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Erosion modelling towards, and sediment transport modelling in unnavigable watercourses in Flanders, Belgium

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Abstract Antea Group and KULeuven were awarded a project in Flanders to identify the regions exporting high sediment loads to unnavigable watercourses and the sedimentation zones within them. Two types of models are applied: hydrological sediment export models (SEM) and hydraulic sediment transport models (STM). The influence of erosion control measures on sediment export as well as river engineering measures needs to be taken into account. A concept will be developed to connect the SEM and STM, enabling the sediment to be routed from upstream to the sedimentation zones. Results of the study will be used by the Flemish government to plan erosion control measures, estimate future sedimentation volumes, steer sedimentation and optimize river engineering and dredging works. Finally, model results could also be used to obtain better insights to the re-suspension risks of contaminated sediment in watercourses.

Key words sediment transport; erosion; sedimentation; hydrological model; hydraulic model; erosion control measures

INTRODUCTION

The Flemish water courses contain approximately 24 million tonnes of, mostly contaminated, sediment. Yearly, an estimated 1.8 million tonnes are added. The major part thereof, approx. 1.1 million tonnes, originates from upstream areas outside of Flanders and from the North Sea. The largest source of sediment supply within Flanders is soil erosion, i.e. about 0.4 million tonnes per year. The excessive amounts of sediment present in the water courses cause serious ecological, hydraulic and nautical problems, which in turn result in high financial costs. Therefore, the reduction of sediment supply originating from soil erosion is crucial to combat Flanders' sediment problems. Erosion Control Measures (ECMs), as source-based as possible, made up the spearhead of the Flemish policy during the last 10 years. Additionally, measures were taken in the waterways themselves, such as dredging and the installation of sediment traps.

In order to develop an effective and efficient policy for sediment control in Flanders, a tool is needed that enables an optimal estimation of soil erosion and sediment supply towards the watercourses, and sedimentation and re-suspension within these water courses. Therefore, the Flemish Environment Agency (VMM) and the Flemish Department of Environment, Nature and Energy (LNE) have awarded Antea Group and KULeuven a project aimed at the development of a suitable (hydrological) sediment export (soil erosion) and (hydraulic) sediment transport model (SEM and STM, respectively) for the unnavigable water courses of Flanders. Briefly, the SEM needs to be capable of calculating the soil erosion, on land sedimentation and sediment export on a pixel base (25 m^2 or smaller), both for an event and on a yearly base. A methodology has to be developed to connect the SEM to the STM, transferring the sediment export from land to water courses. Sewers, roads, preferential flow paths, etc., should be taken into account. The STM then needs to simulate the sediment transport on an event basis along the water courses, together with the sedimentation and re-suspension processes per sector (part of a water course between two subsequent junctions of categorised water courses) of the Flemish Hydrographical Atlas (VHA). The SEM should be able to properly implement ECMs, e.g. grass buffer strips, while the STM-model must deal with water course reorganization projects, e.g. sediment traps.

First, different SEMs need to be analysed for their applicability. The most suitable models must be tested in different catchments for which measurements of the sediment load are available, in order to make a final selection. As far as the STM is concerned, the model choice is limited to a detailed comparison between InfoWorks River Systems (IWRS) and InfoWorks Integrated Catchment Modelling (ICM) developed by Innovyze®, which are the standard hydraulic software packages applied by VMM. Next, seven Flemish erosion prone river catchments (Maarkebeek amongst others) have to be modelled in detail by means of the selected SEM and STM. Moreover, a simplified SEM and STM need to be developed for the 11 Flemish river basins (ranging from 577 to 1916 km^2). The latter must be capable of calculating sediment export and transport for a characteristic annual rainfall based on (sub)basin scale inputs.

In this article, the development and execution of the methodology to achieve the above objectives is described. Given that the project is still in its development phase (exploratory modelling), no detailed calibration results can be shown as yet. However, these will be presented during the ICCE2014 symposium in New Orleans, USA (11–14 December, 2014).

SEDIMENT EXPORT MODEL

Although in the past decades a lot of research effort has been expended in the application of erosion models with varying characteristics in the Flemish Region, the evaluation of these models was based on results for a limited number of small catchments (<200 km^2) in most cases (Heuvelmans *et al*., 2004; Takken *et al*., 1999; Van Oost *et al*., 2004; Van Rompaey *et al*., 2001). Since the SEM in this study eventually needs to be applied for the whole region of Flanders (13 522 km^2), important selection criteria are the model robustness and its applicability in the different environmental settings encountered in this region.

Model comparison

The main properties that were evaluated during model comparison were: (1) model complexity, (2) data requirements and data availability, (3) model output and (4) applicability of the model by policy makers. In a first step a wide range of models were selected and compared based on the main model characteristics. Evaluated models included both empirically-based (WaTEM/SEDEM (Van Oost *et al*., 2000; Van Rompaey *et al*., 2001) and SPADS (de Vente *et al*., 2008)) and process-based models (openLISEM (De Roo *et al*., 1996a), MCST (Fiener *et al*., 2008), PESERA (Kirkby *et al*., 2008) and SWAT (Arnold *et al*., 1998)). Also an empirical runoff model based on a modified and spatially distributed version of the SCS Curve Number (CN) (Van Oost, 2003) was included in the initial comparison. Afterwards both a physically-based model (openLISEM) and a combination of two empirically-based models (modified CN model and WaTEM/SEDEM) were selected for a detailed evaluation. In this way, the added value of model complexity and degree of process-description within the models could be evaluated against data availability for the Flemish Region.

Model description

OpenLISEM (De Roo *et al*., 1996a) is a process-based erosion-, transport- and deposition model that simulates both the dynamics of runoff and sediment for single rainfall events. A large range of processes are simulated, while 24 input data maps are needed in the most basic configuration. To simulate infiltration, the Green and Ampt infiltration module was used.

To assess the influence of the degree of process description in combination with data availability on the model results, two empirical models were also evaluated. To simulate hydrographs at the catchment outlet a modified and both spatially and temporally distributed version of the curve number technique was used in which runoff is routed towards the catchment outlet, taking into account the spatial configuration of the catchment (Van Oost, 2003). Additionally, sediment dynamics are calculated using WaTEM/SEDEM (Van Oost *et al*., 2000; Van Rompaey *et al*., 2001), an empirically-based erosion and deposition model based on the Revised Universal Soil Loss Equation (RUSLE). This model is spatially distributed but temporally lumped. Based on adapted C- and R- factors, erosion can be simulated for single rainfall events.

Study area

To test the applicability of SEMs for different erosion-prone regions in Flanders, two study sites were selected. The first catchment is located close to the city of Leuven (Ganspoel, 114 ha), the second is located south of the city of Sint-Truiden (Heulengracht, 210 ha). Both areas are located in the Belgian loess belt and have been extensively sampled in the past for both runoff and associated sediments (hydrographs and sedigraphs) at the catchment outlet and spatial erosion patterns after large rainfall events. Moreover, in the Heulengracht catchment a large number of ECMs have been implemented (e.g. grass buffer strips, cover crops, retention ponds, etc.). The ability of the SEM to simulate the effect of these ECMs could hence be evaluated.

Results of model comparison

Both SEMS base their soil erosion calculation on hydrological processes. Therefore, the hydrological part of both models was assessed first for the Heulengracht catchment.

As openLISEM simulates a large number of processes, input data is needed for very specific model parameters. This data was not readily available for all parameters in the catchment (e.g. aggregate stability, soil cohesion, leaf area index, etc.) so most of the data were collected based on work by Takken *et al*. (1999) in a nearby catchment. This results in a significant uncertainty concerning input data quality, which is expected to increase when simulating catchments for which no field data is available. After calibrating based on Ksat (saturated hydraulic conductivity) and ψ (hydraulic suction at the wetting front) it became clear that these are effectively calibration parameters and do not reflect measurements of these variables in the field, because their optimal values were not coherent with physical soil values. This implies that openLISEM, despite its process-based structure, cannot be applied to unsampled catchments without calibration.

The application of the modified CN model is much more straightforward. Standard tables were used to determine CN values for different land uses. These CN values are modified based on Van Oost (2003). The average runoff velocity was kept constant at 0.3 m s^{-1} based on measurements by Govers (1992).

Both models were calibrated based on the same dataset and hydrographs were calculated for different events. An example of the comparison between a measured and simulated hydrograph that characterizes most of the simulated events is shown in Fig. 1. The process-based model appeared to largely underestimate the total discharge volume and no distinct discharge peaks were simulated. The modified CN model, on the other hand, reproduced the measured hydrograph much better, both with respect to time of peak discharge and total discharge volume.

Based on the model comparison for the Heulengracht and Ganspoel catchments (which is not shown here), some important conclusions can be drawn concerning the potential applicability of both models for large catchments (up to 2000 km^2) in the Flemish Region:

(a) The lack of detailed spatially-distributed input data reduces the advantages of using a physically-based model in which many natural processes are mathematically represented. Finding the optimal model is a quest to find an optimal combination of model complexity and data availability (Van Rompaey & Govers, 2002).
(b) It is a difficult task to determine the optimal parameter set to be used in unsampled catchments, as calibration of openLISEM is often characterized by equifinality (multiple combinations of parameters lead to an optimal result).
(c) Measurements of the parameters to which openLISEM is most sensitive (Ksat and ψ) cannot be used as model input without calibration, which limits the applicability of openLISEM to unsampled catchments.
(d) In contrast to openLISEM, the modified CN model only takes into account the most important catchment and rainfall characteristics, which are often available, even for large catchments. Hydrographs simulated by the modified CN model show more similarity with measurements compared to openLISEM. For some events, results obtained with the modified CN model still deviate significantly from measurements. However, there are possibilities for improvement.

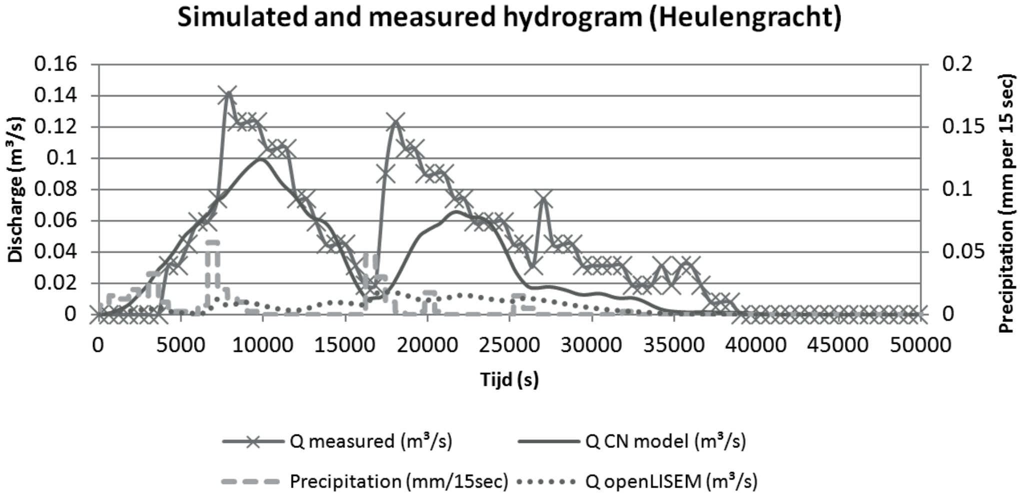

Fig. 1 Simulated (openLISEM and the modified CN model) and measured hydrographs for the event of 29/05/2006 at the Heulengracht catchment

The CN model will be used to simulate runoff dynamics in the continuation of this study. To simulate sediment dynamics for large catchments, WaTEM/SEDEM will be used. The optimal strategy to distribute the amount of eroded sediments over the simulated hydrograph will be determined. For this goal, measured and simulated hydrographs and sedigraphs will be applied for seven Flemish erosion prone catchments. In a final step, the relation determined will be used to simulate water and sediment dynamics in other Flemish catchments.

SEDIMENT TRANSPORT MODEL

The development of the STM started from the IWRS inbank model of the catchment of the Maarkebeek (Fig. 2). This hydraulic model does not contain flooding structures (e.g. storage areas), since these are not compatible with the sediment modelling module. To avoid water impoundment near flooding hydraulic constructions and river banks, a comparison was made between the inbank model and a flood model. This was done for the largest event in the study period (2002–2008), i.e. 4 July 2005 (return period of approx. five years), which is illustrated in Fig. 3. Wherever floods occurred in the flood model, a control structure (vertical sluice) was added to the inbank model so that the latter was able to reproduce the flooding volumes in a simplified way. In this way, model errors due to the lack of flooding structures were limited. Furthermore, spill units had to be replaced, since they are not compatible with sediment modelling. These structures model sudden drops/jumps in the river bed and act as control structures where a higher model stability is required. The structure most suitable to replace them is a vertical sluice. By altering the width of the sluice, the flow-stage relation of the spill unit could be approximately reproduced by the sluice. In this way, it was attempted to limit the effect of this replacement on the hydraulic results, but unfortunately, some divergence of the results is unavoidable. Additionally, several model structures had to be altered for stability reasons (IWRS sediment modelling requires more model stability than mere hydrodynamic modelling).

The major water courses in the IWRS model of the Maarkebeek were modelled in a detailed manner, based on topographic measurements. The smaller, upstream parts were brought into the model in a simplified way: a trapezoidal channel was created for these parts with a bed width of 0.33 m, a depth of 1 m and inter-bank width of 1 m. For each VHA sector, the bed altitude of the up- and downstream end was derived from the digital terrain model (DTM). Between those points, the bed altitude was interpolated linearly. For stability reasons, the 'hard bed' option of IWRS was applied for these upstream parts. One drawback is that erosion of the initial river bed is impossible.

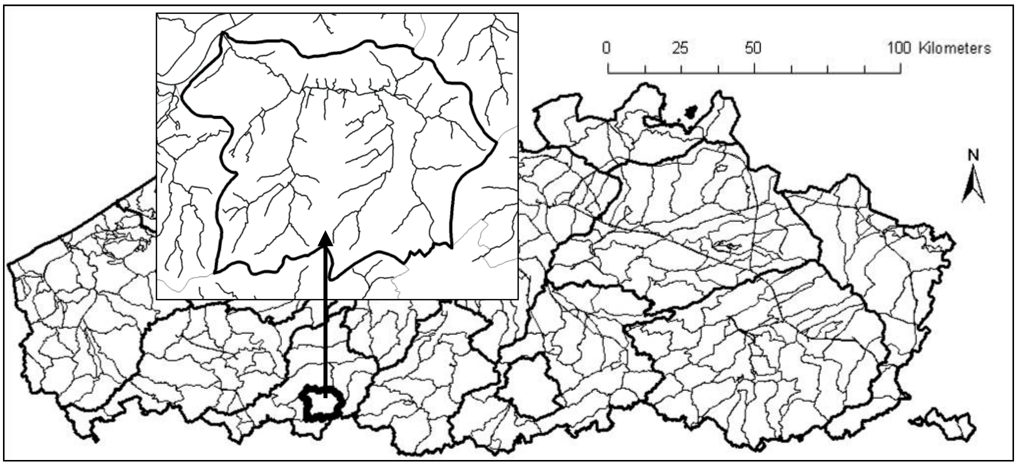

Fig. 2 Overview of the Flemish basins and catchments and detail of the Maarkebeek catchment.

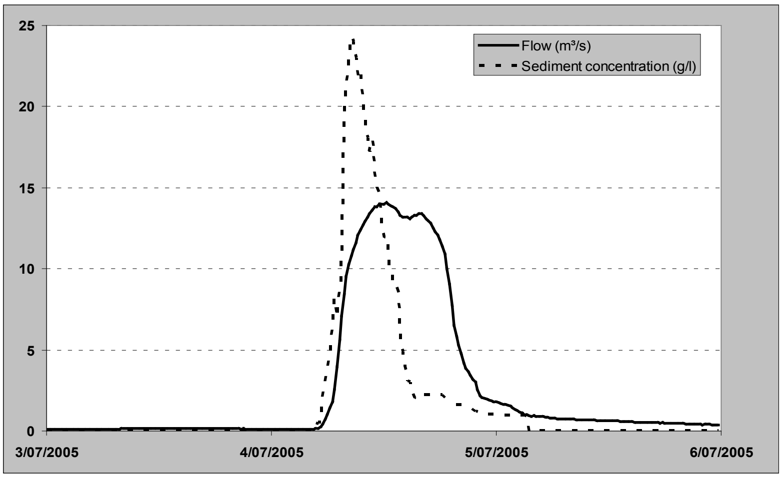

Fig. 3 Flow and sediment concentration on the Maarkebeek (downstream) during the 04/07/2005 event.

At the upstream boundaries of the model, 15 hydrological Probability Distributed Models (PDM) were implemented to calculate an input flow from a rainfall and evapotranspiration time series. These were split into 153 smaller PDM models, so that each VHA sector has its own inflow to which a sediment input (from the SEM) can be linked.

The IWRS model was also converged to an ICM model. In ICM, no model adjustments had to be made for reasons of stability or compatibility with sediment modelling. Therefore the STM in ICM suffers less model divergence from the original model as compared to IWRS.

Sensitivity analysis

A sensitivity analysis was performed for the IWRS model, based on Saltelli *et al*. (2008). A realistic range for each parameter was derived from literature and within it a number of parameter values were selected for the bed porosity (2), sediment diameter (4), density (2), critical shear stress (3) and settling velocity (3). The model was simulated while the parameters were altered by a one-factor-at-a-time screening. Afterwards, the Elementary Effects method was applied to evaluate the sensitivity of a model output (global net deposition) for each of these parameters. The results are shown in Table 1. The settling velocity clearly has the largest influence on the simulation results, followed by the diameter and the density. All parameters have a positive relation with the net deposition: the larger the parameter value, the larger the deposition. The porosity does not seem to have any effect, but a more detailed analysis showed that it does have an effect when the sorted calculation option is applied (simulating sorting processes such as

Table 1 Results of the elementary effects method for the IWRS model (“,” used as thousands separator).

Parameter	μ	μ*	σ
Bed porosity	0	0	0
Diameter	5,651	5,651	293,903,937
Density	4,207	4,207	24,715,204
Critical shear stress	100	100	35,610
Settling velocity	10,057,453	10,057,453	206,209,102,062,370

μ is the average of the elementary effects and μ* is the average of the absolute value of the elementary effects.

armouring). Furthermore, additional simulations with broader parameter ranges revealed that the diameter and critical shear stress have a larger influence than was derived from Table 1.

Four sediment transport equations can be applied in IWRS: Engelund & Hansen (1967), Ackers & White (1973, 1993) and Westrich & Jurashek (1985). The latter equation provided the best results being the most suitable equation for fine sediments, which are present in the Maarkebeek catchment.

In the ICM model a thorough sensitivity analysis has not yet been performed. The parameters have been tested qualitatively for the different sediment transport equations: Ackers *et al*. (1991), Zug *et al*. (1998) and Bouteligier *et al*. (2002). A positive relation was found between the deposition and the sediment diameter, the settling velocity and the specific gravity.

Model performance

Many simulations with both STMs were run for the event of 04/07/2005, while adjusting the model parameters in an attempt to reproduce measurements of suspended sediment concentration (SSC) and deposition. SSC data (determined from continuous turbidity readings and water samples) are available at five locations in the Maarkebeek catchment from 2002 to 2008. Deposition has been measured at selected locations during recent events by measuring the bed level before and after the event. Both the IWRS and ICM models appeared to be capable of reproducing the order of magnitude of these measurements. The authors expect to be able to present detailed calibration results of the selected STM (using different events and measuring locations) and a thorough performance evaluation during the ICCE2014 symposium.

Model applicability

A test was performed to analyse the model applicability in terms of simulating the effect of a river engineering project, such as an upstream sediment trap. The latter can be implemented by locally widening and deepening the water course. This can easily be done both in IWRS and ICM, by adapting the river section profiles. Simulation results (Fig. 4) revealed a drop in flow velocity, an increase in deposition and a reduction of the SSC at the sediment trap. Consequently, both models are applicable to simulate sediment traps.

Stability

During numerous test simulations, IWRS suffered a lot of stability problems. Many simulations failed or gave unrealistic results, such as heavily fluctuating deposition. As a consequence, several model options (e.g. updating the geometry in hydraulic calculations) were inapplicable. Many attempts to stabilize the model were performed, with limited success. According to the software developer, this can only be done by altering the model radically (e.g. smoothing the channel slope). However, it should be noted that the stability problems occur only at a few locations, can be reduced by proper model calibration and have a limited effect on the overall model performance.

The ICM model appeared to be more robust than IWRS and executes its numeric calculations in a more stable way. Moreover, the calculation time is somewhat shorter in ICM than in IWRS. A simulation of 3 days with a time step of 10 s takes 135 min in ICM, while 190 min in IWRS. When performing sediment simulations, a time step of maximum 15 s is advised for IWRS and ICM.

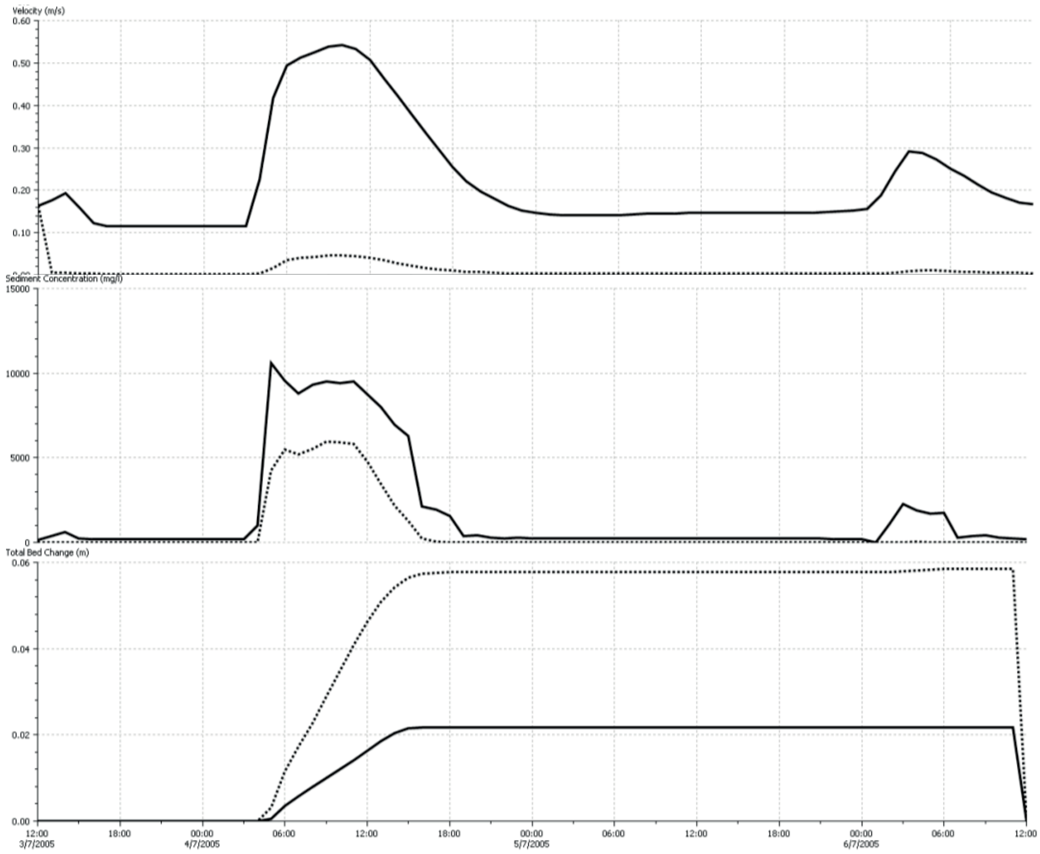

Fig. 4 Flow velocity, SSC and deposition on the Maarkebeek (downstream) during the event of 04/07/2005, without (solid line) and with upstream sediment trap (dotted line)

Additional issues

A serious shortcoming of the IWRS model was discovered when applying the "cohesive option". When this option is used, cohesive forces are taken into account. However, IWRS simulates the full cohesive forces for each sediment fraction independently of other fractions. This overestimates the erosion volumes significantly when multiple sediment fractions are applied. Applying the cohesive option has the advantage that two important parameters (critical shear stress and settling velocity) can be defined and used for model calibration, but because of the shortcoming only one sediment fraction can be modelled, which in turn makes several model options inapplicable (e.g. sorted calculation).

CONCLUSION

Concerning the SEM, the modified version of the CN model will be used in combination with WaTEM/SEDEM in order to obtain an optimal equilibrium between model complexity and data availability. Although simulated hydrographs are still prone to some errors, multiple possibilities exist to improve the modified CN model in the near future. As the SEM should be able to perform simulations for the entire Flemish region, characterized by divergent soil types and land uses, the aim is to capture the general dynamics of the different systems instead of simulating every aspect of the rainfall–runoff process as this is not feasible nor the aim of this study.

While both IWRS and ICM were found to be applicable as STM in the Maarkebeek catchment, ICM appears to have several advantages. It has no need for model adjustments related to stability and compatibility, and calculation is more stable and faster. Moreover, ICM has the interesting possibility to combine a river with a sewer network (which can act as a sediment sink, e.g. along roads next to soil erosion prone areas) and to model sediment transport in 2-D.

Furthermore, Innovyze® is still developing the sediment transport module of ICM, so that modifications are possible, whereas in IWRS no further alterations or updates are planned. Therefore, after further testing, ICM will most probably be selected as STM.

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