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APPLICATION OF SEDIMENT TRANSPORT MODELS IN A SEWER NETWORK

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Abstract

Several sediment transport models have already been developed for closed sewer pipes. The existing models are based on different theoretical and empirical equations and parameters. The application of transport models are determined by the local conditions and data demand. We introduce some applicable existing transport models. Different models were applied for the same selected urban area. Our experiences during application of a hydrodynamic simulation software (Mike Urban) and also the results and recommendations were presented.

KeyWords: transport; sewer network; suspended load; bed load; Mike Urban; hydrodynamics

Introduction

Sedimentation in sewer networks means operational problems for the service providers. The amount of sediment to be removed and the hydraulic capacity reduction of the sedimented pipes have direct cost effects. Calculation of sediment transport by different hydrodynamic models can be used for estimation of the current and future state of the sewer network. The effects of the extension or reconstruction of the sewer network can be predicted by sediment transport models.

Sediment problems in sewers

All the particles can be defined as sediment that are moving in storm water or sanitary sewage. These materials are moving by the flow forces. In case of appropriate conditions, the flowing sediment can settle at the bottom of pipes and structures [1].

Three main source of problems can be determined [1]:

- decrease of hydraulic capacity
- blockage of sewer pipes
- deposition of pollution materials

In case of hydraulic capacity decrease and at its final state (blockages) the sewer system is overloaded, even surface flood events are possible, combined sewer overflows operation are more frequent. The deposition of pollution can result in more pollution load at combined sewer overflows, flush load at wastewater treatment plants and corrosion of the pipes. The deposit accumulating in structures operated in wastewater system can also decrease their efficiency [5]

Materials and Methods

Study area

The study area was selected from a large urban network, Budapest in Hungary. The whole sewer network is operated by one service provider Fovarosi Csatornazasi Muvek Zrt (FCSM), all the network data were provided by FCSM in the frame of a master thesis [6]. The study area is relatively plain part of the city (Figure 1). The catchment area size is about 10ha, the length of the network is 1228m. The pipe diameters are Ø30-40 cm circular and 40/60 egg shape, the pipe material is concrete and vitrified clay. The network part is operating as a combined system.

Mike Urban DHI [3] is one of the most popular hydrodynamic simulation software in Europe for urban storm water networks. Compared to the concurrent hydrodynamic simulation programs its sediment transport capabilities makes it unique. Several sediment transport models are embedded as pollution transport [2]. The most appropriate model can be selected for the certain sediment simulation task. The user can set the theoretical and empirical parameters of the selected model for each model. The models can calculate all the possible morphological changes (settling, erosion, dunes). The effects of dune formation and adhesion can be also included in the precise calculation of sediment. However, the program documentation is giving only slight support for the selection of the appropriate sediment model and its parameters. The built-in sediment models can be used only with additional knowledge acquisition about the model backgrounds. The Mike Urban software was developed as a GIS strongly connected to ESRI ArcGIS [4].

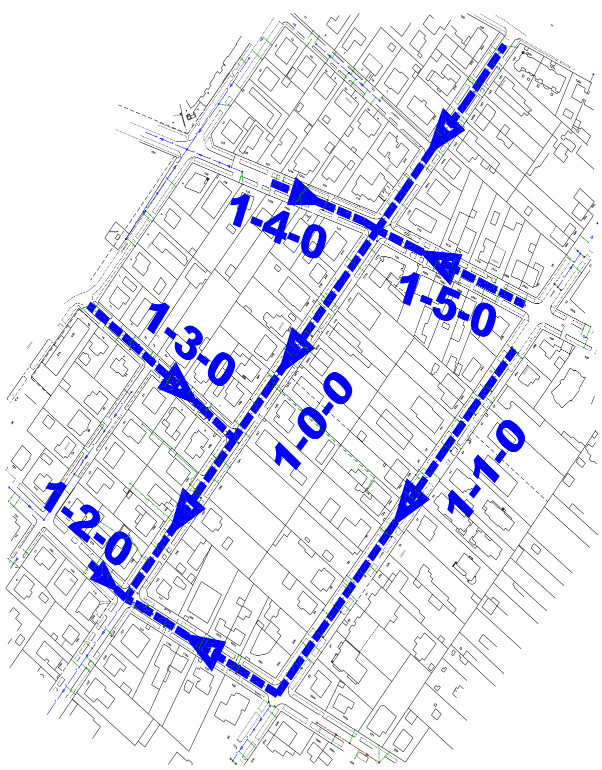

Figure 1: Plain study area with sewer network

Methods

The general classification of sediment transport is including 3 types:

- wash load
- bed load
- suspended load

The transportation type of certain particles are depending on the particle size and the hydraulic conditions. The same particles can be transported as bed load or suspended load changing in time or location.

The wash load is including quite small sized particles suspended evenly in the water. This part is not settling or eroding but moving continuously. Generally, advection-dispersion models are used for its transport.

The bed load is transported by rolling, sliding, jumping but mainly connected to the bottom.

The suspended load means the particles that are moving together the water by its turbulent forces. The vertical distribution of the sediment can be described by the falling velocity and the upward diffusion.

In MOUSE 4 different models are available for sediment transport:

- Ackers-White model
- Engelund-Hansen model
- Engelund-Fredsøe model
- van Rijn model

The Ackers-White and the Engelund-Hansen models are calculating the total sediment transport while the Engelund-Fredsøe and the van Rijn models are calculating separately the suspended load and the bed load. Engelund-Fredsøe and the van Rijn models can calculate with the hydraulic effect of the morphologic changes due to the sedimentation. All types of calculation can be appropriate depending on the local conditions.

2.1.1 The Ackers-White model

The Ackers-White model is based on both empirical experiences and physical equations. The coarse sediment transport is assumed as mainly bed load. The main form of the sediment transport is expressed as a dimensionless general transport parameter:

$$G_{gr} = \frac{X \cdot Y}{s \cdot d}\left(\frac{U_f}{U}\right)^n$$

where:

X: volumetric concentration of sediment transport as a mass flux per unit mass flow rate

Y: water depth

U_f: friction velocity

n: model constant, depending on D_{gr}, in the range 0-1 (coarse to fine material)

s: relative density of the sediment

d: grain size

U: flow velocity

The general transport parameter can be expressed as a function of the general mobility parameter F_{fg} and the dimensionless grain parameter D_{gr}:

$$G_{gr} = C\left(\frac{F_{gr}}{A} - 1\right)^{m}$$

where C, m and A model parameters are depending on D_{gr}.

D_{gr} can be expressed:

$$D_{gr} = d\left[\frac{g(s-1)}{v^{2}}\right]^{\frac{1}{3}}$$

where

v: kinematic viscosity

F_{gr}: general sediment mobility parameter:

$$F_{gr} = \frac{U_f^{n}}{\sqrt{gd(s-1)}} \cdot \left(\frac{U}{\sqrt{32}\log\left(\frac{10Y}{d}\right)}\right)^{1-n}$$

Ackers and White gave different n, A, C, M constant parameters for fine (D_{gr}<1), coarse (D_{gr}>60) and transient grains (1< D_{gr}<60). The sediment transport can be calculated from model parameters and physical parameters D_{gr}, U_f, velocity and water depth.

The Engelund-Hansen model

In the Engelund-Hansen model is derived on the work done by water flow on the sediment. The formula can be used for plain bed or in case of bed forms. The total dimensionless sediment transport is:

$$\Phi = \frac{0,1}{f} \cdot \theta^{\frac{5}{2}}$$

and

$$\Phi = \frac{q_t}{\sqrt{(s-1)gd^{3}}}$$

where:

θ: total dimensionless bed shear stress

f: friction factor, defined as $2U_f^2/U^2$, where U_f and U are the friction velocity and current velocity

q_t: total bed material transport per unit width

The bed shear stress and also the dimensionless bed shear stress can be divided into two parts: shear stress caused by the skin friction on the upstream surface of the dunes and the shear stress caused the form drag of the dunes: $\theta = \theta' + \theta''$

In case of plain bed: $\theta = \theta'$

The observation results for the relation between θ and θ' were used in MOUSE sediment transport model.

The Engelund-Fredsøe model

The bed load in the Engelund-Fredsøe model is assuming that for moderate bed shear stress values all of the bed shear stress exceeding the critical value is transferred to the bed through drag forces on the moving bed load particles.

$$\Phi_b = \left[1 + \left(\frac{\pi/6\beta}{\theta' - \theta_c}\right)^4\right]^{\frac{1}{4}} \left(\sqrt{\theta'} - \sqrt{1/2}\sqrt{\theta_c}\right)$$

where:

β: dynamic friction coefficient = 0.65

θ': dimensionless skin friction

θ_c: the critical dimensionless bed shear stress

The suspended load can be calculated as the integral of the current velocity u(y) and the concentration of the suspended sediment c(y):

$$q_s = \int_a^h c\,u\,dy$$

where:

a: thickness of the bed layer = $2*d_{50}$, where d_{50} is the mean grain diameter

The current velocity at a distance of y above the bed level has a logarithmic profile:

$$u = 2.5U_f' \ln\left(\frac{30y}{k_s}\right)$$

where

U_f: boundary layer thickness

k_s: equivalent sand roughness=2.5d_{50}

The concentration is calculated from the concentration at the bed and the settling velocity of the suspended material.

The integral of the suspended load can not be expressed in an analytical form therefore should be calculated numerically.

The van Rijn model

The van Rijn model is separated into bed load transport and suspended load transport. The bed load motion is forced by the gravity. The bed load transport is calculated from the saltation height and velocity of the particle and the concentration of the bed load:

$$q_b = \sqrt{(s-1)\cdot g\cdot D_{50}^3}\cdot 0{,}053\cdot \frac{T^{2,1}}{D_*^{0,3}}$$

where

D*: dimensionless particle diameter

The dimensionless transport stage parameter T is defined:

$$T = \frac{(u'_*)^2 - (u_{*,cr})^2}{(u_{*,cr})^2}$$

where

u_*’: bed shear stress

u*,cr: critical bed shear stress by Shields [7]

The critical bed shear stress can be calculated from:

$$\theta_{cr} = \frac{u_{*,cr}^2}{(s-1)\cdot g\cdot D_{50}}$$

where

θ_c: the critical dimensionless bed shear stress is read as a function of D_* from the Shields-curve (Figure 2)

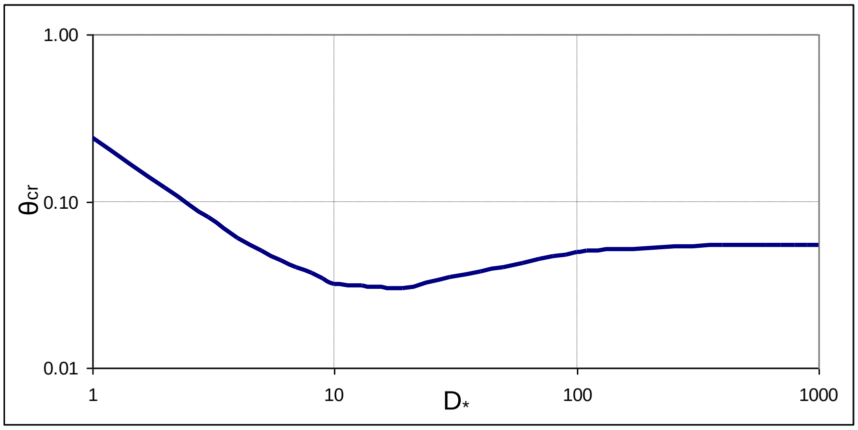

Figure 2: Shields curve for particle diameter vs. critical bed shear stress

The suspended load transport is calculated if the bed shear velocity is more than the fall velocity. The suspended load is integrating the flow velocity and concentration in the depth. The suspended load transport is using the bed load as reference concentration.

$$q_s = \int_a^Y c\,u\,dy$$

approximated as:

$$q_s = F\,u\,Y\,c_a$$

where F is given as:

$$F = \frac{\left[\frac{a}{D}\right]^{Z'} - \left[\frac{a}{D}\right]^{1.2}}{\left[1 - \frac{a}{D}\right]^{Z'}\left[1.2 - Z'\right]}$$

where

a: level of reference concentration, as the level below which all sediment is considered to be transported as bed load

Z: the influence of the upward turbulent fluid forces and the downward gravitational forces

RESULTS

The total study area was divided into 78 subcatchments. The surface runoff was defined mainly from public areas (road, pavement, and a narrow green lane). Only 5% of the private areas was defined as impervious area. The rain event was 180 minutes long with 94mm summed precipitation height. Dry weather flow was also added as base flow. The sediment load consisted from 4 fractions according to the site measurements (Table 1):

Grain size (mm)	Fraction size (%)	Concentration (mg/l)
0.8-1.25	6	0,26
0.2-0.8	64	1,37
0.1-0.2	29	0,41
<0.1	1	0,01
total	100	2,05

Table 1: Sediment load fractions

All the fractions were calculated by the DHI MOUSE Sediment Transport (ST) and the Advection-Dispersion (AD) part was not used because of the negligible size of the fine fraction.

We had to face with several software problems, probably all concerned with the available early version of Mike Urban. Only 3 from the available sediment models could be run.

- Ackers-White model
- Engelund-Hansen model
- van Rijn model

The sediment load could be given 3 different way:

- as surface pollution, washing off from the surface by the surface runoff
- as part of point-source inflows at manholes
- as existing sediment on the bottom of the pipes

The first load mode was not working in this software version, therefore we could use only the other three methods.

The first results were achieved by giving sediment load as pollution content of the dry weather (DWF) base load (Figure 3).

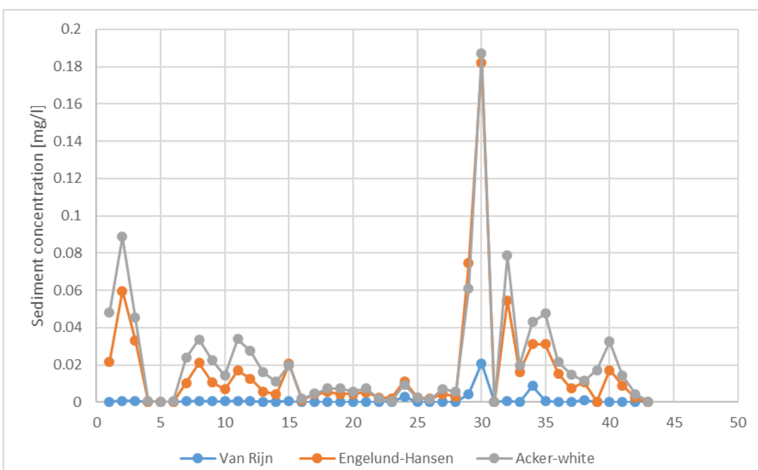

Figure 3: Total sediment transport, sediment load given with DWF

The sediment concentrations are shown for each conduit section. On the subsequent figures the conduit sections are in the same order but named (Figure 1). The Engelund-Hansen and the Acker-White models were producing similar results. The van Rijn model was giving relatively small concentrations because the bed load transport was calculated separately.

We have carried out severeal sensitivity aanlyis for the model parameters like porosity and relative density of sediment and its organic ratio, critical bed shear stress and manning friction. Most of them were showing slight sensitivity, like the critical bed shear stress (Figure 4).

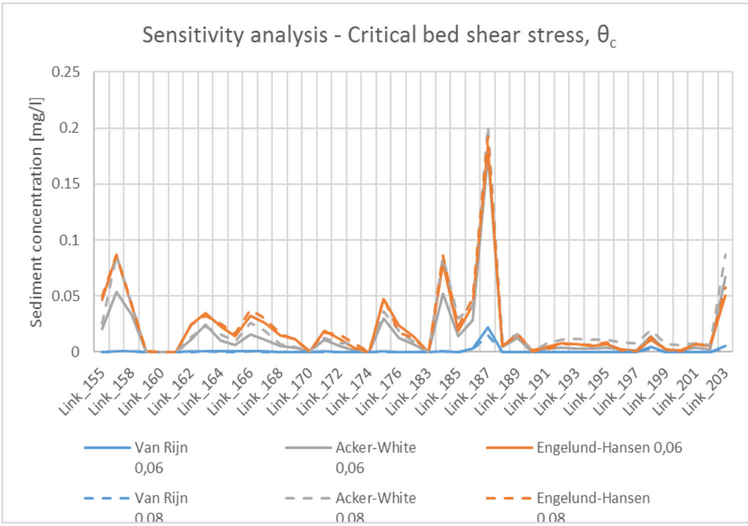

Figure 4: Sensitivity analysis for critical bed shear stress, θ_c

We were also giving sediment load as pollution content of the surface runoff loads (Figure 5). The sediment load accumulated on the surface could be washed off automatically by the rain event, but in the program version that was not working. Therefore we set 60% of the sediment to be washed off in the first 40% time of the rain event. The rest of the sediment was washing off until the end of the rain event.

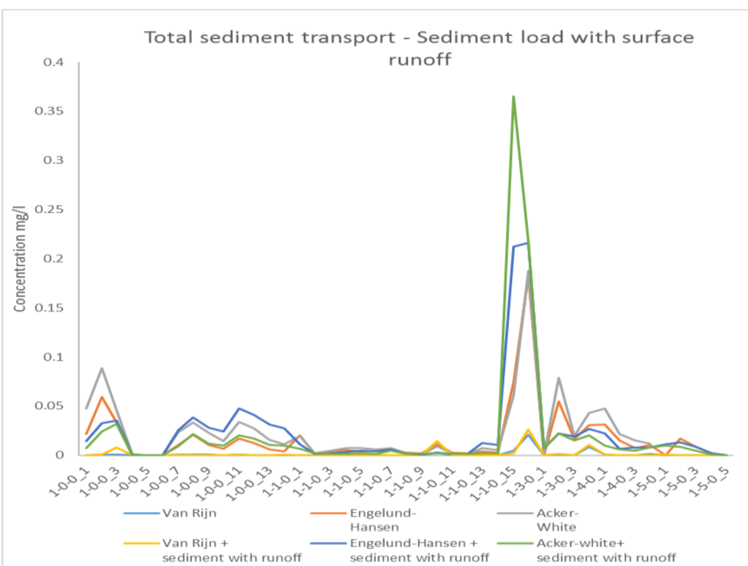

Figure 5: Total sediment transport, sediment load given with surface runoff

We could also try the effect of the previously sedimented material at the bottom of the pipe (Figure 6) in case of 2 models. This means a quite realistic situation. The sediment transport is increasing where the erosion occurs in the network, but the sediment is settling at farther sections, meaning system problems.

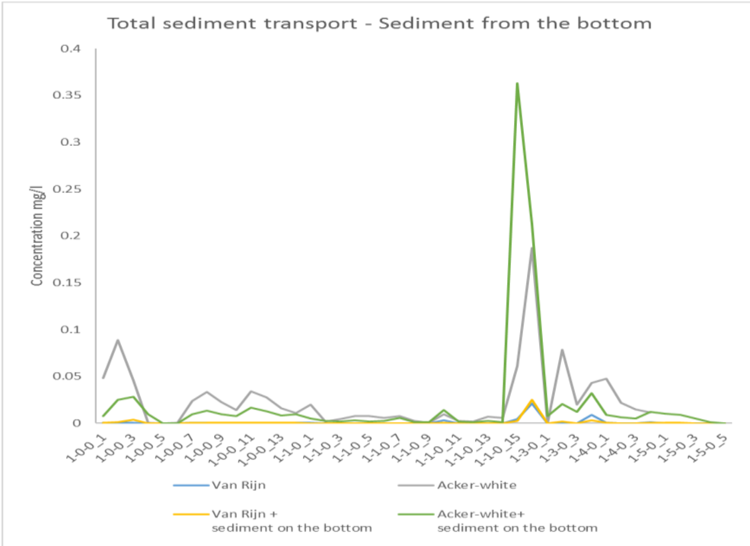

Figure 6: Total sediment transport, sediment load given by sediment erosion from the bottom

We also analysed the effect of reconstruction as diameter, slope, material change at the high sedimentation pipe section. Increasing the slope right up to the critical pipe sections the sediment transport increased because of settling and sudden erosion (Figure 7).

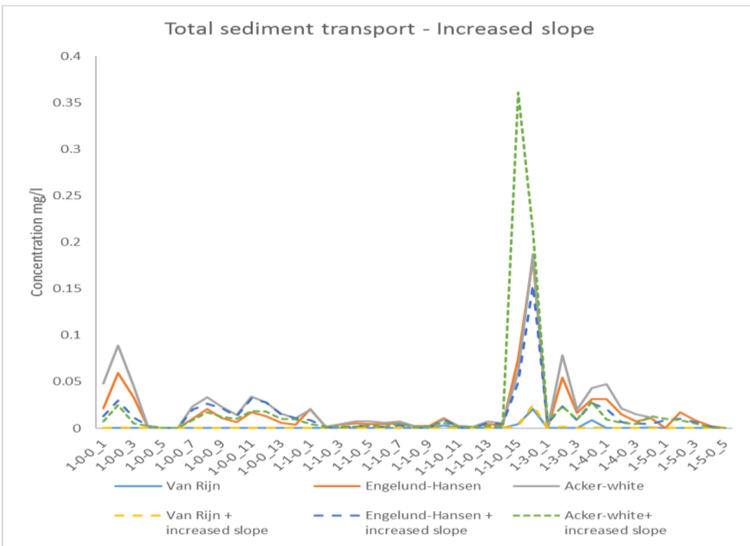

Figure 7: Total sediment transport with increased slopes

Building a sediment trap right up to the critical pipe section, the sediment transport eliminated down to this point (Figure 8).

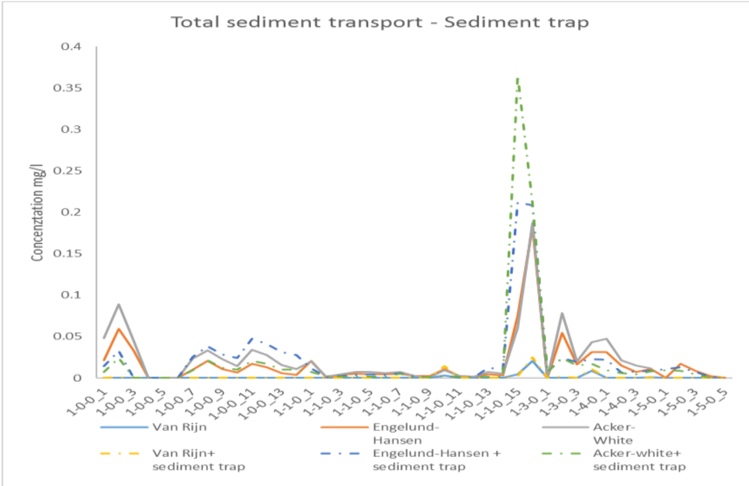

Figure 8: Total sediment transport with sediment trap

DISCUSSION

Sediment transport calculations carried out for the study area are showing the critical role of data acquisition. Especially sediment load estimation can be critical in case of scarce of measurements. The subcatchment data are also including uncertainty.

In the study area on the upper part of the network the sediment transport was quite small because of the minor slopes. The reconstruction of these pipe sections (like inner lining) or building sediment traps can solve the problems, but the effects should be checked previously by model calculations.

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Author Profile

Dr. Marcell Knolmar was graduated at the Budapest University of Technology as civil engineer and has been working for the same university at the Department of Sanitary and Environmental Engineering as researcher and teacher. He has significant results on the fields of computer aided sewer design, geographical information system of sewer networks and designing of rain monitor device. He certificated his PhD degree in the field of the computer aided sewer design. His current research scope is the hydraulic modelling of sewer networks, specially the sediment transport of sewer networks.

Attila Nemeth was graduated as Bsc at Eotvos Jozsef Foiskola, Baja, then at the Budapest University of Technology as MSc civil engineer. Spent a semester at Karlruhe Institut fur Technologie by Erasmus stipendium. Presently working as civil engineer for Viziterv Environ Ltd. in Hungary.