Sensitivity of urban drainage wash-off models: compatibility analysis of HydroWorks QM and MouseTrap using CDF relationships

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ABSTRACT

One of the key aspects in urban drainage (water quality) modelling is the accurate simulation of the input into such models. The modelling of surface sediment build-up, erosion and wash-off is discussed in this paper. An analysis and a comparison of the quality modelling tools of the commercial urban drainage software packages HydroWorks (Wallingford Software, UK) and Mouse (DHI, Denmark) reveal important differences between, and incompatibilities in, both models. The analysis is performed using concentration–duration–frequency (CDF) relationships. A generalised model, accounting for the common model principles used in both models and incorporating the model principles lacking, is proposed.

Key words | HydroWorks QM, MouseTrap, urban hydrology, wash-off models, CDF relationships

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INTRODUCTION

Both Wallingford Software (UK) and the Danish Hydraulic Institute (Denmark) provide in their urban drainage software, respectively HydroWorks and Mouse a quality-modelling tool. One of the key aspects in urban drainage (water quality) modelling is the accurate simulation of the inflow into the pipe model. Various sources that generate a pollutant inflow into the sewer system can be defined. During dry weather, domestic foul flow, as well as industrial and commercial pollutant discharges, are the most important sources of pollution into a sewer system. During wet weather sediments and pollutants are washed off from the surface and transported into the combined sewer system.

The total wash-off pollutant load can be divided into a dissolved fraction and a fraction that is attached to sediment particles. In both models gully pots are considered to be the sole source of dissolved pollutants. The concept of sediment-attached pollutants is dealt with by means of introducing a potency factor Kpn depending on the maximum rainfall intensity (HydroWorks QM) or a pollutant partitioning coefficient PPC (MouseTrap). Due to the definition of the potency factor K_{pn} and the PPCs, the wash-off of attached pollutants is considered similar to the wash-off of sediment particles.

The focus in this paper will be on surface sediment wash-off modelling as implemented in the HydroWorks QM *Hydrology Model* (Wallingford) and the MouseTrap *Surface Run-off Quality Module* (DHI). The contribution of atmospheric contaminants present in the precipitation (Zug 1998; Schlütter 1999; IWA Task Group on Sewer Sediments 2001) and the impact of the gully pots to the total wash-off pollutant load entering the sewer system is beyond the scope of this study. Only the wash-off of sediment particles will be considered. The aim is to compare both packages and to evaluate the physics behind the equations. Special attention goes to limit values and applicability for continuous simulations.

WASH-OFF QUALITY MODELLING

Most of the surface pollution that enters the sewer system originates from street run-off (Xanthopoulos & Augustin

1992). Various surface pollutant sources can be defined (Schlütter 1999; IWA Task Group on Sewer Sediments 2001), e.g. erosion of road material, wear of vehicle tires, dry deposition of fine solids from the atmosphere, solid wastes and litter, animal droppings and vegetation, de-icing materials and construction sites.

In HydroWorks QM one single sediment fraction is used in order to model the sediment wash-off. MouseTrap offers the possibility to model the wash-off of a fine and a coarse sediment fraction. Coarse sediments are presumed to be available in unlimited quantities. The modelling of the coarse sediment fraction is governed by transport capacity calculations using the Meyer–Peter equation (bed load transport) and the Einstein equation (suspended load transport). Coarse sediments originate from (DHI, personal communication) winter gritting, construction sites and soil erosion. In this paper there will be no further discussion on the modelling of the wash-off of this coarse sediment fraction. Only the fine fraction will be considered.

The classical approach in surface run-off quality modelling is to divide the model into three parts, namely build-up, erosion and wash-off. Hence the modelling concept is as follows:

- in dry weather particles accumulate on the catchment surface (build-up);
- during rainfall these particles are eroded due to the raindrop impact (erosion);
- once the particles are eroded, they get entrained by the run-off flow and transported into the sewer system (wash-off).

Both HydroWorks QM and MouseTrap are developed on an event-based and conceptual approach. Although deterministic wash-off models do exist, e.g. Deletic *et al*. (1997), they are not commonly used. Bertrand-Krajewski *et al*. (1993) give a good overview of different wash-off model concepts, most of which are based on the SWMM model (Jewell & Adrian 1978).

The build-up of surface sediment deposit is based on the assumption that on a clean surface the rate of sediment deposit is linear with time but, as the surface mass increases, a maximum value M_{max} will be attained exponentially.[1] The sediment mass available for wash-off at the end of the antecedent dry weather period (ADWP), namely M_{ADWP} (kg ha^{-1}) is a function of the initial sediment mass on the catchment M_{init} (kg ha^{-1}) before the start of the ADWP, the ADWP itself and the build-up parameters as described by (1):

$$M_{ADWP} = M_{init} e^{-decay \cdot ADWP} + M_{max}(1 - e^{-decay \cdot ADWP}). \quad (1)$$

Table 1 gives an overview of all parameters used in the build-up equation (1) as implemented in HydroWorks QM and MouseTrap.

The build-up of surface sediment continues during rainfall. The impact of this continued build-up during rainfall is mostly small. Due to the impact of the raindrops on the sediments on the catchment, the sediment particles get eroded. The erosion rate, as defined in HydroWorks QM, E_{HW} (kg s^{-1} ha^{-1}), is a function of the rainfall intensity, the remaining mass of surface sediment and the user-editable parameters C_1, C_2 and C_3 as decribed by (2):

$$E_{HW}(t) = (C_1 i(t)^{C_2} - C_3 i(t))M(t). \quad (2)$$

In MouseTrap, the erosion rate E_{MT} (kg s^{-1} ha^{-1}) is a function of the rain intensity i_r and a number of parameters as described by (3):

$$E_{MT}(t) = D_r \left(\frac{i_r}{i_d}\right)^{exp} (1-\varepsilon)\rho_{fs} \times 10\,000/3600. \quad (3)$$

Table 2 gives an overview of all parameters used in the erosion equations (2) and (3) as implemented in HydroWorks QM and MouseTrap.

Once the rain erodes the sediment particles on the catchment, they are entrained by the overland flow and washed off into the sewerage system. The washing off is implemented in HydroWorks QM by means of the Desbordes run-off model (Desbordes 1975; Wallingford 2002), irrespective of which run-off model is used for hydraulic run-off calculations. This implies that it is possible that wash-off occurs when there is no water flowing from the catchment into the system. In order to avoid such

[1] MouseTrap also offers the possibility to work with a linear build-up type with an upper limit. Differences with the asymptotical exponential build-up type are small. Due to the discontinuity in the linear build-up type the latter is less suited for computational purposes.

Table 1 | Build-up equation parameters as used in HydroWorks (HW QM) and MouseTrap (MT)

Symbol	Parameter description	MT	HW QM	Units
M_{init}	Initial surface sediment mass	—†	M_d	(kg ha^{-1})
M_{ADWP}	Surface sediment mass at the end of the ADWP	—	M_0	(kg ha^{-1})
M_{max}	Maximal attainable mass of surface sediment	M_{max}	P_s/K_1	(kg ha^{-1})
Decay	Decay rate	A_c/M_{max}	K_1	(d^{-1})
acc	Accumulation rate	A_c	P_s	(kg ha^{-1} d^{-1})

†It is not possible to define an initial sediment mass in MouseTrap. All sediments have to be built up during the ADWP. In order to tackle this problem, a virtual time *t'* can be added to the observed ADWP (cf. Deletic *et al.* 1997).

Table 2 | Erosion equation parameters as used in HydroWorks (HW QM) and MouseTrap (MT)

	Symbol	Parameter description	Default	Units
HydroWorks QM	$i(t)$	Rain intensity	—	(m s^{-1})
	$M(t)$	Mass of surface sediment	—	(kg ha^{-1})
	C_1	Rainfall erosion coefficient	10^8	
	C_2	Rainfall erosion coefficient	2.022	
	C_3	Rainfall erosion coefficient	29	
MouseTrap	i_r	Rain intensity	—	(mm h^{-1})
	i_d	Rain intensity constant	25.4	(mm h^{-1})
	exp	Power exponent	2	
	D_r	Detachment rate	0.001	(m h^{-1})
	ε	Fine sediment porosity	0.350	
	ρ_{fs}	Sediment density	2650	(kg m^{-3})

a physical incompatibility one is recommended to use the Desbordes run-off model for the run-off calculations as well. In MouseTrap the eroded particles are routed with the same routing that was selected for run-off calculations. Whether or not a wash-off routing is applied has no significant influence on the total washed off mass, but a routing flattens out the instantaneous mass flow curve. The impact of the type of wash-off routing is considerable (see further).

CONTINUOUS MODELLING—CDF RELATIONSHIPS

HydroWorks QM as well as MouseTrap apply an event-based modelling approach. One of the key aspects for calibration purposes in event based modelling is the determination of the initial state (ADWP, initial sediment mass, build-up parameters). In order to avoid such a difficult determination of the initial state and to be able to perform some statistics on the results (CDF relationships, etc.), the continuous modelling of long time series is of vital importance. Therefore a continuous urban drainage wash-off model was developed. The model consists of a single, continuous run-off module and two different wash-off modules in which the HydroWorks QM and the MouseTrap equations are incorporated. The continuous run-off model and its parameters are also used to model the wash-off routing. The shift from an event-based to a continuous model complies with the change of event-based parameters into continuous parameters. In order to match the HydroWorks QM approach as closely as possible, the developed run-off module is based upon the event-based Desbordes linear reservoir run-off model (Desbordes 1975). The linear reservoir coefficient K of the Desbordes run-off model is calculated as follows:

$$K = K_{desb} Ar^{0.18} Pnt^{-0.36} (1+C)^{-1.9} T_3^{0.21} L^{0.15} Hpe^{-0.07} \quad (4)$$

where

K_{desb}, coefficient determined from calibrated data;
Ar, subcatment area (ha);
Pnt, slope of the subcatchment (%);
C, fraction of impervious area;
T_3, event duration (s);
L, length of the subcatchment (m);
Hpe, total cumulated rainfall (m).

The Desbordes model includes a term T_3 (s) with a positive exponent value of 0.21 and a term Hpe (m) with a negative exponent value of -0.07. These event-based parameters are both rainfall dependent and are replaced in the continuous run-off model by the (continuous) parameter $i(t)$ (m s^{-1}) (rainfall intensity), having a negative exponent value of -0.21. After some other modifications in order to match the continuous run-off model with the original event-based run-off model, a time-varying reservoir coefficient $K(t)$ was found, as described in (5) (Bouteligier & Van Aerschot 1999), in which K^* is equal to 1375:

$$K(t) = \frac{K^* Ar^{0.255} Pnt^{-0.36} (1+C)^{-1.9}}{0.4 i(t)^{0.21} + 0.6} . \quad (5)$$

Having established a continuous model creates the possibility of using long term simulations in order to calculate concentration–duration–frequency (CDF) relationships, as shown in Figure 1. One of the advantages of using CDF relationships is that the influence of different time scales (duration) and different severity levels (frequency) are shown in one single graph. The sediment concentration of the wash-off flow (g l^{-1}) that lasts for a certain duration (min) is plotted for different frequencies (yr^{-1}). The point indicated by the marker denotes that once a year (i.e. 1 p.a.) a wash-off concentration of 687 mg l^{-1} that lasts for 80 min will be flowing off the catchment surface.

MODEL COMPARISON

In this section HydroWorks QM and MouseTrap will be compared and an attempt will be made to explain the origin of the differences encountered. The latter will be done by examining the different phases in the wash-off quality module and its effects on the CDF curves by means of the continuous urban drainage wash-off model. A distinction will be made between differences due to model concepts and differences due to distinct parameter settings. A catchment of size 1.2 ha, slope 2%, fully impervious and the 27-year 10-min rainfall time series of Uccle (Belgium) are applied to the continuous model.

Figure 1 shows a comparison of the CDF curve of the HydroWorks QM and MouseTrap models for frequencies of 1 yr^{-1}, 6 yr^{-1} and 12 yr^{-1} using the default model settings and the HydroWorks QM residential land use.[2] The continuous routing model that is described above is used for the HydroWorks QM calculations whereas for the MouseTrap calculations the Mouse run-off model A (i.e. time-area method) is used. The run-off coefficient is set to 1 in both routing models.

As can be seen in Figure 1, MouseTrap will generate a significantly higher wash-off concentration for a given frequency and duration. Also, a difference in the slope

[2]Mousetrap does not define different land use types.

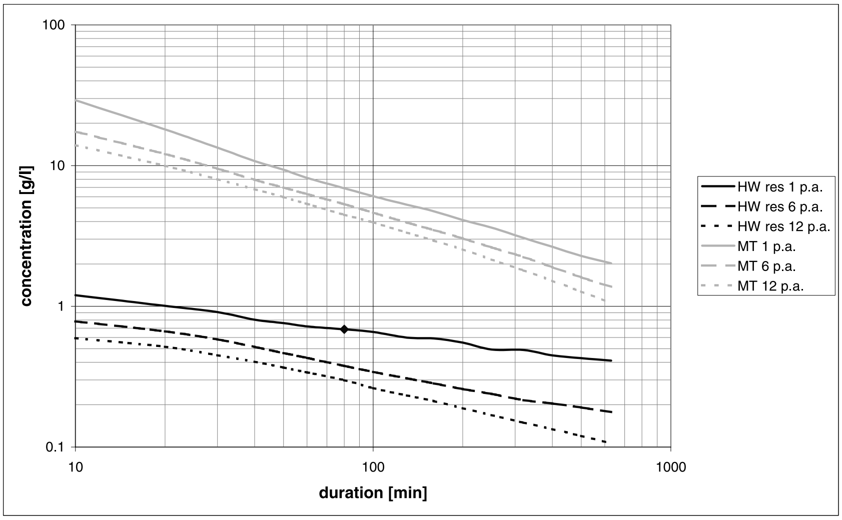

Figure 1 | HydroWorks QM and MouseTrap CDF comparison: default settings.

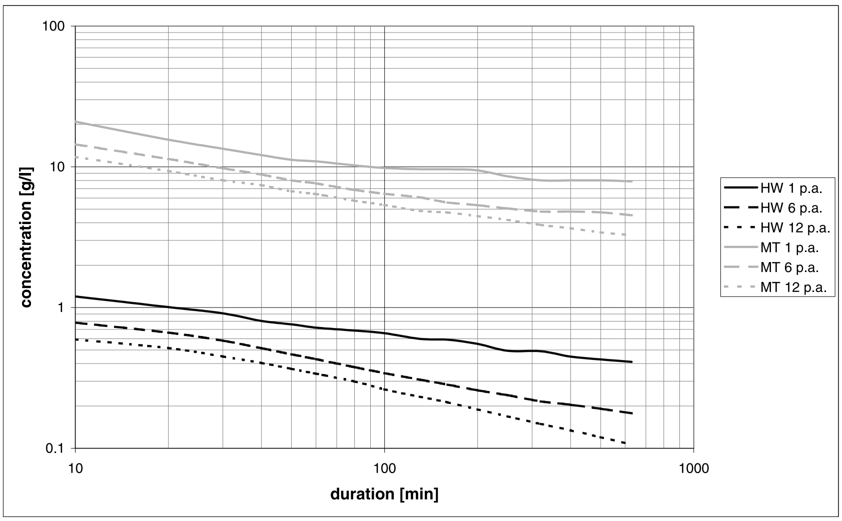

Figure 2 | HydroWorks QM and MouseTrap CDF comparison: use of equal wash-off routing to the MouseTrap module.

of the CDF curves can be detected in Figure 1. In CDF plots, deviations of the curve slope and shape are due to differences in model concepts. Parameter calibration can be a means of closing the gap between different CDF curves having the same slope.

Wash-off processes

As can be seen in Figure 1 an important difference between the HydroWorks QM and MouseTrap curves is the slope of the CDF curves. The addition of the same wash-off routing as implemented in HydroWorks QM to the MouseTrap model results in CDF curves (with approximately the same slope) as shown in Figure 2. This is a clear indication that the type of wash-off routing already explains a significant part of the differences in model settings between both models and that the choice of the routing model and its parameters has a considerable impact on the generated results.

Table 3 | Comparison of the default build-up parameters as a function of land use

HydroWorks QM	P_s [kg/ha/day]	K_1 [–/day]	P_s/K_1 [kg/ha]
Residential	6	0.08	75
Commercial	25	0.08	312.5
Industrial	35	0.08	437.5
MouseTrap	A_c **[kg/ha/day]**	A_c/M_{max} **[–/day]**	M_{max} **[kg/ha]**
Default	50	0.1	500

Build-up processes and parameter values

Looking at the default build-up parameters (see Table 3), rather big differences can be observed. These differences in build-up parameters have a major impact on the built-up mass during the ADWP. MouseTrap will generate more built-up mass and therefore more sediment mass will be available for erosion and wash-off of the surface. This is a clear indication that the use of default values is highly questionable.

Figure 3 shows the results of a simulation in which the same build-up settings are used for the HydroWorks QM model as for the MouseTrap model. As can be seen in Figure 3, a great part of the difference between the wash-off generated by HydroWorks QM and MouseTrap can be contributed to the build-up parameters. Therefore it can be concluded that the build-up factor and, to a lesser extent the decay rate, are model parameters that are well suited for calibration purposes.

Erosion processes and parameter values

In order to reduce the (default) MouseTrap erosion rate, the detachment rate D_r (see Equation (3)) is calibrated as such that the total washed-off mass approaches the HydroWorks QM value. In doing so, approximately 0.1 times the default D_r value is needed. This indicates that one has to be extermely careful using default parameter values. Figure 4 shows a CDF comparison of HydroWorks QM and MouseTrap in which the reduced erosion rate is applied. Figure 4 shows that an acceptable correspondence between the CDF curves of both models is achieved.

Due to the limited range of ε and ρ_{fs} and acknowledging the fact that 'exp' is a very sensitive parameter not

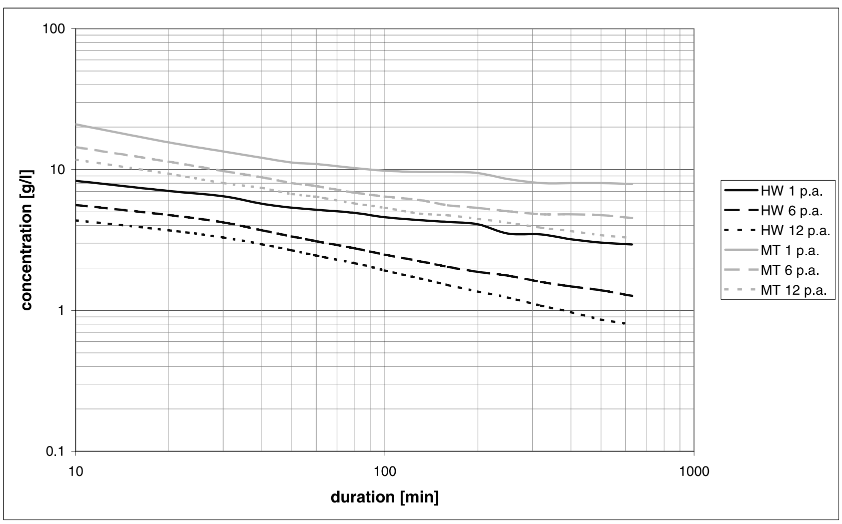

Figure 3 | HydroWorks QM and MouseTrap CDF comparison: use of equal build-up settings.

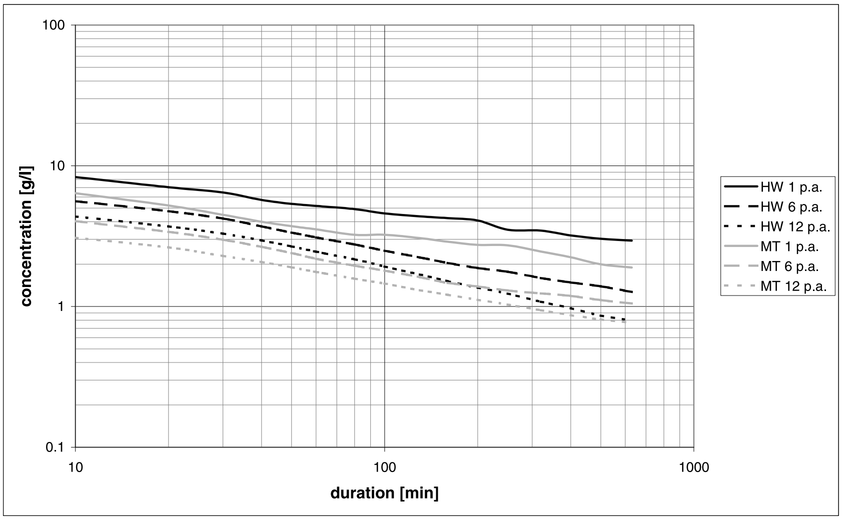

Figure 4 | HydroWorks QM and MouseTrap CDF comparison: reduced MouseTrap erosion rate.

suited for calibration purposes, it can be concluded that D_r is a good calibration factor (cf. Equation (3)). In a similar way it can be stated that, due to its sensitivity, the C_2 parameter that is defined in HydroWorks should not be altered by much and that the focus should be on the C_1 parameter when calibrating the HydroWorks model, bearing in mind that the impact of a variation of C_3 is rather small.

GENERALISED APPROACH

Although the constant MouseTrap erosion rate multiplier, as defined above, is calibrated to an extent that the total washed-off masses are the same, there still exist some differences between the HydroWorks QM and MouseTrap CDF curves. This is mainly due to the difference in the definition of the erosion rate. Whereas the HydroWorks QM erosion rate is a function of both the rainfall intensity and the surface sediment mass (2), the MouseTrap erosion rate is only a function of the rainfall intensity (3). In Figure 5 the erosion rate is plotted as a function of the surface mass (for a rain intensity of 18 mm h^{-1}).

Figure 5 clearly points out that, in order to obtain equal erosion rates, the surface sediment mass needs to have a value that can never be attained using the default build-up parameter settings. The maximal attainable value of surface sediment mass is 500 kg ha^{-1} using the default MouseTrap settings, whereas values larger than 1200 kg ha^{-1} are needed in order to obtain equal erosion rates. The difference in erosion rate that is illustrated in Figure 5 has a large impact on both the total washed-off mass as the instantaneous mass flow. When a storm washes off all sediment from a surface there will hardly be any difference in total washed-off mass, but the generated mass flow will differ significantly whether MouseTrap or HydroWorks QM is used. MouseTrap will wash off sediments a lot faster than HydroWorks QM will.

Although the larger part of the existing wash-off models, e.g. SWMM (Jewell & Adrian 1978), incorporate both the rainfall intensity as the available mass of surface sediment into their equations (Bertrand-Krajewski *et al.* 1993), it is not possible to say which approach is the more convenient without a thorough comparison of both approaches with reliable and (statistically) relevant field data. Nevertheless some remarks can be made. In HydroWorks QM high surface sediment masses may correspond with (high) erosion rates that cannot be explained physically.[3] In MouseTrap, on the other hand, the lack of a relation between surface mass and erosion rate can

[3] It should be noted that the mass of surface sediment is limited by the build-up equation. Nevertheless, when only looking at the erosion equation, the remark is still valid.

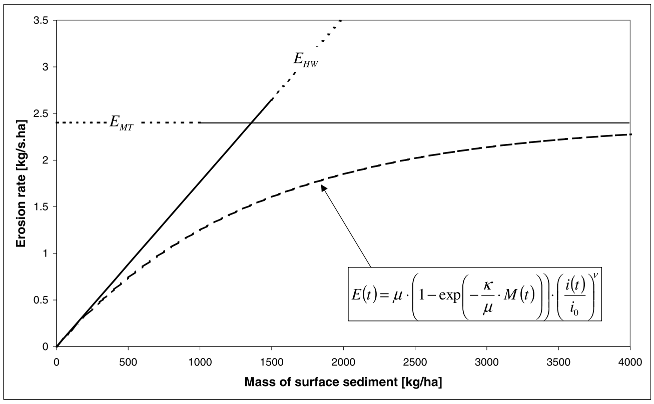

Figure 5 | Erosion rate as a function of the surface mass for a given rainfall intensity of 18 mm/h.

cause erosion rates that would be able to wash off more sediments than there are available on the catchment surface. An alternative definition of the erosion rate that expresses the relation between the erosion rate, the surface mass and the rain intensity by four parameters, namely $\varkappa$, μ, ν and i_0, is proposed (see Figure 5). By doing so the facts that high surface masses would imply physically impossible erosion rates and that the eroded mass would exceed the available mass for wash-off calculations at low available surface sediment masses are avoided. The proposed equation incorporates both the HydroWorks QM and the MouseTrap approach. The value of ν is close to 2 in a large number of existing wash-off models, e.g. the default FLUPOL parameter is 2.1 (Buyon 1988) and should preferably not be used for calibration purposes due to the high sensitivity of the wash-off model to any variation of this parameter. Therefore ν is set to 2. The rainfall intensity constant i_0 can, for example, be considered to be equal to the one that is implemented in MouseTrap, namely 25.4 mm h^{-1}. This means that there are only two parameters left for calibration purposes. The resulting CDF curves of an implementation of the newly proposed erosion equation (with $\varkappa = 3.8347 \times 10^{-3}$ (s^{-1}) and $\mu = 4.7847$ (kg s^{-1} ha^{-1}))[4] into the continuous urban drainage wash-off model have approximately the same slope and are situated within the curves plotted in Figure 4.

The proposed erosion equation has a limited number of calibration parameters, approaches both the HydroWorks QM as well as the MouseTrap CDF curves and is therefore believed to be well applicable for urban drainage wash-off modelling. The equation is flexible, having sufficient calibration parameters and the limits are physically based. Any application of the equation, however, should be compared with relevant and sufficient field data.

CATCHMENT CHARACTERISTICS

Up until now abstraction was made of the catchment characteristics as they were presumed to be well calibrated during the hydraulic (run-off) modelling. In HydroWorks QM the surface sediment mass, as well as the wash-off flow, are calculated per unit area and afterwards multiplied by the area of the catchment and the fraction of the area that is impervious. Using a simple run-off model only producing run-off from impervious areas (and not from pervious areas), wash-off is only possible from impervious areas. In MouseTrap the erosion rate is a function of the area A_r and the fraction of the surface that is covered with sediment, A_s. Using the MouseTrap run-off model A (time–area method) the latter is equal to the run-off coefficient multiplied by the fraction of the catchment that is impervious. Sediments are built up on the whole area. Using the same simple run-off model (run-off from impervious areas – no run-off from pervious areas), the MouseTrap erosion rate will be calculated accounting for the impervious area characteristics, but the whole catchment is used as a sediment source. The latter implies that sediments that are built up on the pervious catchment as well as on the impervious catchment will be washed off. For example, assuming that all sediments are washed off, a catchment of 2.4 ha, of which 50% is impervious, will wash-off twice as many sediments as a catchment of 1.2 ha, of which 100% is impervious. The wash-off rate, on the other hand, will be the same in both cases. DHI is aware of this problem and will make the required corrections to the software.

[4]The values of $\varkappa$ and μ are derived from the default HydroWorks QM and MouseTrap erosion equation parameter settings. When i_0 is changed, the values of $\varkappa$ and μ need to be recalculated.

CONCLUSION

The HydroWorks QM *Hydrology Model* and the MouseTrap *Surface Run-off Quality Module* are analysed and a comparison between the models was made using continuous long-term simulations and CDF relationships. In order to be able to generate CDF curves, a continuous urban drainage wash-off model was developed incorporating the HydroWorks QM and MouseTrap equations. The default parameter settings vary significantly, but can be accounted for through calibration. Applying the default parameter settings, MouseTrap will generate a non-negligible larger amount of total washed-off sediment mass. Therefore default values should not be used without a calibration and validation of the model with sufficient and reliable field data. An indication of which parameters are useful and which parameters are too sensitive for calibration purposes is given. Differences in model concepts can be found in the application of the type of wash-off routing model and in the description of the erosion process. A generalised erosion equation is proposed that accounts for both the HydroWorks QM and MouseTrap approaches. The limits of this generalised erosion equation are more physically based. The suggested erosion equation has a limited number of calibration parameters and is believed to be suited for general urban drainage wash-off computations if calibrated and validated with field data.

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