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Computational Aspects of River Hydraulics.

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Summary

Research of river systems is expanding enormously. Therefore, the amount of needed measurements is also increasing rapidly. To limit this effort, computer modelling is an interesting tool. The environment 'Femme' ('a flexible environment for mathematically modelling the environment') is used to model ecological processes as the transport of nutrients and polluents. Here, the hydraulic part, which is incorporated and based on the Saint-Venant equations, is used to check the influence of river roughness (expressed by the Manning coefficient) on discharges and water levels.

It is shown that the Manning coefficient of a specific river is influenced by the discharge and the amount of vegetation in the river. The variation of biomass over the year includes also a seasonal variation of the Manning coefficient. Next to good numerical approximation of the physical processes in rivers by good calibration, three sensitivity analysis are carried out.

First, the influence of the discharge on the water level is checked and in general, discharges are more sensitive to variations then water levels and are preferred as upstream boundary condition. Second, the influence of discharge and Manning coefficient on celerity and dispersion of waves is studied. Celerity and dispersion are larger when Manning coefficient or discharge is increasing. Third, it is shown that higher Manning coefficients can cause larger back watereffects and can consequently cause flood problems.

As a conclusion, the calibration of the Manning coefficient in any numerical model is indicated at very important to come to accurate results and realistic simulation of the hydraulic characteristics of the river.

KEYWORDS: ecosystem modelling, Manning coefficient, flood routing, vegetated rivers.

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1. INTRODUCTION

Numerical modelling is an important discipline in the study of river hydraulics. Next to measurements, this branch of computer engineering is giving plenty of information regarding to water management. Measurement of velocities, discharges and water levels is fundamental in data collection of the river system, but in longer terms, predictions of inundations are required and numerical models are introduced in this science.

A large database is the first step in the study of river systems, it allows to get feeling with the field and to set up a model. Furthermore, the model can be calibrated and validated, using the dataset.

2. STUDY AREA

Focus of the study is the downstream part of the river Aa (Fig. 1), this is the stretch between weir 3 and weir 4, a distance of 1.4 km, near the village of Poederlee. In this area the interaction between groundwater, surface water and vegetation will be studied. Regular measurements of discharge and water level allow to gather data to calibrate the model. The catchment basin of the river Aa is situated in the region of Antwerp and is hydrographical part of the Nete basin. More than 40 % of the water in the Nete basin is going to the river Aa, which is although an important river. The river Aa flows into in the Kleine Nete near the city of Grobbendonk. The origin of the river Aa is found near the communities of Merksplas and Turnhout and is streaming through Turnhout, Gierle, Gielen, Poederlee and Vorselaar. The river Aa has a total length of 36.8 km and the drainage area is about 23,700 ha.

Hydraulic data as water levels and discharges are necessary, but also topographical data of the river bed and banks has to be collected. While carrying out velocity measurements in the river, the water depth and consequently, the bottom profile is registered. However, this is not sufficient to collect a useful topographical data set. Therefore, the study area of the river Aa is monitored in more detail. The stretch covers 1.4 km and every 50 m, a section is surveyed. So a set of 30 sections is available containing detailed information on the different cross sections and the bottom slope of the river. The cross sections are irregular due to the meandering aspect of the river. The average bottom slope (from upstream to downstream) is 0.0002 m/m. The monitoring results date from 1997.

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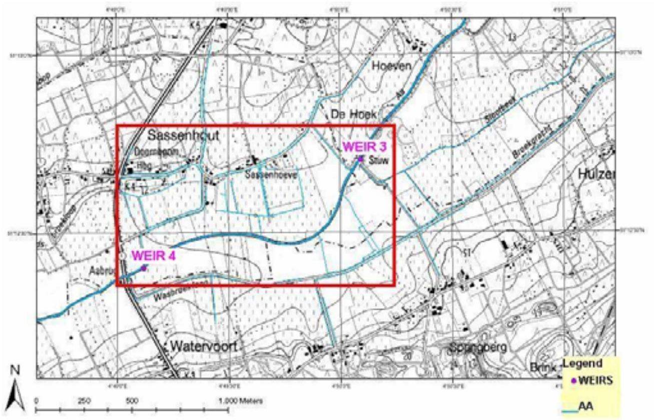

Figure 1: The river Aa

2. MODEL CALIBRATION

2.1 Equations and Manning Coefficient

Using a numerical model to describe the river processes asks for model calibration. The measured discharges and water levels are used for the calculation of the roughness coefficient of the stretch, making use of the Bresse equation and the Manning equation. In general, hydraulic models for surface flow are based on the Saint-Venant equations for one dimensional unsteady open channel flow (Chow et al. 1988). These equations (continuity equation and momentum equation) are the one dimensional simplification of the Navier Stokes equations, which describe water flow in three dimensions. Starting from the values of the discharge and the water levels, the Saint-Venant equations allow for the calibration of the roughness of the bottom expressed by the roughness coefficient or friction factor.

Here, this roughness is represented by the Manning coefficient n and is calculated from the energy slope. For steady flow, the momentum equation is known as the Bresse equation (Eq. 1). In steady state conditions and assuming uniform flow, the energy slope is equal to the bottom slope and discharge, water levels and Manning coefficient are linked directly by Manning’s equation (Chow et al. 1988). The roughness coefficient is determined out of the measurements. Channel flow is also connected with the hydraulic and geometric characteristics of the channel.

$$\frac{dh}{ds} = \frac{S_0 - S_f}{\sqrt{(1 - S_0^2)} - \frac{Q^2 B}{g A^3}} \qquad (1)$$

$$S_f = \frac{f P Q^2}{8 g A^3} \qquad (2)$$

The Manning coefficient n is easily linked to the Bresse equation and the expression for the energy slope S_f (Eq. 2) by the roughness coefficient of Darcy-Weisbach f (Eq.3):

$$f[-] = \frac{8 g n^2}{R^{1/3}} \qquad (3)$$

$$n\left[m^{-1/3} s\right] = \frac{S_f^{1/2} R^{2/3}}{U} = \frac{S_f^{1/2} A^{5/3}}{Q P^{2/3}} \qquad (4)$$

with Q = discharge [m^3/s], U = average velocity [m/s], A = wetted cross section [m2], B = channel width [m], P = wetted perimeter [m], R = hydraulic radius [m], g = gravity [m/s^2], S_f = energy slope [m/m], S_0 = bottom slope [m/m], h [m] = water height, s [m] = distance along the channel, n = Manning coefficient [$m^{-1/3}s$] and f = roughness coefficient of Darcy-Weisbach [-].

Although, the Manning coefficient can be used as calibration parameter. This roughness coefficient includes factors as the bed material and average grain size, the surface irregularities of the channel, channel bed forms, erosion and depositional characteristics, meandering tendencies, channel obstruction, geometry changes between channel sections and vegetation along the bankline in the channel (Dyhouse et al., 2003). The variable vegetational influence over the year is studied in the following.

2.2 Manning coefficient

So, the Manning coefficient is determined as more than only a calibration parameter, it is linked to the physical processes in the river.

The Manning coefficient can be seen as a constant value, which is a good and easy choice for the modeling of one short event (e.g. the simulation of discharge and water levels over a couple hours). Although, this is already doubtful due to the relation between discharge and Manning coefficient. So, a constant Manning coefficient is an accurate value for baseflow simulations.

Longer events and peak flows have to be simulated using a variable Manning coefficient. The relation between Manning coefficient, discharge and biomass is plotted in Figure 2 and Figure 3 (De Doncker et al., 2007). In the following, it is shown that the Manning coefficient is an important parameter which has to be determined as accurate as possible to avoid wrong estimations and calculations of discharge and water level.

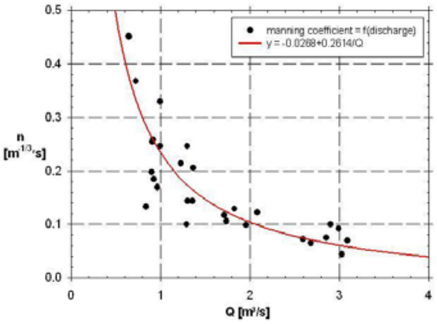

Figure 1: Correlation between discharge and Manning coefficient in the river Aa from September 04 to May 07.

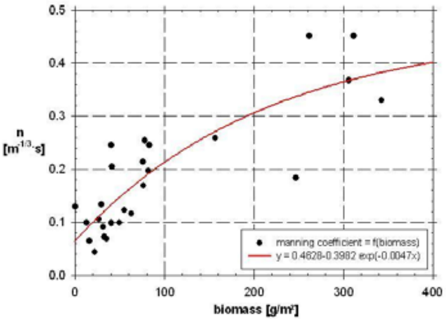

Figure 3: Calculated Manning coefficient and measured biomass in the period from September 04 to March 06 in the river Aa

The relation proposed in Fig. 3 is a good approximation of the measured values but Fig. 5 indicates next to the exponential also a sigmoidal approximation.

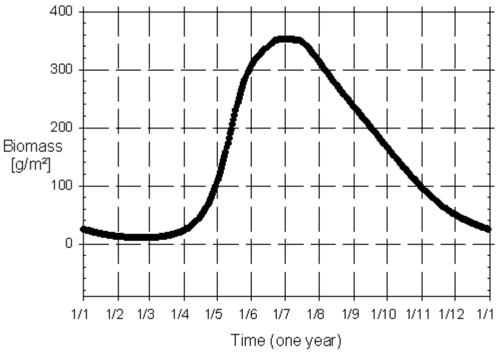

Figure 4: Variation of the amount of biomass over the year

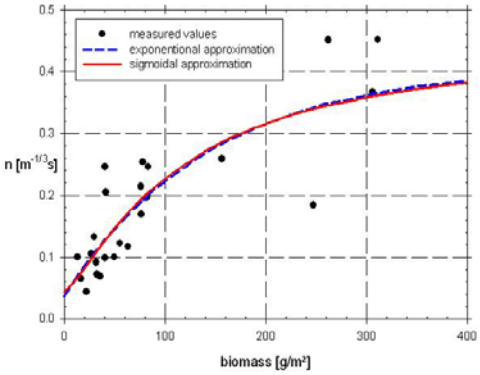

Figure 5: Correlation between biomass and Manning coefficient in the river Aa from September 04 to May 07 (exponentional and sigmoidal correlation)

The Manning coefficient is calculated using Eq. 4 and the measured data. A numerical curve is fit on these values. Different possibilities are tested. Here, it was clear that not only the mathematical accurateness is important, but also the physical interpretation. A well known relation is the exponential one (Fig. 3), the trend gives the most accurate correspondence between the continuous numerical curve and the values calculated out of the measurement. A sigmoid curve however, allows to follow the physical processes. First of all, no numerical instabilities occur, due to the fluent curve, while for the exponential trend the Manning coefficient for very low and very high amount of biomass is set on a fixed constant value and build in the model with a switch function.

Further, it can be seen that for low biomass, the Manning coefficient is determined by other characteristics as the river bed, the hydraulic characteristics, etc. Then, the resistance is increasing with increasing amount of vegetation. And, for very high values of the biomass, macrophytes are gathered in a patch and obstruction of the flow decreases again.

3. MODEL SENSITIVITY

3.1 Introduction

’Femme’ or ’a flexible environment for mathematically modelling the environment’ is developed by NIOO (Netherlands Institute of Ecology) (Soetaert et al. (2004)). ‘Femme’ is a modelling environment for the development and application of ecological time dependent processes by use of numerical integration in the time of differential equations. The program is written in Fortran.

‘Femme’ consists of a wide range of numerical calculations and model manipulations (as integration functions, forcing functions, linking to observed data, calibration possibilities, etc.). These technical possibilities allow the user to focus on the scientific part of the model and detailed research of the model without the confrontation with real program linked problems.

‘Femme’ is focused on ecosystem modelling, is open source (no black box) and exists of a modular hierarchical structure (implementation of different models next to each other). What was missing up till now was the implementation of a hydrodynamic surface water model to couple ecology and surface water in each timestep. For the study of the interaction of ecological processes and flow in the river, a realistic modelling of the surface water flow is necessary. Here, the implementation of a one dimensional hydrodynamic model for surface water flow in ‘Femme’ is reported.

With this ‘Femme’ model, some calculations are carried out. As a first verification of the model, a stretch of a river is modelled. The wave, measured upstream, has a given hydrograph Q(t). The hydrograph is derived from a gamma function. The resulting hydrograph at the downstream boundary is calculated next to the water levels over the stretch. The total length of the channel is 5000 m. The channel is rectangular, has a bottom width of 12 m and a bottom level of 8.89 m.

3.2 Influence of discharge on water level

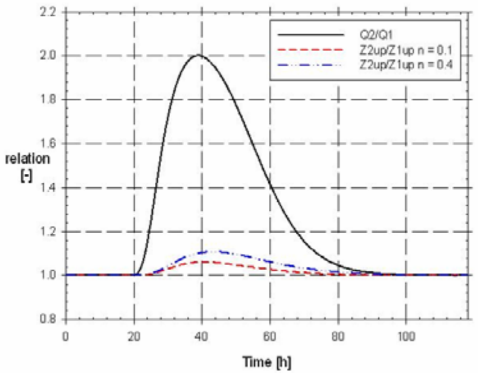

Figure 6: Influence of discharge on water level

In Fig. 6 the impact of the discharge on the water level is checked if the discharge increases. Two different hydrographs are chosen, $Q_1(t)$ and $Q_2(t)$. The relation between the basic hydrograph $Q_1(t)$ and the increased discharge $Q_2(t)$ is plotted and shows a peak value of 2. The impact on the water level, however, is much smaller and varies with varying Manning coefficient. For $n = 0.1\ m^{-1/3}s$, the relation is 1.06, while for $n = 0.4\ m^{-1/3}s$, the relation is 1.10. The impact on the water level is higher for a higher Manning coefficient. In general, discharges are much more sensitive to changes then water levels and therefore, upstream hydrograph values are preferred above water levels as a boundary condition.

3.3 Influence of discharge and Manning coefficient on celerity and dispersion of waves

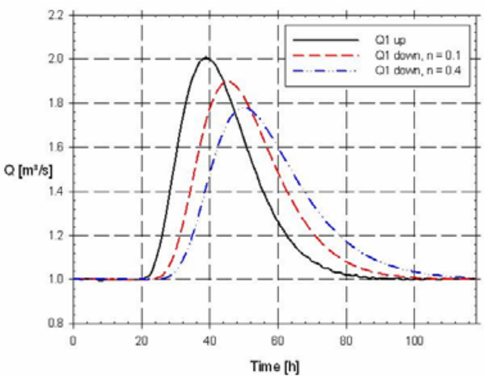

Figure 7: Influence of discharge Q1(t) and Manning coefficient on celerity and dispersion of waves

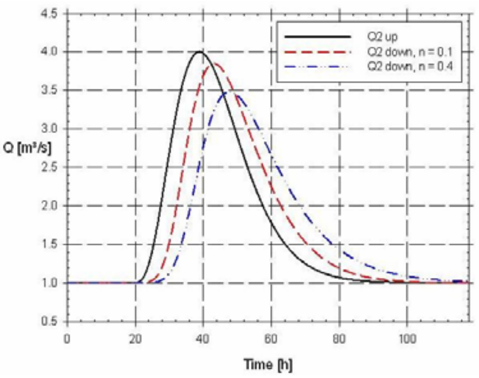

Figure 8: Influence of discharge Q2(t) and Manning coefficient on celerity and dispersion of waves

Figure 7 and Figure 8 show results for different hydrographs $Q_1(t)$ and $Q_2(t)$ with relation as mentioned in Fig. 6. The upstream hydrograph is a fixed boundary condition and the downstream discharge values are mentioned for comparison (Table 1). For both values of the discharge, it seems that the wave celerity (velocity by which a disturbance travels along the flow path) and the dispersion (tendency of the disturbance to disperse longitudinally if it travels downstream) (Chow, 1959) is larger for higher Manning coefficients (higher roughness). Furthermore, the wave celerity is larger when the discharge increases. This is according the continuity equation, agrees with larger celerities in streams with larger water levels (Verhoeven, 2006) and corresponds with the larger backwater effect for larger roughness coefficients. Not only the larger dispersion is an effect of the larger Manning coefficient but also the slower decrease of the wave is due to the higher resistance.

Table 1. Comparison of celerity and dispersion for different discharge and Manning coefficient

	Qup	Qdown (n = 0.1)	Qdown (n = 0.4)
Q1	2	1.898 m	1.779 m
Q2	4	3.844 m	3.481 m
Q1	0	6 h	4 h
Q2	0	11 h	9 h

3.4 Influence of discharge and Manning coefficient on water levels

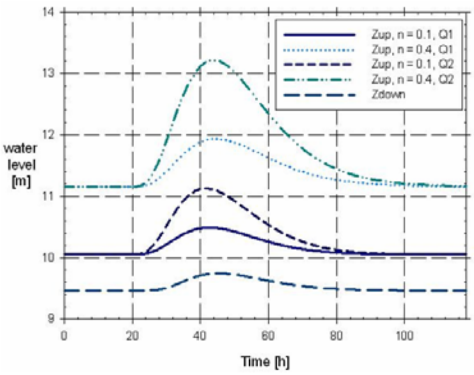

Figure 9: Influence of discharge and Manning coefficient on water levels

Fig. 9 depicts the back water effect which is higher for higher Manning coefficients and higher. It can be seen that peak flows (higher discharge) in summer situations (more vegetation and although higher resistance described by a higher Manning coefficient) can cause dangerous situations. When the height of the dikes is rather low, inundations will occur.

4. CONCLUSIONS

The importance of numerical modeling is well known. River research is based on data collection, but predictions and studies of inundations and floods ask for hydraulic software. The Femme environment allows modelling of ecological processes. It is shown that the hydraulic model can come up with quick and accurate results. Attention is paid to the importance of the Manning coefficient. This parameter is used as a calibration coefficient, taking into account the physical properties of the river processes.

Acknowledgements

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