Numerical simulation of sewer sediments transport with SWMM by decoupled approach

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Abstract: Management of sewer solids becomes an important research due to the related hydraulic and environmental problems caused by sediment deposition and flushing. Plenty of researches have been carried out focus on water quality deterioration due to sediment erosion during rain events in certain segment of sewer conduit, but hydraulic and quality modelling of sewer network with consideration of sediment transport has not gotten enough attention. So that in scale of sewer network, sediment bed deformation and its impact to water quality caused by deposition and flushing cannot be evaluated by modelling measures. This research aims at sewer network hydraulic and quality simulation with consideration of sediment transport and proposed a novel coupling process of SWMM5 and sediment transport model (STM). With this coupling process, the sediment load concentration and hydraulic cross section deformation of conduit in the sewer network can be simulated. The proposed coupling model is tested by two study cases. The simulation results showed that this coupling model can give stable and logical simulation results. Sediment flushing and deposition cycle and its impacts to load concentration and hydraulic cross section deformation of conduits can be simulated. Comparisons between simulation results and observed data showed that with proposed coupling process load concentration simulation results fit the observed data better than simulation results without coupling process.

Keywords: Sewer sediments; Numerical simulation; SWMM; Sediment transport model

1. Introduction

Sediment transport caused by flushing and deposition of solid loads can bring many uncertain and undesired consequences to urban sewer systems, such as reduced hydraulic capacity, blockage and serious pollution to the receiving water(Ahyerre & Chebbo 2002; Tait et al. 2003; Gasperi et al., 2010). These problems become more obviously and seriously along with the development of urbanization, especially for places with combined sewer systems (Gasperi et al., 2008; Rodríguez et al., 2012). In recent decades, the management of sewer solids has become an important research subject due to the related hydraulic and environmental problems caused by sediment deposition and flushing (Banasiak & Tait, 2008; Keener et al., 2008; Schellart et al., 2010; Mannina et al., 2012; Ashley et al., 2015).

Experimental studies on sediment transport in sewer systems have been carried out in field sites and at laboratory scale (e.g. Chebbo et al., 1996; Banasiak et al., 2005; Bertrand-Krajewski et al., 2005; Dettmar & Staufer, 2005; Campisano et al., 2006), in order to figure out sediment particle characteristics, sediment accumulation and removal laws in particular cross section conduit in sewer systems. On the other hand, sewer sediment transport process also has been studied by means of modelling approaches (Ashley & Verbanck, 1996; De Sutter et al., 2000; Creaco & Bertrand, 2009; Fang et al., 2017; Hodges, 2019). Early modelling works focused more on analysis of the hydraulic propagation of flushing waves in sewer channels, with emphasis on the evaluation of the shear stress generated by various flushing devices (e.g., Campisano & Modica,2003; Shirazi et al., 2014). Recently, more studies have been carried out using more complex 1D or 2D approaches based on the coupled solution of flow and sediment transport equations for modelling the impact of the sediment flushing and deposition (Bach et al., 2014; Guyonvarch et al., 2015; Greifzu et al., 2016; Mehta et al., 2018).

Although plenty of researches have been carried out for investigation of sediment transport in sewer systems, results of these studies focus more on water quality deterioration due to sediment erosion during rain events in certain segment of sewer conduit, but hydraulic and quality modelling of sewer network with consideration of sediment transport has not gotten enough attention. So that in scale of sewer network, sediment bed deformation and its impact to water quality caused by deposition and flushing cannot be evaluated by modelling measures. Seco et al. (2018) developed a method for prediction of organic combined sewer sediment release and transport by coupling SWMM5 with sediment erosion model, so that analysis of sediment release and transport in sewer network can be performed, however, in

Seco's study only erosion effect is considered during simulation therefore sediment accumulation-flushing cycle in long term process cannot be simulated. And because SWMM5 and sediment erosion model are coupled in a splitting approach in which SWMM5 and sediment erosion model run totally separately, impact of changing of hydraulic cross section due to sediment transport is not considered in the coupling process.

In order to achieve hydraulic and quality simulation with consideration of sediment accumulation-flushing effect and its impacts to pollutant concentration and hydraulic cross section deformation of conduits, a real coupling process of SWMM5 and sediment transport model (STM) is invented. In this coupling process, the suspended load transport model of river sediment transport process was introduced for modelling bidirectional behaviour of sediment accumulation and flushing.

2. Governing Equations and Closures

One of the most commonly used numerical approach for description of sewer sediment transport is the Saint-Venant-Exner system, referred to as SWExner in the following. The Saint-Venant-Exner system (SWExner system) can be synthetically described by the following equations:

Continuity equation $$\frac{\partial A}{\partial t}+\frac{\partial Q}{\partial x}=0 \tag{1}$$

Momentum equation $$\frac{\partial Q}{\partial t}+\frac{\partial (Q^2/t)}{\partial x}=-\mathrm{gA}(\frac{\partial H}{\partial t}+\mathrm{S_f}) \tag{2}$$

Exner equation $$\rho_s(1-e)\frac{\partial A_d}{\partial t}+\frac{\partial (AC)}{\partial t}+\frac{\partial (QC)}{\partial x}=0 \tag{3}$$

Where x is flow distance, t is time, A is flow cross-sectional area, Q is flow rate, H is hydraulic head of water in the conduit, S_f is friction slope (head loss per unit length), g is acceleration of gravity, ρ_s is dry density of sediment solid phase, e is porosity of sediment layer, C is load concentration, A_d is area of sediment cross section.

The SWExner system is a system of nonlinear conservation laws with source term and also can be viewed as a coupling between 2 distinct systems in a “fluid-structure interaction” approach: on the one hand, a fluid system, the classical Saint-Venant system (1)-(2); and on the other hand, a conservation equation for the mass of sediment (3) (Audusse et al., 2018). With this coupling view of SWExner system, it allows to use classical fluid solvers coupled to an extra Exner equation solver to achieve SWExner solvers for sediment transport simulation. This solution concept has been investigated and implemented in the last decade by several authors (e.g. Cao et al., 2002; Hudson, J. & Sweby, P. K., 2003; Hudson et al.,2005; S. Cordier et al., 2011; Serrano-Pacheco, A.,2012; Audusse et al., 2013).

Although SWExner solvers mentioned above all follow the coupling concept, the implementations of solvers can be divided into two different categories: coupled and decoupled approaches. In coupled method, effects of variable bed and unsteady flow in each routing step are considered in simulation process, so that Saint-Venant system and Exner equation must be solved synchronously in each routing step. On the other side, in decoupled method the water flow is assumed to be steady and the changes in the bed update have a negligible effect on the water flow in each routing step, and with these assumptions, in each routing step the decoupled method solves Saint-Venant system firstly, and then the Exner equation is solved using the flow variables newly obtained by Saint-Venant system (Wu et al., 2004). Comprehensive comparisons about coupled and decoupled approaches have been performed by several authors (e.g. Colombini & Stocchino, 2005; Garegnani et al., 2011;). The general conclusion is that coupled approaches have better performances especially in conditions of highly variable discharge and sediment inputs so that this method can deal with most of sediment transport scenarios, but this method has drawbacks of higher computational cost and complex coupling mechanism. On the other hand, decoupled approaches can give reliable simulation results only with limitation ranges of load concentration and Froude number, because beyond these ranges, the steady flow state and steady bed assumption is no longer reasonable. Cunge et al. (1980) stated that for most physical cases, the bed moves at a considerably slower speed than the water flow. So that the wave speed of the bed updating in Exner equation can be expected considerably smaller in magnitude than the wave speeds associated with the water flow. This enables the steady assumptions to be derived, where the water flow and the bed update can be solved in decoupled approaches. Decoupled approaches have their unique advantages such as considerably easier to numerically approximate, easily to couple with existing hydraulic simulation frameworks. In addition, in some cases that the sediment transport flux cannot be written analytically and is determined by using a "black box" approach where the flux is deduced from empirical data. The decoupled approach can easily incorporate all of these sediment transport fluxes whereas the coupled approach may experience difficulties (Hudson & Sweby, 2003). With consideration of flow and sediment transport conditions in sewer network and properties of coupled and decoupled approach, the decoupled approach is used in this research as solution framework.

SWMM5 (Rossman, L.A., 2009) is a rainfall-runoff simulation model based on either a single rain event or a long-term rain series. Currently, SWMM5 is widely used in simulation, analysis, and design in areas such as urban storm runoff, drainage piping systems, catchment planning. SWMM5 is an attractive choice to be used in proposed coupling process because SWMM5 is in the public domain making it free of charge and its source code is open-source making it customizable. Therefore, in the present coupling process the SWMM5 software package was employed for solving 1D Saint-Venant equations of SWExner system. In SWMM5's hydraulic and quality routing step, spatial variation of concentration along the distance of one conduit is ignored, so that in the present work equation (3) is transformed to a simplified form as:

$$\rho_s(1-e)\frac{\partial A_d}{\partial t}+\frac{\partial (AC)}{\partial t}=0 \tag{4}$$

The STM is responsible to obtain the results of A_d and C at the end of given routing step. Since there are two unknown variables and only one equation, an extra equation should be added in order to close the STM. Here a bed deformation equation is introduced into the solution procedure:

$$\frac{\partial A_d}{\partial t} = \frac{\alpha\omega B(C - C_*)}{\rho_s(1-e)} \tag{5}$$

Where α is coefficient of saturation recovery, the meaning of α is proportion of sediment mass flushed (or deposited) accounts for sediment mass which is potential to be flushed (or deposited) and its value has no measured value can be referenced from previous study for sewer sediment mass. The only measured values can be referenced is data measured from suspended load of rivers and its values are in the scope of 0.25~1.0 (Zhang, 1998). ω is sedimentation velocity of sediment particles, value of ω has a strong relationship with sediment particle diameter d_s, in this paper relationship between ω and d_s is referenced of conclusion obtained by Chen N. (1997), B is width of hydraulic cross section in which deposition and erosion happens, C_* is sediment carrying capacity, here the equation proposed by Zhang (1998) is used for calculation of C_*:

$$C_* = k\left(\frac{U^3}{gR\omega}\right)^m \tag{6}$$

Where U is mean velocity of cross section; k and m are parameters which values are determined by value of $\frac{U^3}{gR\omega}$, in this paper relationships between values of k, m and value of $\frac{U^3}{gR\omega}$ follow the relationships that concluded by Zhang R. (1989).

3. Coupling of SWMM and STM

The decoupled concept mentioned in section 2 is used to implement the coupling process between SWMM5 and STM.

3.1 Coupling process

With decoupled concept, SWMM5 is responsible to obtain hydraulic and quality variables' values such as Q, H, U and C at the beginning of each coupling step. Subsequently, the STM will be solved by using the results obtained from SWMM5 routing step. Since decoupled concept is used, water flow in conduit is assumed as steady flow in each routing step, so hydraulic results obtained from SWMM5 will remain unchanged and used as initial conditions for STM. But variable C is different from hydraulic variables, the results of C from SWMM5 routing step will be used as initial conditions for STM, and it will also be updated together with A_d after STM routing step evolved.

Generally the decoupled method can be summarized as steps listed below:

Step1. SWMM5 evolved one routing step: values of Q, H, U and C are obtained.

Step2. Preparation of STM's routing step: ω, R, B obtained and then k, m are obtained according value of $\frac{U^3}{gR\omega}$, and at last the value of C_* is obtained.

Step3. Joint solution of equations (4) and (5): A_d and C are updated.

Step4. Validation and correction process: A_d and C are validated and corrected.

Step5: Update of hydraulic cross section of conduits: conduits hydraulic cross section is updated according value of A_d. The updated parameter values of Q, H and U (updated in step1) and C (updated in step3) will be used for next routing step. If continue go to step 1.

At the beginning of simulation, besides initialization of SWMM5 options there are some parameters involved in STM should be initialized, such as α, ρ_s, d_s, and these parameters can be used as calibrated parameters in calibration process to achieve parameter localization. In the proposed coupling process, the parameter C is represented by the concentration of a pollutant created in SWMM5, for example, we can create and appoint total suspended solid (TSS) used as parameter C in the coupling process. And then concentration of TSS will be updated both in the SWMM5 and STM in the coupling process.

3.2 Conduit hydraulic cross section updating

In **step5** hydraulic cross section of conduit will be updated after A_d updated, but in SWMM5 there is no cross section type whose geometry parameters can be modified during simulation process. So in the coupling process, a new mechanism for updating conduit cross section is introduced into SWMM5. In this mechanism, the cross section type “filled circular” is used and its function has been expanded in order to update its cross section parameters during simulation process. For “filled circular” there is a property called filled depth which can represent the depth of sediment bed at bottom of conduit. However Filled depth is a static parameter in simulation process, so it cannot be modified during simulation. In order to achieve cross section updating, a new function which is responsible for updating filled depth and other derived parameters will be added and called at the end of each coupling step. The updating process in the added function can be summarized as 3 steps:

i) Calculation of sediment depth according sediment area A_d;

ii) Update filled depth and filled area of cross section, and recalculate width and wetted perimeter of filled area.

iii) Update inlet offset and outlet offset of conduit according sediment depth.

3.3 Numerical stability

In the decoupled approaches, the 1D Saint-Venant equations and the sediment bed-updating equation are numerically approximated sequentially in an overall time step. And the coupling process can be divided into 2 stages as fixed sediment bed stage and varied sediment bed stage. In the fixed sediment bed stage, 1D Saint-Venant equations are iterated to an equilibrium state in the condition of all conduit cross section parameters kept fixed. And in the varied sediment bed stage, sediment mass conservation equation is solved and conduit cross section parameters are updated in the condition of hydraulic variables fixed.

The arbitrary changing of conduit cross section in the varied sediment bed stage may bring numerical instability and continuity error to 1D Saint-Venant equations solutions. The Severity of numerical instability and continuity error depends on the magnitude of conduit cross section changing and time step length. And time step length is the fundamental factor because magnitude of conduit cross section changing is also controlled by it. So the time-step control is the key point for obtain a stable and low continuity error simulation.

In the coupling process, the Courant-Friedrichs-Lewy (CFL) criterion is applied in SWMM5 to achieve numerical stability in SWMM5 simulation. Because SWMM5 is the main model in the coupling process and STM is embedded into SWMM5, so the time-step of coupling process is also controlled by CFL criterion. However CFL criterion is only responsible for numerical stability of hydraulic simulation but not for numerical stability of STM. Sometimes, step length obtained by CFL criterion can lead to over deposition or over flushing in STM and further lead to large magnitude of cross section changing and bring numerical instability or high continuity error to coupling process. The most natural solution for this problem is to calculate appropriate step lengths respectively for both SWMM5 and STM and pick the short one as the time step for coupling process. But this concept has several drawbacks such as STM and coupling process will become more complex, and step count of whole simulation will become larger. A better solution for this problem is that the time step obtained by CFL criterion of SWMM5 are still used as time step for the coupling process and some modification is implemented to STM to adapt to SWMM5 time step.

The fundamental reason of over deposition and over flushing in STM is because that extremely large time step obtained from CFL criterion may cause calculated pollutant concentration (C) lower (in the case of deposition) or higher (in the case of flushing) than carrying capacity (C_*) of conduit flow and leads to unstable and illogical results. In fact in a routing step when load concentration meets the carrying capacity of conduit flow, the deposition and flushing of conduit sediment achieve a balance and load concentration will remain unchanged in the rest of time for the given time step. So a validation and correction process (step4 mentioned in section3.1) should be added to make sure that the calculated C is not violate the limitation of carrying capacity of conduit flow. The concept of this validation of correction process is that if calculated C is not violate carrying capacity of conduit flow, the calculated C and A_d will be accepted as simulation results, otherwise, the load concentration C will be assigned the value of C_*, and A_d will be recalculated by formula (4). The flow chart of this validation and correction process is shown in Fig. 1.

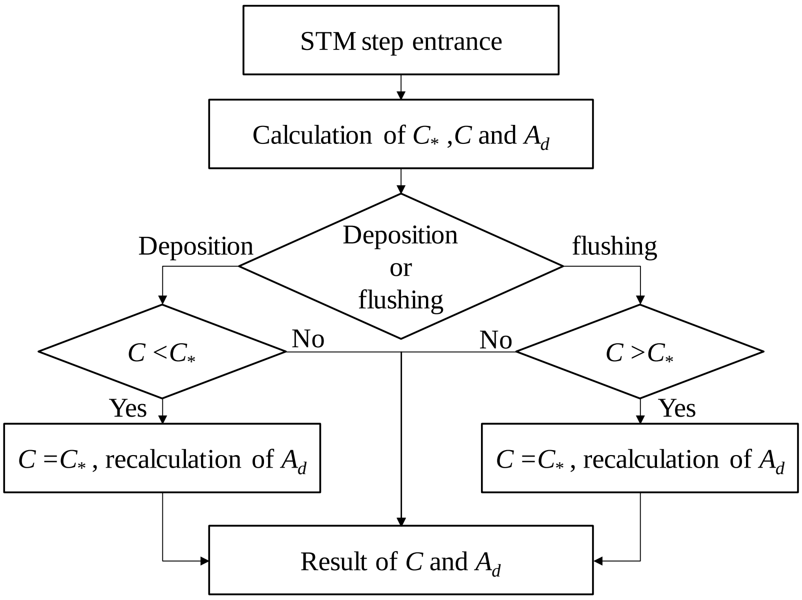


Fig. 1 flow chart of validation and correction process of STM

In fact the validation and correction process proposed above is not perfect and high continuity error will also appear in some extreme cases. For example, if sediment load is much higher than carrying capacity of conduit flow meanwhile the sediment load is very easy to settle (e.g. with high value of coefficient of saturation recovery). In such cases, although time step is controlled by CFL criterion and implementations mentioned above is used for STM, there still has opportunity lead to high continuity error. But this kind of situations often appears in bed load transport of river bed. So the proposed time-step control method can deal with most situations happened in sewer systems. And in extreme cases, shortening time step can be the ultimate method for elimination of the continuity error. More numerical tests and analysis about numerical stability and continuity error will be discussed in section 5.

Generally, SWMM5 is used as the framework in the coupling process, and STM is embedded into SWMM5. The hydrology, hydraulics and quality process are totally implemented by original code of SWMM5. And the overall time step is controlled by SWMM5. The STM is added at the end of each SWMM5 routing step and the load concentration and conduit cross section are updated in the STM. The flow chart of proposed coupling process is illustrated by Fig. 2.

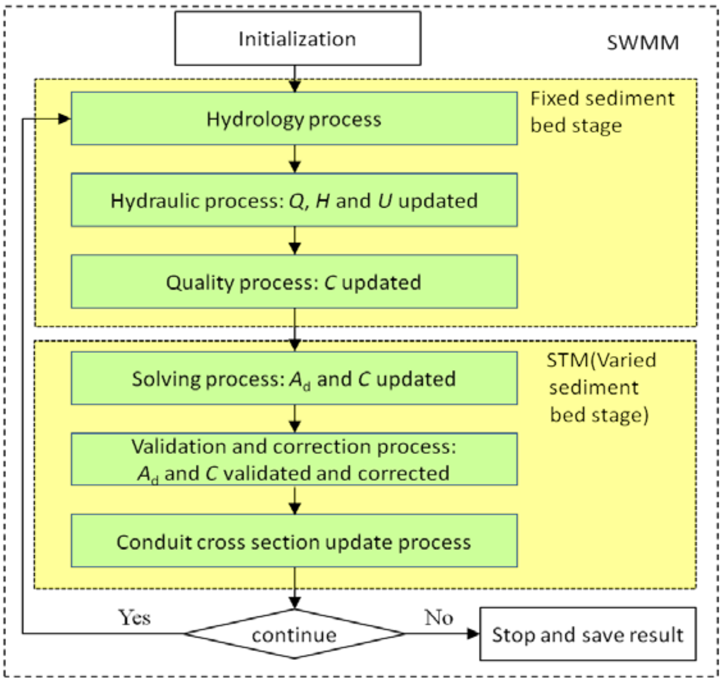


Fig. 2 flow chart of the coupling process between of SWMM5 and STM

4. Case study

The proposed coupling method is tested by two study cases. One is a fictitious and simple sewer network. This study case is used for testing the simulation stability and flow, mass conservation during coupling process. The skeleton of the fictitious and simple network is shown in Fig. 3. And basic information of features in the network is shown in Table 1.

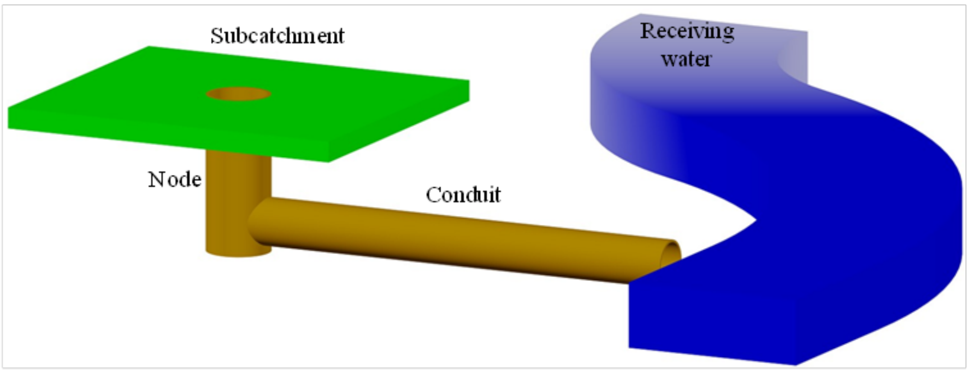


Fig. 3 skeleton of the fictitious and simple network

Table 1 Basic information of features in the fictitious and simple network

Feature type	Property	Value	Feature type	Property	Value
Subcatchment	Area/ha	10	Dry weather inflow	Flow rate/L/s	10
	Width/m	200		TSS concentration/mg/L	200
	%imperv	60	Land use	Build up function type	POWER
Junction	Max depth/m	13		Max build up	15
	Invert elevation/m	31		Build up rate constant	1
Outfall	Invert elevation/m	0		Build up power constant	1

	Type	Normal	Wash off function type	EXP
Conduit	Length/m	200	Wash off coefficient	0.1
	Diameter/m	0.6	Wash off exponent	2
	%Slope	0.5		

The second study case is a combined sewer network which is situated in the city of Hefei that located in middle-east of China. Flow rates, load concentration in conduits and rainfall intensity were collected during storm events at dates of 2011/6/24, 2011/7/12, 2011/7/17, and 2011/7/26. The obtained field data is used to validate the proposed modelling work. The SWMM network of second study case is shown in Fig. 4.

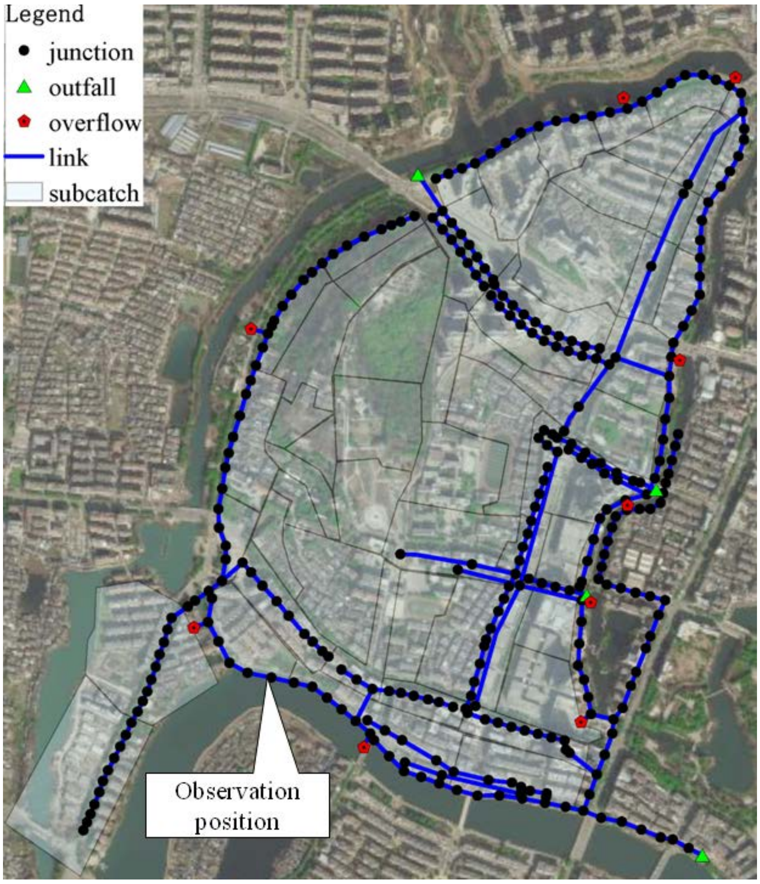


Fig. 4 combined sewer network of study case 2

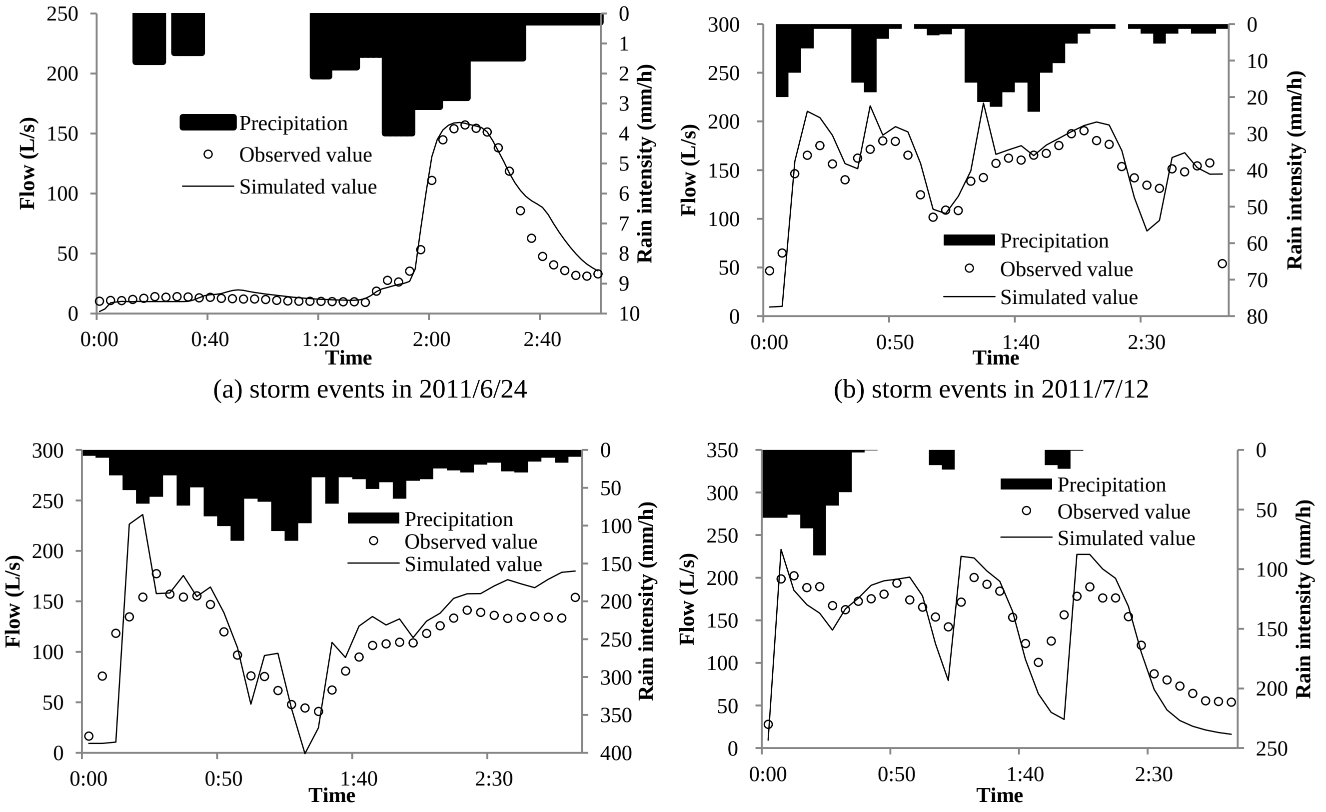
Basic information of features in the combined sewer network of study case 2 is shown in Table 2.

Table 2 Basic information of features in the combined sewer network of study case 2

Feature type	Property	Value
Subcatchment	Total area/ha	118
Junction	amount	300
Overflow well	amount	12
Outfall	amount	1
Conduit	Total length/km	12.15
Dry weather inflow	Flow rate/L/s	118
	TSS concentration/mg/L	200

	Build up type	Initial build up
	Initial build up	15
Land use	Wash off function type	EXP
	Wash off coefficient	0.1
	Wash off exponent	2

Before implementation of coupling simulation of SWMM5 and STM, the hydraulic simulation result of SWMM5 has been validated. For second study case, the hydraulic simulation results of SWMM5 can meet an acceptable level after calibration. The calibrated simulation results of 4 storm events are shown and compared with observed data in Fig. 5.



(a) storm events in 2011/6/24
(b) storm events in 2011/7/12
(c) storm events in 2011/7/17
(d) storm events in 2011/7/26

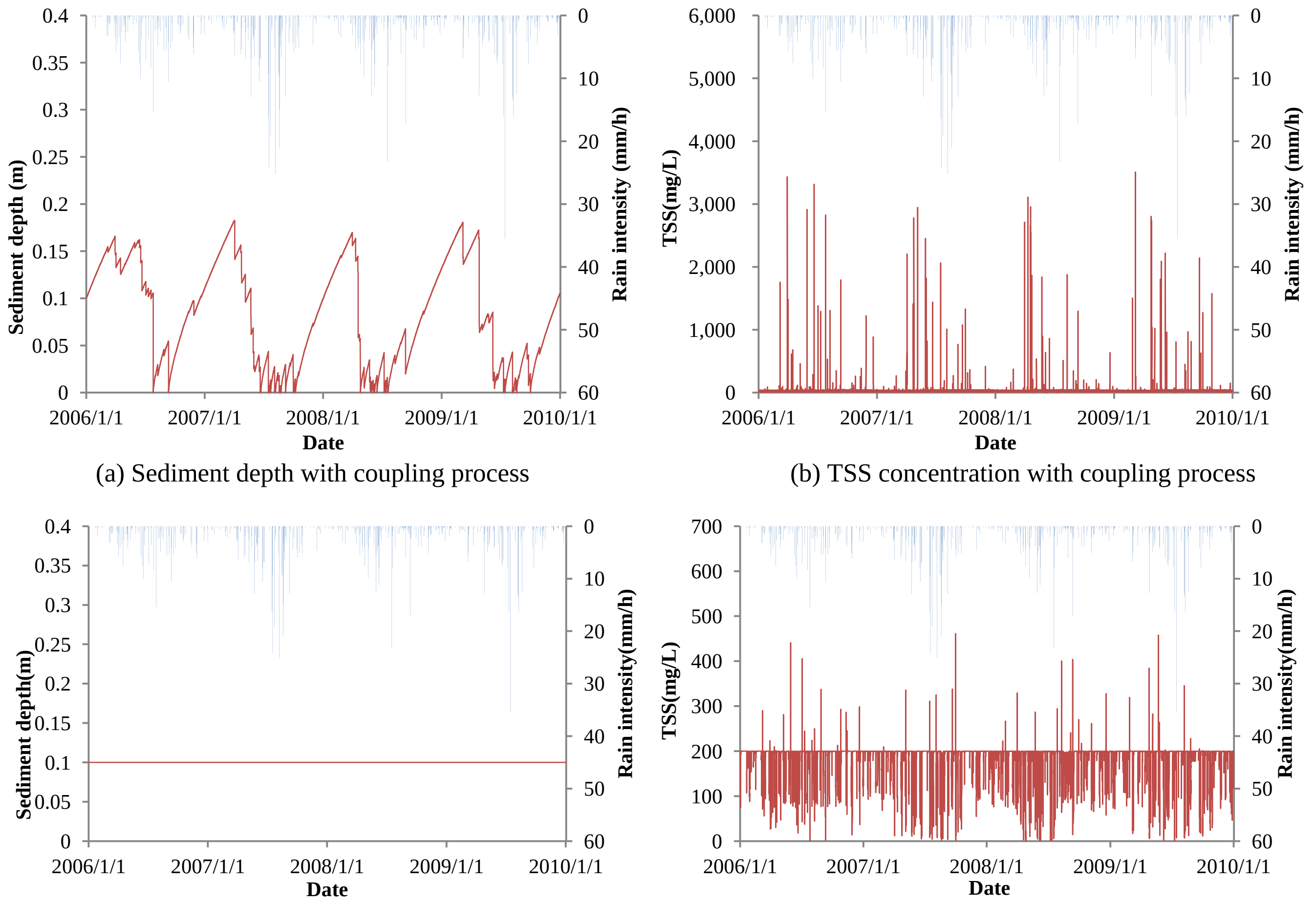
Fig. 5 calibrated result of SWMM hydraulic simulation of study case 2

5. Results and discussion

In order to simulate the sediment flushing and deposition cycle happened in combined sewer network, a long term simulation is implemented with a 4 year precipitation record for fictitious and simple sewer network. And simulation results of sediment depth, TSS concentration and mass continuity error are illustrated and discussed in the following sections. For the second study case, the simulation result of TSS concentration will be validated by observed data collected at study site. And comparison of simulation results with and without consideration of sediment transport will be shown and discussed.

5.1 Fictitious and simple network simulation results

The simulation results of sediment depth and TSS concentration are shown in Fig. 6. As a comparison the simulation results without coupling process are also illustrated in Fig. 6.



(a) Sediment depth with coupling process

(b) TSS concentration with coupling process

(c) Sediment depth without coupling process

(d) TSS concentration without coupling process

Fig. 6 comparison of simulation results with and without coupling process

Sub figure (a) of Fig. 6 shows that the proposed method can simulate the variation of sediment depth caused by deposition and flushing of sediment mass in conduit. Comparison between sub figures (b) and (d) shows that with and without coupling process, the load concentration results showed significant differences. With consideration of sediment transport, in dry weather periods sediment particles deposit in conduit bottom and load concentration maintains in a lower level. In wet weather, sediment mass is flushed and load concentration increased obviously, and its fluctuation range is much higher than simulation result without consideration of sediment transport.

A 6 hours wet weather simulation result is extracted from the 4 year simulation to illustrate the mass error during coupling simulation. The simulation result is recorded with time step of 5 minutes, and in each time step the inlet TSS (M_{inlet}), outlet TSS (M_{outlet}) and deposition or flushed TSS (M_{df}) of sediment mass is recorded. In ideal condition there should have a balance between inlet, outlet and deposition or flushing which can expressed as: $M_{inlet} – M_{df} = M_{outlet}$. Fig. 7 shows the mass continuity error in the 6 hours simulation.

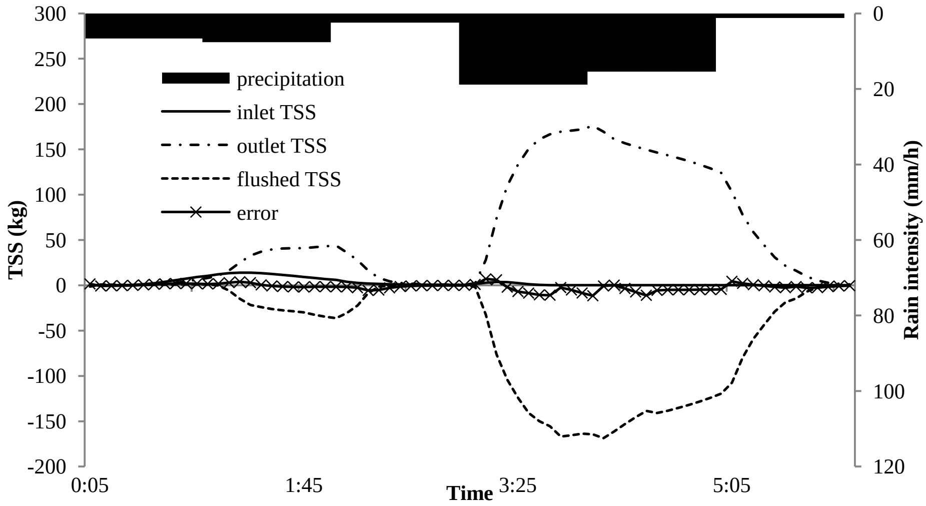


Fig. 7 Time evolution of mass error

It can be seen from Fig. 7 that mass continuity error is stable and stays in a low level. And the final error of the whole 4 year simulation is 1.828%. This indicates that the assumptions of steady flow and steady sediment bed of decoupled concept are acceptable in coupling process of SWMM5 and STM. The flow rate fluctuation and hydraulic cross section changing rate are in the ranges that make the steady flow and fixed bed assumptions reasonable. Even in heavy storm events, the water and mass error is still small and acceptable. It also can be seen from Fig. 7 that in the conduit with sediment mass, most of pollutant mass outlet from it is not pollutant mass introduced by surface runoff, but flushed sediment mass in conduit. And this simulation result is consistent with phenomena observed in combined sewage network that heavy pollution to the receiving water not only happened in initial surface runoff but also in overflowed runoff.

The analysis above can only prove that the proposed coupling method can meet continuity error criterion in the common situations. How it works in the extreme situations need more validations. In the subsequent tests, the load concentration of dry weather flow is enhanced to an extremely high level of 5000mg/L, and coefficient of saturation recovery for deposition and flushing (*α*) and time step (⊿*t*) are assigned with values of different levels. Values of *α* are 0.01, 0.025, 0.05, 0.1, 0.25, 0.5 and 1. Values of ⊿*t* are 0.5s, 1s, 2s, 5s, 10s, 30s and 60s. So there are 49 combinations of *α* and ⊿*t*. Models of each *α* and ⊿*t* combination are simulated and the flow continuity error and quality continuity error are recorded and shown by Fig. 8.

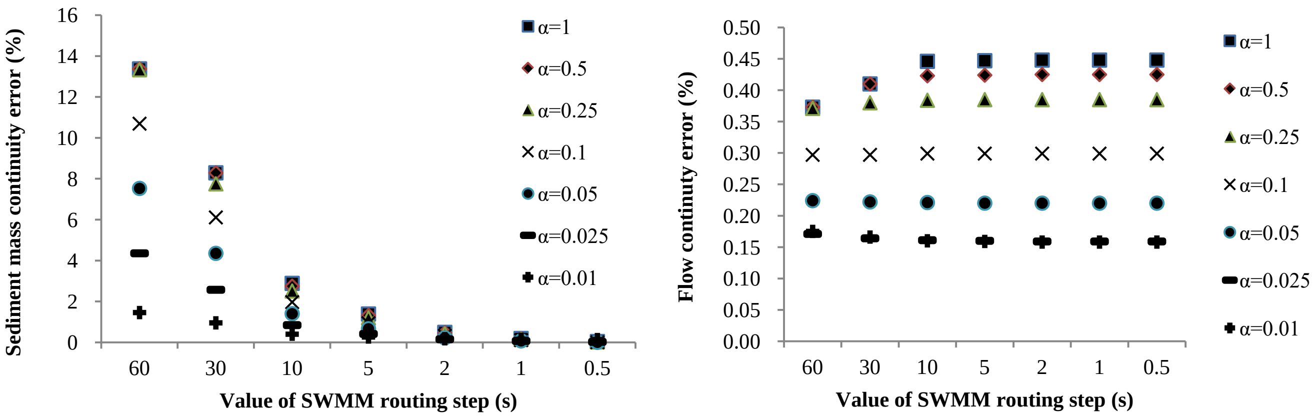


Fig. 8 Time evolution of flow and mass error

It can be seen from Fig. 8 that in all combinations flow continuity errors are smaller than 0.5%. Variation of ⊿*t* almost has no impact to flow continuity error, and variation of *α* has slightly impact to flow continuity error. Although the flow continuity errors are small, it can find out that continuity error has an obvious trend with *α* that continuity errors increased when *α* become higher. This indicates that in the decoupled approach sequentially solving of SWMM5 and STM will introduce flow continuity error to the simulation process and the magnitude of error has an obvious relationship with conduit cross section changing rate (*α* impact sediment deposition and flushing rating directly and then impact conduit cross section changing rate). Because Δt has no impact to conduit cross section changing rate, so it seems that flow continuity error changes very slightly with Δt. Since Δt is controlled by CFL criterion and make sure that hydraulic calculation is stable, so that in the time step controlled by CFL criterion the magnitude of cross section changing is generally small, so the effect introduced by the arbitrary changing of conduit cross section is slightly, so that the flow continuity error in the coupling process is also guaranteed to be small.

But for sediment mass continuity error, α and Δt both have obvious impact to continuity error. Although special modification has been implemented to STM to adapt to SWMM5 time step, there are still large mass continuity error in simulation process in the case of high α and large Δt. In the most extreme case among all combinations (Δt =60s, α=1) the mass continuity error is higher than 13%. Because CFL criterion is only responsible to numerical stability of hydraulic simulation (in SWMM5 it is common that quality error is higher than flow routing error), long time step will lead to large mass continuity error in condition of high mass concentration formed by particles that very easily to deposit. The fundamental reason of this obvious mass continuity error is that quality routing process in SWMM5 will bring mass continuity error and this error will be inherited and magnified in the finite difference solving process of STM. And the most effective method for reduce continuity error caused by finite difference algorithm is shortening the length of time step, and this is validated by Fig. 8. From left sub figure, it can be seen that when time step become smaller the mass continuity error declined rapidly. In condition of time step less than 10s the mass continuity error is less than 4% no matter what value of α is.

5.2 The combined sewer network simulation results

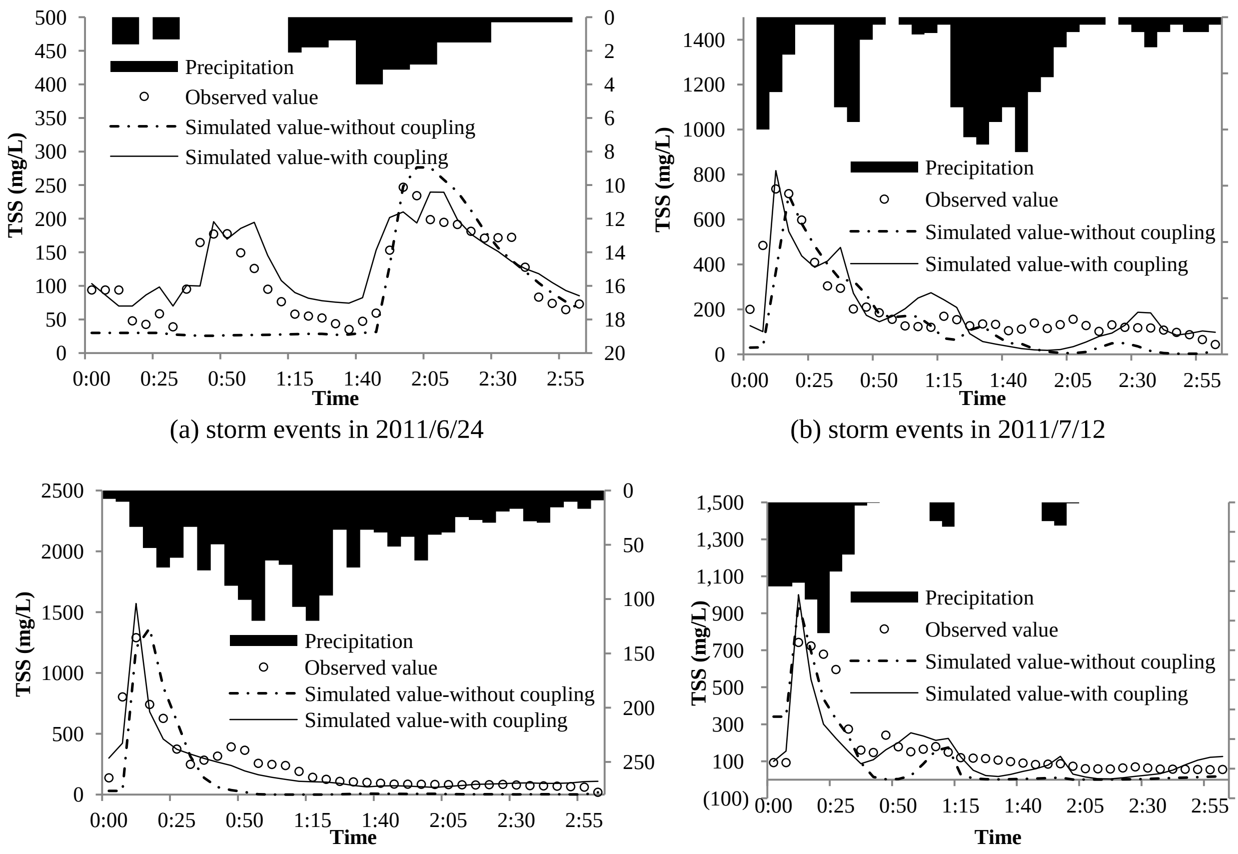
In order to achieve best simulation results both in conditions with and without consideration of sediment transportation, models with and without coupling process are calibrated separately. Calibrated values of these parameters are listed in Table 3. The TSS initial build up of SWMM5 and sediment depth ratio of STM are calibrated separately for each storm event. And a universal value set of other parameter values are used for all storm events. The values of d_s, ρ_s and e in STM are referenced from values obtained by sampling and testing of sewer conduit sediment mass. The calibrated values of α in the present work are much smaller than values obtained from field test of suspended load of rivers. The possible reason of this difference is that characteristics of sediment mass in sewer conduit have a significant difference from suspended load of rivers. Sediment mass in sewer conduit has higher viscosity and colloidal properties so that it is more difficult to be flushed or deposited than suspended load of rivers.

Table 3 Calibrated values of parameters in SWMM5 and STM with and without coupling process

Model	parameter	storm event	without coupling	with coupling
SWMM5	initial build up (*kg/ha*)	2011/6/24	15	2
		2011/7/12	20	2
		2011/7/17	25	2
		2011/7/26	15	2
STM	sediment depth ratio	2011/6/24	/	0.001
		2011/7/12	/	0.008
		2011/7/17	/	0.003
		2011/7/26	/	0.01
	d_s(*mm*)	/	/	0.23
	ρ_s(kg/m^3)	/	/	2000
	e	/	/	0.67
	α in flushing process	/	/	0.01
	α in deposit process	/	/	0.0075

The comparison of simulation results with and without coupling process is shown by Fig. 9. Generally, simulation results with consideration of sediment transportation meet observed data better. The problem of simulations without consideration of sediment transportation is that the load concentration decreased rapidly after surface initial build up have been washed off. And this problem caused by two main reasons, firstly pollutant input from surface runoff reduced to nearly zero after initial runoff finished and secondly flow rate increased to several times than flow rate in initial rainfall period. With consideration of sediment transportation simulation results after initial rainfall period got improved because pollutant mass flushed from sediment mass at bottom of conduit make pollutant concentration remains in a reasonable scope, this improvement can be illustrated obviously by comparison of simulation results of storm events at 2011/7/12, 2011/7/17 and 2011/7/26.

For storm event of 2011/6/24 the simulation result with consideration of sediment transportation got a significant improvement than simulation result without consideration of sediment transportation. Simulation results obtained without coupling process can’t simulate the two peaks curve of TSS concentration that the observed data shows. That is because with very small rainfall intensity the wash-off function can’t bring enough pollutant mass into initial surface runoff to form the first peak of pollutant concentration. But flow rate in conduits is different from surface runoff that the flow rate in conduits will be accumulated from upstream links to downstream links, so that at downstream links the flow rate is significant large than dry weather flow and the sediment mass at conduit bottom has been flushed and the first TSS concentration peak shows.



(a) storm events in 2011/6/24

(b) storm events in 2011/7/12

(c) storm events in 2011/7/17

(d) storm events in 2011/7/26

Fig. 9 Comparison of simulation results with and without coupling process

But for the 4 storm events, the observed load concentrations after initial rainfall period are still decreased, it seems that sediment flushing didn’t bring much sediment mass into conduit water flow. The reason of this phenomenon is that the observed storm events happened in wet season and sediment mass at conduit bottom has been flushed several times by previous rains before observation. So there was few sediment mass can be flushed for observed storm events.

In order to quantify the simulation accuracy and continuity error in both simulations with and without coupling process Nash-Sutcliffe efficiency (NSE), flow continuity error and sediment mass continuity error are shown in Table 4.

Table 4 Numerical accuracy evaluation of simulation results for each storm event.

storm event	NSE		Flow continuity error (%)		Sediment mass continuity error (%)	
	without coupling	with coupling	without coupling	with coupling	without coupling	with coupling
2011/6/24	0.0011	0.6436	3.153	6.673	3.076	5.604
2011/7/12	0.4420	0.5961	1.484	1.924	5.856	6.802
2011/7/17	0.2459	0.8346	0.082	0.100	2.554	2.257
2011/7/26	0.5807	0.6218	4.433	5.370	0.192	2.969

From Table 4, it can be seen that simulation results with coupling process have higher NSE values and located in an acceptable level. For continuity errors, the simulation results with coupling process are a little higher than errors of simulation results without coupling process, but the quantity of errors with coupling process is still small and acceptable. Generally the simulation results comparison shows that with consideration of sediment deposition and flushing, the coupling model can describe the flow and mass transportation in sewer system more precisely.

6. Conclusions

A novel coupling process between SWMM5 and STM is proposed in the simulation of sediment transport in the sewer networks. In the coupling process two assumptions of steady flow and steady sediment bed in each routing step are introduced so that the decoupled concept can be employed when the coupling model are solved. With this proposed coupling process, the mass concentration of each link in the sewer network can be simulated with the consideration of sediment flushing and deposition, and the hydraulic cross section of each link can be updated in the simulation process with consideration of sediment transport.

In the proposed coupling process, a numerical stable simulation mechanism is invented. In this mechanism the routing step length for coupling process is controlled by SWMM5 and simulation result of STM will be validated and corrected by mass carry capability of flow rate in each conduit, therefore over flushing and deposition of sediment mass in simulation process is eliminated and more stable and logical simulation results obtained.

In order to update hydraulic cross section of conduit in the coupling process, some extra functions are coded and implemented to the conduit cross section object to achieve cross section updating. In the present work only “filled circular” shape type is available for coupling process and conduit with other shape type cannot be involved in the coupling process. In this paper, because all conduits in the study cases are in shape of circular so that the coupling process can be implemented well. In the future, more cross section types will be implemented in the coupling process.

The proposed coupling model of sewer sediments transport is applied to two study cases. The simulation results showed that this coupling model can give stable and logical simulation results. Long term sediment flushing and deposition cycle and its impacts to load concentration and hydraulic cross section deformation of conduits can be simulated. In the coupling model, the continuity errors of water flow and sediment mass are maintained in a low and acceptable level. Comparisons of simulation results and observed data showed that with the proposed coupling model and solving process, the simulation results of pollutant concentration fit with the observed data better than simulation results without coupling process.

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Conflict of interest statement

Conflict of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Informed consent: Informed consent was obtained from all individual participants included in the study.

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