# Modelling of snowmelt from a small urban catchment
## - Dynamics of road runoff and suspended solid transport

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**Abstract** The impacts of road runoff are particularly severe in cold climate due to the longer pollutant storage in the snowpack and raised levels of pollutants. Because of this, it is of great importance to understand the dynamics of pollutants but also to use this knowledge in models to predict and prevent environmental damage.

In this paper a simple model concept is presented to describe the dynamics of road runoff and suspended solid transport from a small urban catchment in the central areas of Luleå, in the north of Sweden. The study period stretches from March 27 to May 28 and it includes both snowmelt and rainfall. A modified degree day method is used to describe the snowmelt and the transport of suspended solids is described by a linear build-up function and a wash-off model. The results from the simulations showed that this simple model concept was capable of describing the dynamics of road runoff and suspended solids for a continuous course of events. However, when looked upon the detailed course during single events the model approach was seemingly too simple.

*Keywords:* modelling, urban snowmelt, road runoff, suspended solids, sampling

## Introduction

To protect the natural environment and the safety and health of community residents it has recently been of primary concern to amend the quality of receiving waters affected by runoff from urbanized watersheds. The physical, chemical, biological, and combined effects on receiving waters, caused by runoff, differs depending on the climatic conditions but it seems 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 is that precipitation in cold climates will accumulate as snow on the ground with a residence time of several months depending on the weather conditions. During this time the snowpack will store chemicals, solids and other pollutants which also have a higher release during winter months compared to the rest of the year due to heating of houses, burning of fuels, cold starts of engines, tyre-wear, road-wear due to studded tyres, anti-skid control, etc (Malmqvist, 1983).

The snowmelt quantity modelling is much better developed than the snowmelt quality modelling (UNESCO, 2000). A number of different models for urban snowmelt quantity i.e., stormwater and snowmelt runoff, have been successfully reported up to now. Attempts to model urban snowmelt quality dates back to early 1970s and progress have been done in conjunction with, for example, the U.S EPA Stormwater Management Model (Huber and Dickinson, 1992) and as the form of independent model algorithms (Bartosova and Novotny, 1999).

To decrease impacts from road runoff in cold regions it is of great importance to understand the dynamics of pollutants but also to use this knowledge in models to predict and prevent environmental damage.

**Objectives**

The objective of this article is to test a model concept for the dynamics of road runoff and suspended solids within a small urban catchment during for both snowmelt and rainfall.

**Model description**

*General*

The model of the catchment area (Figure 2 and 3) is defined by two different surfaces, the road surface and the grassed area beside the road. During the period when runoff is dominated by snowmelt it is assumed that only the grassed surface is contributing since when precipitation falls as snow in the catchment area it will almost immediately be ploughed off the road surface to the grassed surface. When the runoff is dominated by rainfall it is assumed that the contribution from the grassed area is negligible and that only the road surface is contributing.

The model consists of two parts, one describing the dynamics of the road runoff and the other describing the dynamics of SS. To develop a model for quality parameters such as SS, it is crucial to simulate the road runoff accurately as a first step. The dynamics for the melt runoff was simulated in a spread sheet and later, both the melt and rain runoff, was simulated in the MOUSE environment. The dynamics of the SS transport was simulated in MOUSE TRAP.

*Runoff*

The snowmelting process in the model is based upon the simple degree day 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 is used. Precipitation together with a negative air temperature implies an addition of the precipitation to the snow cover while a positive temperature starts the snowmelting process. In the simplest form, the degree day method can expressed as following:

$$Q = k \cdot (T_a - T_m)$$

Q=melt rate (mm/day) $T_a$=air temperature

k=melt rate factor (mm/ºC/day) $T_m$=threshold melt temperature

However, a modification of the degree day method was done according to Hernebring (1996), where consideration is taken to the capability of the snow pack to retain water. The snow storage is divided into two parts, a liquid and a frozen part. During thaw, the liquid part is first filled up until a certain percentage of the frozen part. The runoff from the snow storage will not start until the melting has proceeded long enough to fill up the liquid part. A description of refreezing of the snow storage is also included in the modification. A detailed description of the model concept can be seen in Figure 1. This concept is implemented in MOUSE RDI, however, all the calibration constants are not available to the user for manipulation. The surface runoff is routed with a simple linear time-area method and the concentration time set to 10 min.

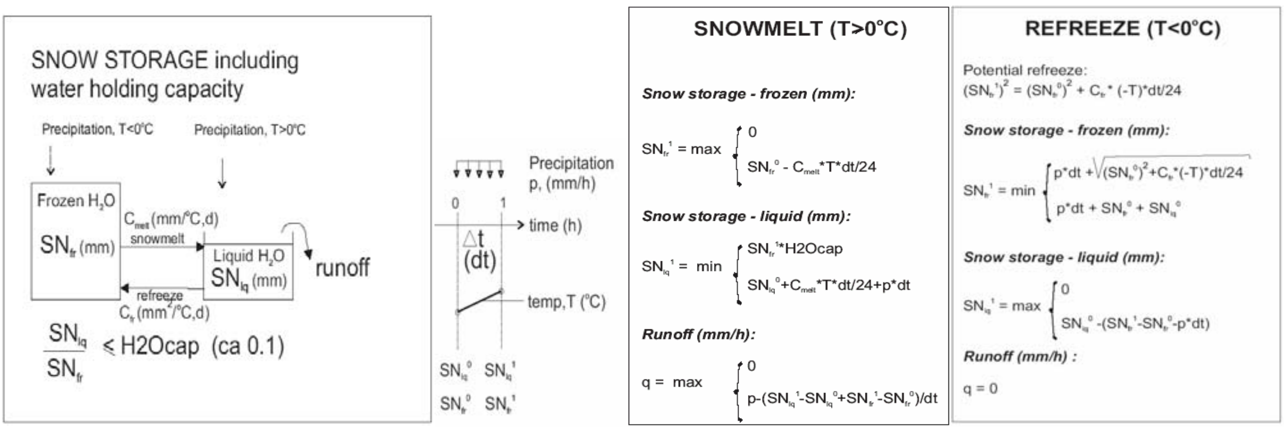



**Figure 1** Details of the model concept for runoff - modified degree day method.

*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 catchment surface. The wash-off of particles is described in the model by raindrop erosion, equation 1 and 2, and is divided into a part for fine particles and a part for coarse particles.

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

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

QS=masstransport 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
k=porosity constant (fine or coarse particles)

The fine particles will 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).

**Catchment area**

The small catchment area is situated at Södra Hamnleden in the central urban areas of Luleå, see Figure 2. The runoff was collected from two lanes which are drained via a curb to a gully pot. The gully pot, which receives runoff from 110 meters of road, is connected to a separate storm water pipe that conducts runoff to a nearby recipient. The traffic intensity of the road is 7400 vehicles/day and it has a width of 6 meters. Sand is used as an anti-skid material but no de-icing salts are used in the central parts of Luleå.

**Sampling**

During the period of March 25 to June 26, year 2000, flow measurements were performed for all snowmelt, rain-on-snow and rainfall events. However, events after the beginning of June was excluded due to less reliable flow measurement data. Also, measurements were performed during May and June, 2001, which were used to verify parts of the model. The gully pot at the road surface was equipped with a flow weir, logged every two minutes during runoff, and an automatic water sampler (EPIC 1011), designed to take flow-weighted samples, see Figure 3.

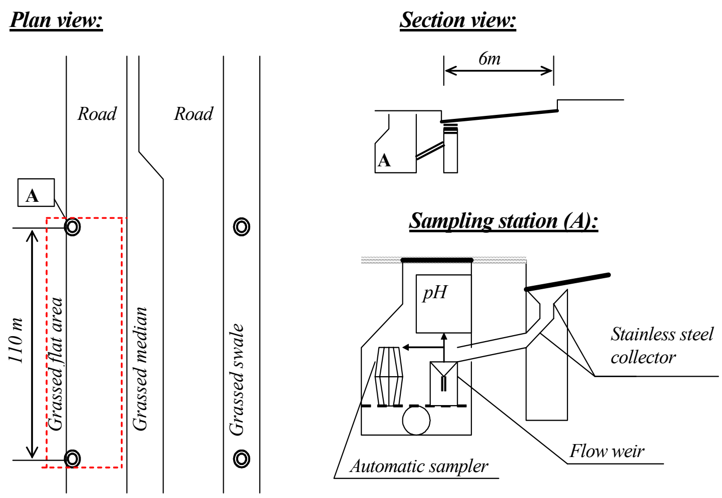



**Figure 2 and 3** The road side at Södra Hamnleden in Luleå and a plan view of approximate catchment area (broken lines) and a section view of the sampling station.

For every 100 or 200 litre of runoff to the gully pot, a sample was taken for laboratory analyses. Temperature (measured every 3 hours) and precipitation (measured every 12 hours) data together with snow observations (measured every 24 hours) were received from the nearest meteorological station, Kallax Airport, about seven kilometres from the catchment area. The temperature was also logged every 48 minutes within the catchment area. Measured parameters were the flow, pH, conductivity, concentrations of suspended solids (SS) and concentrations of total and dissolved heavy metals. However, only the flow and suspended solids were regarded in this article. The concentrations of SS were measured in accordance to the standard method SS 02 81 12.

The accumulated amount of road runoff ($m^3$) and massload of SS (kg) during the considered measuring period can be seen in Figure 4. As seen in the figure, at certain events, there is a large contribution of runoff while the contribution of SS is small, but also, the opposite around, i.e., there is no linear relationship between accumulated runoff and accumulated load of SS. A model concept was tried out to describe this dynamics of road runoff and SS transport.

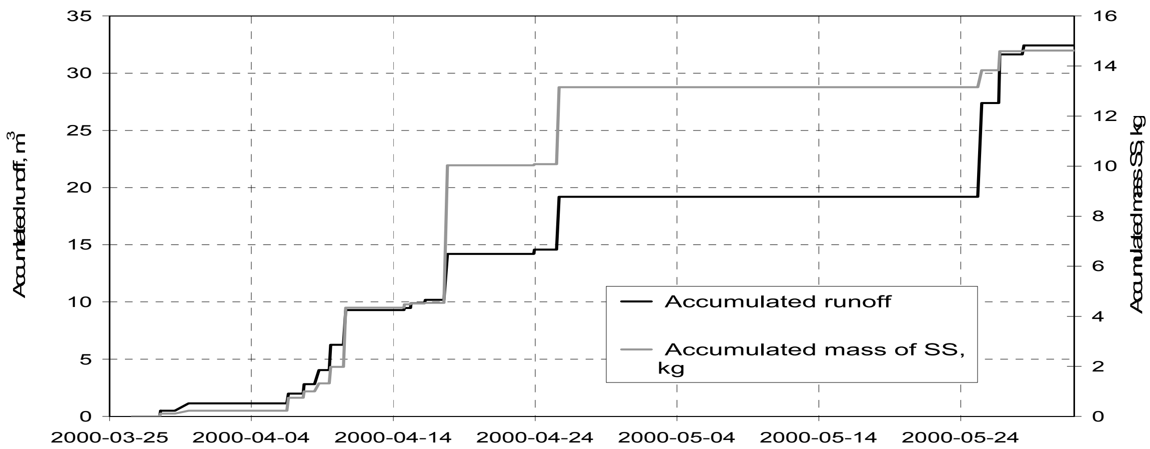
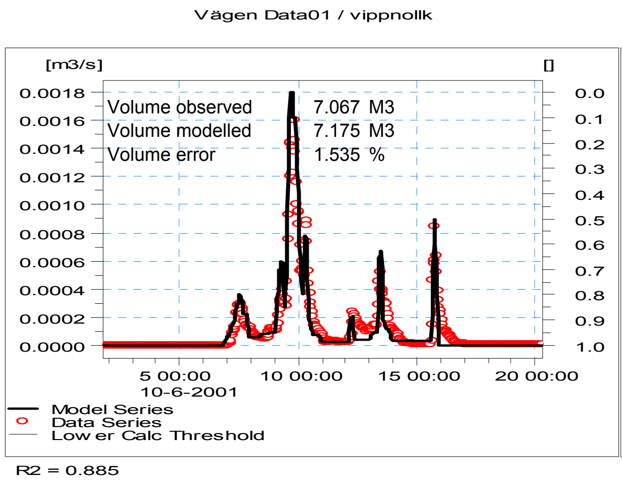



**Figure 4** Accumulated runoff ($m^3$) and massload of suspended solids (kg) during the measuring period.

## Results and Discussion

*Runoff calibration*

It has been shown that during the rainfall period, the contributing road area is about 0.06 ha. This has been verified with flow measurements and logged precipitation data during rainfall in May and June, 2001, see Figure 5 and 6.



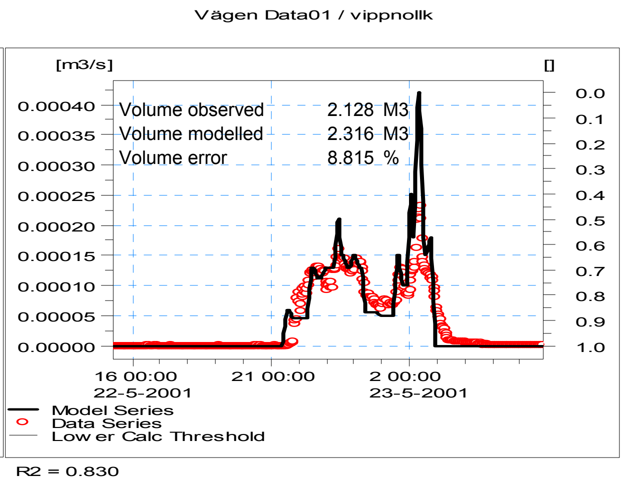




**Figure 5 and 6** Verification of contributing area during rainfall.

However, during snowmelt it is assumed that the dominating part of the runoff is coming from the snowpack on the side of the road, and how large is this contributing area? Unfortunately, no snow taxation or documentation (like photos) of the grass snowpack was made during this period, so indirect estimations had to be made based on water balance and the temporal variations of the snowmelt runoff.
The first step was to reproduce the actual growth and melting of the snow cover, i.e., the total snow storage (mm), during the snowmelt period within the catchment area. This was done by estimating and adding the amount of frozen and liquid $H_20$ according to the model concept in Figure 1. Precipitation data from Kallax airport (measured every 12 h) and the logged temperature data from the catchment area (measured every 48 minutes), were used. To calculate the frozen and liquid $H_20$, the melt rate factor together with the water retaining capacity were calibrating factors. The melt rate factor was calibrated to 4 mm/$^o$C, d and the water retaining capacity to 0.08 and these values were then kept constant for the whole simulation period. The freezing rate is set to a fixed value of 10 mm$^2$/ $^o$C, due its difficulties to be used as a calibrating parameter (Hernebring, 1996). The initial snow storage was estimated to 25 mm. The reference temperature in the model is always set to zero degrees. The runoff which the modelled snow storage would produce during the measuring period was calculated (mm) and compared to the actual measured runoff. The calibrating factor in this case was the contributing runoff area. The result was a contributing area of 0.011 ha, which was held constant throughout the simulation.

The results for the measuring period showed a good correspondence between modelled and measured volume of road runoff, see Figure 7. However, if looked upon single melt events, the accuracy in volume and timing was not as good. One explanation for that could be that in the model the melt rate factor was kept constant throughout the simulation period. This is a simplification and it could improve the model concept if the melt rate factor was changed during the melting period. It can also been seen that after April 17 the curves for modelled and measured runoff volume agreed very well. The reason for this is that the precipitation during this period was estimated from the measured runoff. This was done because the precipitation data from Kallax airport was simply not accurate enough to produce the measured runoff from the catchment area (and that the installed tipping bucket rain gauge at the site was not working properly). Evidently, a rather intense rain was locally occurring at the catchment area which was not measured at Kallax airport.

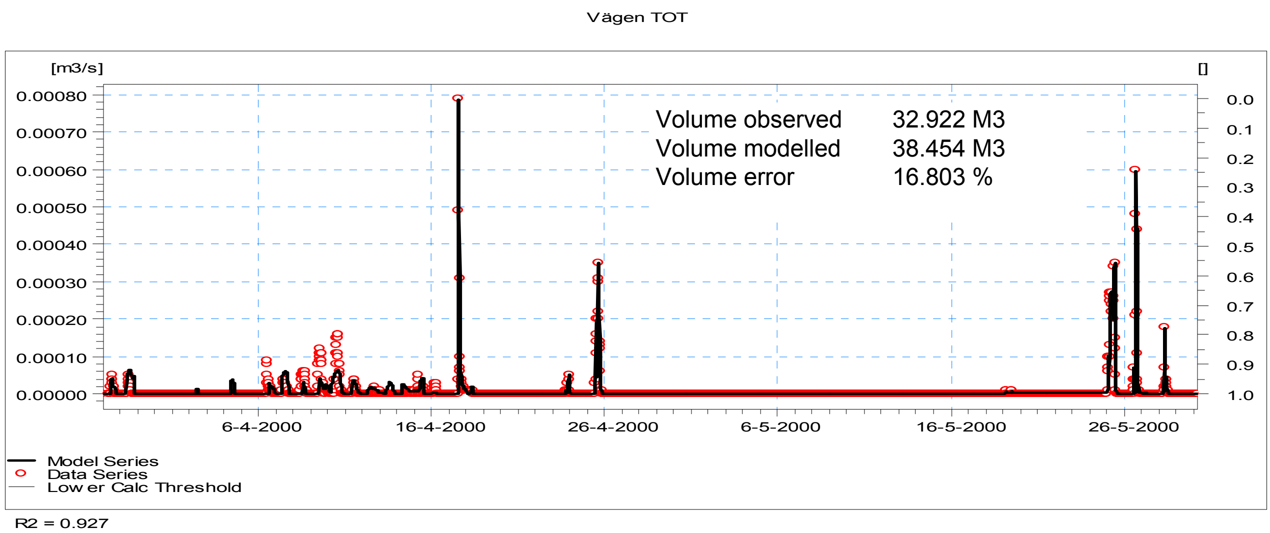



**Figure 7** Measured and modelled volume of road runoff during the measuring period.

*Calibration of Suspended Solids*

In MOUSE TRAP, the calibrating factors were the build-up rate of fine SS which was chosen to 7 kg/ha/day, the maximum value of SS on the surface which was set to 48 kg/ha and the dry weather period was set to 10 days. The size of the coarse fraction was set so that enough energy would be provided for transport by the overland flow, at least during a few of the events during the simulation period. These values were kept constant for the whole simulation period. The simulation with the calibrated values gave a very good agreement between measures and modelled load of SS. The only part of the measuring period where the agreement was not good was after April 25 where the modelled load of SS was much higher compared to the actually measured load. According to the municipality of Luleå, the street sweeping begun April 25, and Södra Hamnsleden was one of the first streets to be cleaned from anti-skid material, see Figure 8.

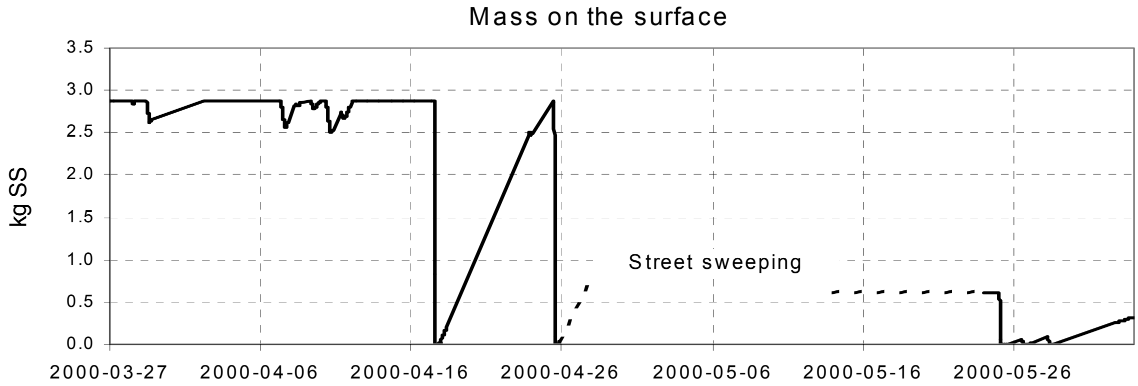
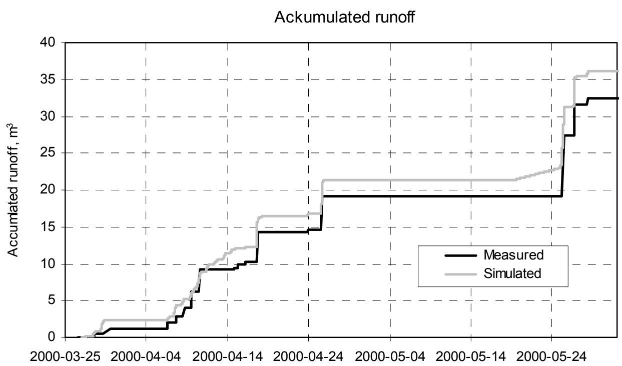



**Figure 8** Mass of SS (kg) on the surface of the catchment area.

Due to this information, the simulation for SS was divided into two parts. The first simulation, prior to April 25, with the calibrated values described above and a second simulation subsequent to April 25 with new calibrated values for fine SS. The new values were a build up rate of 1 kg/ha/day, a maximum value of SS of 10kg/ha. The same number of adjacent days without precipitation, 10 days, was used. Practically, this means that the maximum amount of fine particles is available at the start of each simulation. The actual dry weather period before May 25, is a month.

When these two simulations were put together in one graph, the measured and modelled load of SS were very coherent, see Figure 10. However, during two events, April 10 and April 17, the congruence is not satisfactory between measured and modelled SS. The rationale behind the lower modelled load of SS during April 10 could be that the intensity of runoff is not accurately modelled, see Figure 9. This results in a lower overland flow that are not capable of transporting the large amount of coarse SS accumulated towards the end of the melt period. The missmatch during April 17 could to a great extent be explained by a too simplified description of the transport of coarse sediments. April 17 is the only event when transport of "coarse" sediments was assumed to occur.



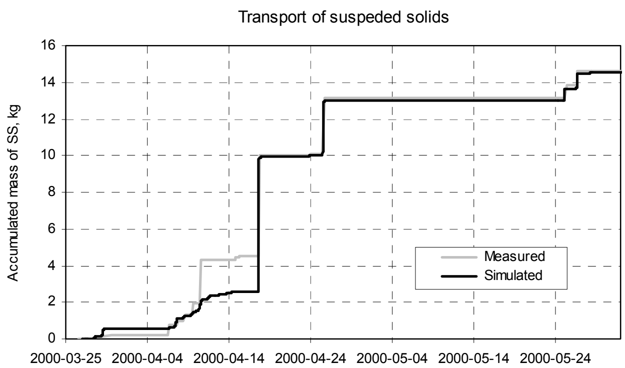




**Figure 9 and 10** Measured and modelled accumulated road runoff ($m^3$) and load of SS (kg).

**Event summary**

The measured and modelled road runoff (l) and SS (kg) for each event during the measuring period is shown in Table 1. As noticed, the total accumulated runoff in Figure 9 does not correspond to the sum in Table 1. The explanation is that there are simulated events between April 11 and 14 which are not measured. An event is defined as the time period from the start to the end of the runoff measurement. It is evident, when looking at Table 1 that the agreement between measured and modelled runoff volume and load of SS varies among the different events. As explained earlier, the measured and modelled runoff volumes for events after April 17 agree very well. Also, the agreement between measured and modelled SS after April 17 has a fairly good agreement. This demonstrates the importance of an accurate runoff volume to simulate the SS correctly. It also shows that the model concept for SS works very well when the precipitation is falling as rain. For events previous April 17, it is difficult to draw any conclusions. However, the total measured runoff volume and load of SS agree very well with the modelled values.

**Table 1** Table of measured and modelled road runoff (l) and SS (kg) for each event during the measuring period.

| | Measured | | Modelled | |
|---|---|---|---|---|
| **Date** | **Runoff vol. (l)** | **SS (kg)** | **Runoff vol. (l)** | **SS (kg)** |
| 2000-03-28 | 500.0 | 0.114 | 744.1 | 0.134 |
| 2000-03-29 | 566.0 | 0.078 | 1473.0 | 0.419 |
| 2000-03-30 | 74.1 | 0.018 | 0.0 | 0.000 |
| 2000-04-06 | 851.9 | 0.470 | 522.7 | 0.067 |
| 2000-04-07 | 825.1 | 0.267 | 1550.0 | 0.477 |
| 2000-04-08 | 1240.9 | 0.322 | 736.2 | 0.127 |
| 2000-04-09/10 | 886.8 | 0.263 | 1604.6 | 0.302 |
| 2000-04-10 | 2218.6 | 1.681 | 2126.8 | 0.617 |
| 2000-04-14 | 119.5 | 0.093 | 614.0 | 0.068 |
| 2000-04-14/15 | 338.4 | 0.035 | 153.6 | 0.002 |
| 2000-04-16 | 299.7 | 0.016 | 90.3 | 0.001 |
| 2000-04-17 | 3885.7 | 6.373 | 4041.5 | 7.342 |
| 2000-04-23/24 | 379.4 | 0.050 | 318.0 | 0.080 |
| 2000-04-25 | 4606.9 | 3.521 | 4535.5 | 3.005 |
| 2000-05-25 | 8185.4 | 0.854 | 8198.5 | 0.632 |
| 2000-05-26/27 | 4265.8 | 0.512 | 4187.6 | 0.795 |
| 2000-05-28 | 778.6 | 0.028 | 725.9 | 0.098 |
| **Sum** | **30547** | **14.9** | **31622** | **14.2** |

**Conclusions**

Despite a rather simple model concept it was possible to describe the dynamics of road runoff and suspended solids for a continuous course of events. However, when looked upon the detailed course during single events the model approach was seemingly too simple.

**Future research**

Future work which will be done is a verification of this model with measurements from the same catchment area, the year 2004. There are also plans to verify the model concept with measurements from another catchment area with different conditions. Future improvements of the model would be to upgrade the model with more a detailed surface runoff description if a more physically based representation is found to be essential in describing the suspended solids transport dynamics. Also, it could be of interest to look into the build up of pollutants in the snow pack since it differs from the build up on bare ground. A possibility would be to connect the traffic intensity to the build up of pollutants. It is desirable to include routines in the model for the metals which have also been measured at the catchment site. Finally, it would be of great interest to approve the runoff accuracy within single events, and consequently, also the accuracy of massloads and concentrations for pollutants.

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