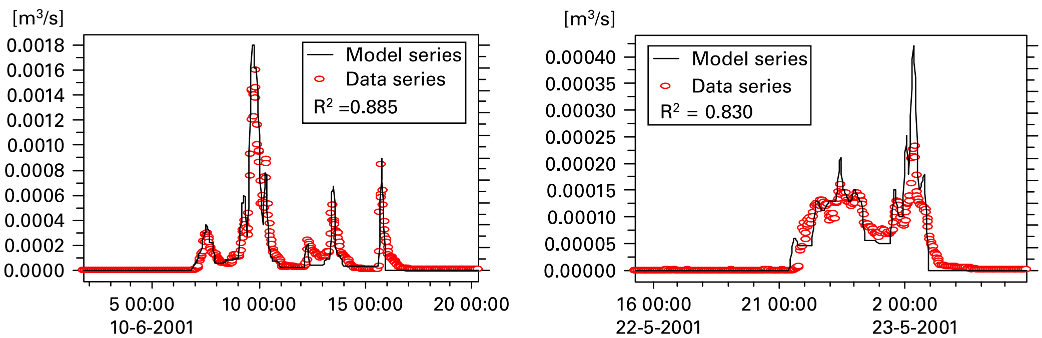

Figure 5 | Verification of contributing area during rainfall.

snow storage was estimated to be 25 mm. The reference temperature in the model was set to zero degrees. The runoff that the modelled snow storage would produce during the measuring period was calculated (mm) and compared to the measured runoff. The calibrating factor in this case was the contributing runoff area. The result was a contributing area of 0.011 ha, which means that approximately 1.5 m of the snowbank is contributing to runoff, considering the physical length of 72 m. The area of 0.011 ha was held constant throughout the simulation.

During rainfall, i.e. after 17 April, the curves for modelled and measured runoff discharge agree very well ($R^2 = 0.927$) (Figure 6). The good agreement was because the precipitation during this period was estimated from the measured runoff. This estimation was used because the precipitation data from Kallax airport were not accurate enough to produce the measured runoff from the plot and because the installed, site-specific tipping bucket rain gauge was not working properly. However, if only single-melt events were considered, i.e. before 17 April, the accuracy in volume and timing was not as good as for the complete study period. The explanation for this was the good agreement of the modelled and measured rainfall-induced runoff, concealing the less accurately modelled snowmelt part of the period.

Calibration of total suspended-solids transport

In MOUSE TRAP, the calibrating factors of fine TSS were the build-up rate (set to 7 kg/ha/d), the maximum value of TSS on the surface (set to 48 kg/ha) and the dry weather period (set to 10 d). The model of build-up and wash-off of fine particles at the runoff plot can be seen in Figure 7. The reason why Figure 7 does not include the coarse particles is

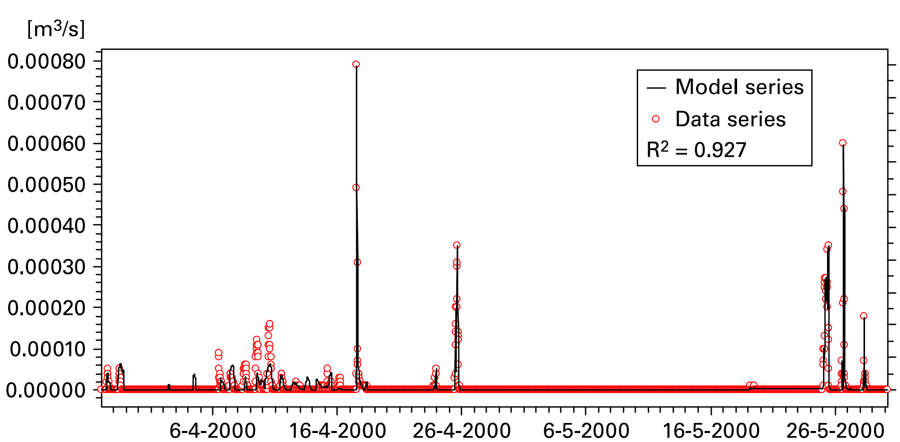

Figure 6 | Measured and modelled discharge (m^3/s) of road runoff during the measuring period.

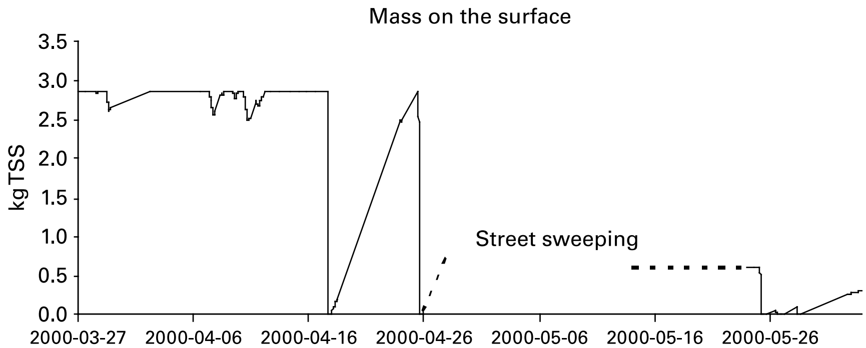

Figure 7 | Mass of TSS (kg) on the surface of the runoff plot.

because this fraction is unlimited in supply but limited in transport capacity. The size of the coarse fraction was calibrated so that enough energy was provided for transport by overland flow, at least during one of the events. These values were kept constant for the whole simulation period. The simulation using the calibrated values gave a good agreement between measured and modelled loads of TSS, except after 25 April, where the modelled load of TSS was much higher. The reason for the lower measured load of TSS was the street sweeping at the end of spring, where a lot of the anti-skid material was removed. According to the municipality of Luleå, street sweeping began on 25 April.

Due to this removal of material, the simulation for TSS was divided into two parts: the first simulation, prior to 25 April, with the calibrated values described above, and the second simulation, subsequent to 25 April, with new calibrated values for fine TSS. The new values were a build-up rate of 1 kg/ha/d and a maximum load of TSS of 10 kg/ha. The two simulations put together showed good agreement between the measured and modelled load of TSS (Figure 8(B)). However, during two events on 10 April and 17 April, the congruence is not satisfactory.

VERIFICATION

Runoff

The verification of the runoff model was made with flow measurements from 22 March to 22 May 2001. The initial snow storage was set to 57 mm, based on the water balance and the variations of the snowmelt runoff. Since site-specific precipitation data were not available, data from Kallax airport were modified to match the rainfall-induced runoff measured during 9 April to 22 May. After these modifications, which were necessary for the subsequent TSS modelling, the measured and modelled runoff was very coherent (Figure 9(A)).

Total suspended-solids

The results for the verification of TSS indicated very high loads towards the end of the simulation period. It was mainly the coarse fraction showing a mismatch during 19–21 May, with an unreasonably high transport of 67 kg.

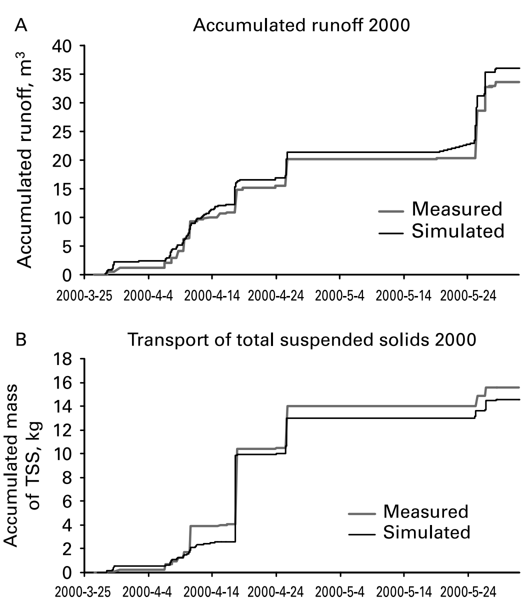

Figure 8 | Accumulated measured and modelled runoff (m^3) (A) and load of TSS (kg) (B), 2000.

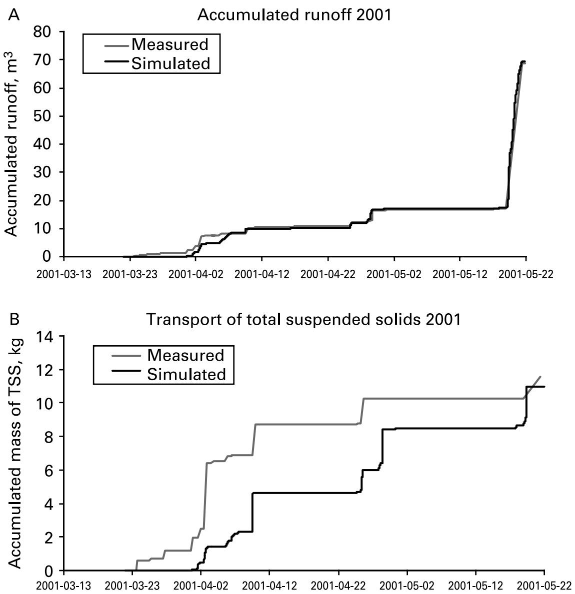

Figure 9 | Accumulated measured and modelled runoff (m^3) (A) and load of TSS (kg) (B), 2001.

The model was therefore re-calibrated by increasing the diameter of the coarse particles. In 2001, the simulations are also divided into two parts prior to, and subsequent to, the street sweeping that occurred on 17 May. The measured and modelled accumulated TSS for the two periods can be seen in Figure 9(B).

DISCUSSION

After calibrating the model for 2000, the results showed a good congruence between modelled and measured runoff and the transport of TSS, based on the continuous course of events for the whole modelling period. However, when looking at the period before 17 April, i.e. during snowmelt, the runoff was not accurately described (Figures 6 and 8(A)). For both years, accurate modelling of the snowmelt was difficult. This difficulty illustrates that the modified temperature-index method is inadequate in describing the snowmelt process, i.e. it does not take into account the radiation balance of urbanised catchments (Semadeni-Davies *et al.* 2001). Also, features included in the model could influence the inaccuracy, e.g. that the melt rate factor and water retaining capacity were kept constant throughout the simulation period. Measured and modelled runoff volumes for events subsequent to 17 April 2000 agree very well. Also, the agreement between measured and modelled TSS subsequent to 17 April is also good (Figure 8(B)). The conspicuous events where there is a large difference between measured and modelled TSS transport in the year 2000 are during 10 and 17 April (Figure 8(B)). The rationale behind the lower modelled load of TSS during 10 April could be that the intensity of the runoff is not accurately modelled (Figure 8(A)). This resulted in a lower overland flow that is not capable of transporting the large amount of coarse TSS accumulated towards the end of the melt period. The higher modelled load during 17 April could be explained by a too-simplified description of the transport of coarse sediments. 17 April is the only event where the overland flow is high enough to transport coarse sediments. The modelled and measured flow rates are at their highest (approximately 0.8 l/s) during 17 April (Figure 6). This mismatch might be improved by upgrading the model with a more detailed surface-runoff description more suited for a cold climate. A more physically based representation might be essential in describing TSS transport dynamics for both coarse and fine TSS. Another way of improving the model could be to improve the description of the build-up as well as the wash-out of pollutants from a snowpack because it differs compared to bare ground conditions. A possibility would be to connect the traffic intensity to the build up of pollutants.

The more accurate runoff in 2001 after 9 April is reflected in the better agreement of TSS transport within the events (Figure 9(B)). This demonstrates the importance of an accurate runoff volume to simulate the TSS correctly. It also shows that the model concept for the transport of TSS works better when the precipitation is falling as rain. The measured and modelled result for the transport of TSS during 2001 is discrepant at the beginning of the snowmelt because almost no runoff is produced in the model before 31 March due to the problems with the temperature-index method (Figures. 9(A, B)). For the same reason a large difference exists during 2–3 April between the modelled and measured TSS transport. Shortly after (4–7 April) the model over-predicts both runoff and TSS transport because the modelled snowmelt started later than the measured melt. Therefore, larger snow storage is left to generate more runoff and TSS in the model. Subsequent to this period, the runoff was modified and the transport of TSS is seemingly more accurate. The last large event (19–21 April) is the only one during 2001 where coarse TSS was transported, and a recalibration was required to fit the measured TSS. Again, this shows the need for a more physically based representation in describing TSS transport dynamics. Finally, it should be mentioned that the size of the runoff plot is small and further research should be conducted on larger areas.

CONCLUSIONS

The temperature-index method is inadequate to describe the snowmelt dynamics well for this small urban runoff plot. The simulation of the build-up and transport of fine and coarse TSS should be improved during snowmelt conditions. Despite a simple model concept it was possible to describe the dynamics of road runoff and TSS rather well, based on the continuous course of events for the whole modelling period. However, if the model was used for simulating a snowmelt period, or single events during snowmelt, the model approach would be too simple.

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