HYDRAULIC MODELLING OF RIVER FLOW - DATA COLLECTION AND PROBLEM SOLVING

R. Verhoeven[1], R. Banasiak[1]
T. Okruszko[2], D. Świątek[2], J. Chormański[2], P. Nowakowski[2], I. Kardel[2], M. Stelmaszczyk[2]

Abstract: The discrepancy between the theoretical solution of the Saint-Venant equations for flood routing calculations and the problems encountered during practical implementation is often quite big. This paper tries to give an overview of the different bottle necks and the possibilities to cover the gap between theory and practice.
After a brief overview of the equations used for steady and unsteady flow simulation, collection of topographical and hydraulic data is discussed. Follows some practical considerations on the processing of input data on cross-sections, longitudinal profile and friction coefficient. Finally the impact of different approaches on the quality of the numerical simulation is illustrated by some practical examples.

Keywords: numerical simulation, river flow, data processing, data collection

INTRODUCTION

Engineers are supposed to be able to analyse, understand and solve problems. Mathematics is the basic tool that is used to reach this goal. A deterministic approach with exact translation of a natural phenomenon into a formula is the most comfortable situation to encounter. The hydrostatic law, describing the variation of pressure as a function of water depth is a typical example. However as soon as motion starts, an exact deterministic representation becomes impossible, mainly due to the fact that the physics of friction cannot be translated into exact formula. This means that in these cases a solution needs to be found in a stochastic representation, making use of observations leading to empirical formula. In these formula coefficients fill the gaps in theory. It is also obvious that the definition of the natural boundaries in between which a phenomenon is researched is subjected to

[1] Hydraulics Laboratory, Ghent University, Belgium
[2] Dept. of hydraulic engineering and environmental recultivation, Warsaw Agricultural University, SGGW, Poland

simplification. The prismatic river bed which is normally used in numerical simulations of river flow is only a poor average of the real topography. Moreover the complexity of 3 dimensions in nature is reduced to 2 or even 1 dimension. In what follows, an overview is given from the differences between theory and practice when dealing with modelling of river flow. Possible solutions how to tackle the encountered problems are discussed.

OPEN CHANNEL FLOW MODELLING

Suppositions

When modelling open channel flow the river bed is supposed to be prismatic. The discrete information on cross-sections in a certain river reach is averaged and transformed into a constant section that must represent the whole reach. Although serious local variations may appear, the bottom slope is taken constant in every part of the model. The sections are supposed to be hydrostatic and the velocity distribution to be uniform, by this allowing a one dimensional approach. The friction factor is constant in every part of the model and may vary with water depth and time.

Steady flow

In case of steady flow, continuity is expressed by

$$Q = A \,.\, U$$

And motion by the equation of Bresse

$$\frac{dh}{dx} = \frac{S_0 - \frac{f}{8g}\frac{PQ^2}{A^3}}{\sqrt{1 - S_0{}^2} - \frac{BQ^2}{gA^3}}$$

Where: h = water depth; x = distance along the river; S_0 = bottom slope; f = friction factor; g = gravitational acceleration; P = wetted perimeter; Q = discharge; A = flow area; B = width at the water surface.

The effect of all approximations made is concentrated in the friction factor, mainly taken from formula such as Manning-Strickler, Bazin, White-Colebrook-Thijsse,… The quality of the numerical solution of this relatively simple equation is guaranteed by a correct choice of dh or ds.
Sometimes the flow is supposed to be uniform, using for example the Manning formula

$$U = 1/n \; R^{2/3} \; S_0^{1/2}$$

Unsteady flow

The Saint-Venant equations describe the unsteady flow situation:

$$\frac{\partial Q}{\partial x} + B\frac{\partial h}{\partial t} = q$$

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{Q^2}{A}\right) = gA\left(S_0 - S_f - \frac{\partial h}{\partial x}\right) + q\frac{Q}{A}$$

where q = lateral inflow per unit length along the river; t = time

and $S_f = \frac{f}{8g}\frac{PQ^2}{A^3}$

The effect of friction is simulated in the same way as it is done in the steady state case, not taking into account the variable aspects of flow.
One normally uses an implicit finite difference Preissman scheme to solve these more complex, non linear equations. The quality and reliability of the solution are strongly dependant on the right choice of the transfer coefficient θ and of Δ x and Δ t, which should fit to the particular characteristics of the flow. In figure 1 it is shown that taking the time step Δ t too big may lead to loss of accuracy of the input data and thus of the final result.

Extension to flood plains

As unsteady flow simulation often focuses on peak flow situations, it is important to model the impact of bypass channels and flood plains. These can be modelled by a quasi two dimensional model using a network structure for those parts where flow is dominant to storage and a combination of interconnected cells if storage capacity is more important. Figure 2 demonstrates how the picture of a wetland area is transformed into a simulation scheme. The course of the river, where water is transported can be clearly seen from the picture, but one realizes that a good simulation of the flood plains can only be effected if thorough knowledge of the field situation is available.

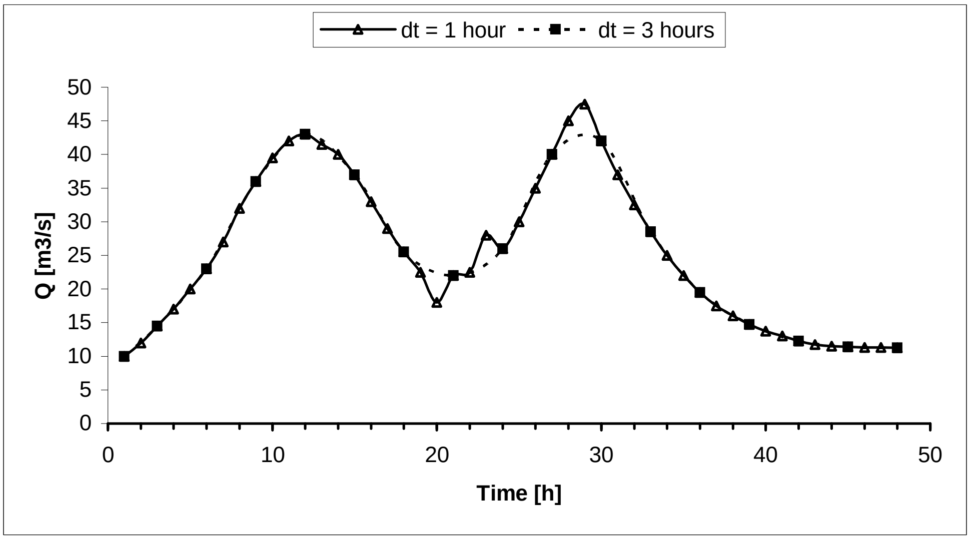

Figure 1: Impact of time step on the quality of the input data

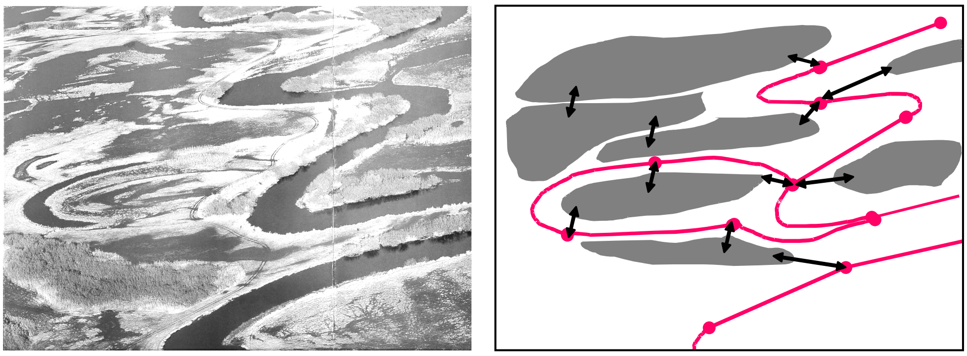

Figure 2: Transformation of a field situation into a topological hydraulic scheme.

Input data

As input data for the model, topographical and hydraulic information must be available. Topographical measurements collect data on the cross-sections of the river and the floodplains and on the evolution of the longitudinal profile (thalweg). Data on the variation of water level as a function of time may form an interesting boundary condition in the model. Hydraulic measurements must help to determine the hydraulic characteristics of the model. They will provide data on discharges (as a function of time), lateral flow, friction coefficients (as a function of stage and time), sediment transport etc.

DATA COLLECTION

Topographical data

For the collection of topographical data one must decide on the choice of the distance between 2 cross- sections. In case of a big river with a uniform profile less data is needed than when confronted with a small meandering creek flowing through a wetland area as shown in figure 2. For cross-section measurements, classic levelling as well as GPS instruments may be used. The boundaries of the flood plains and the interconnections between different storage cells can be read from topographic maps, air photo's or satellite pictures. Thanks to GPS devices, great progress was made in this kind of topographical measurements. But although GPS accuracy is fantastic (1-2 cm) in the horizontal plane, it often is insufficient for the vertical measurement (about 2 - 5 cm). Depending on the devices used, data collection may suffer from the presence of mud, vegetation, obstacles in the cross-section, soft bottom etc.

Hydraulic data

Handbooks on Hydrometry give a nice overview of the huge arsenal of instruments and methods allowing hydraulic data collection of different parameters under various circumstances and for multiple purposes. They often provide valuable information on precautions to be taken, conditions to be available and possible problems to encounter. Discharge measurements making use of the method of integration of the velocity over the cross section are often applied when collecting data for a numerical river flow model. So comments on hydraulic data collection are limited to this method in this paper.

The method is mainly applied from a bridge or from a boat, using a (well-calibrated) propeller meter or an electromagnetic or acoustic velocity meter.

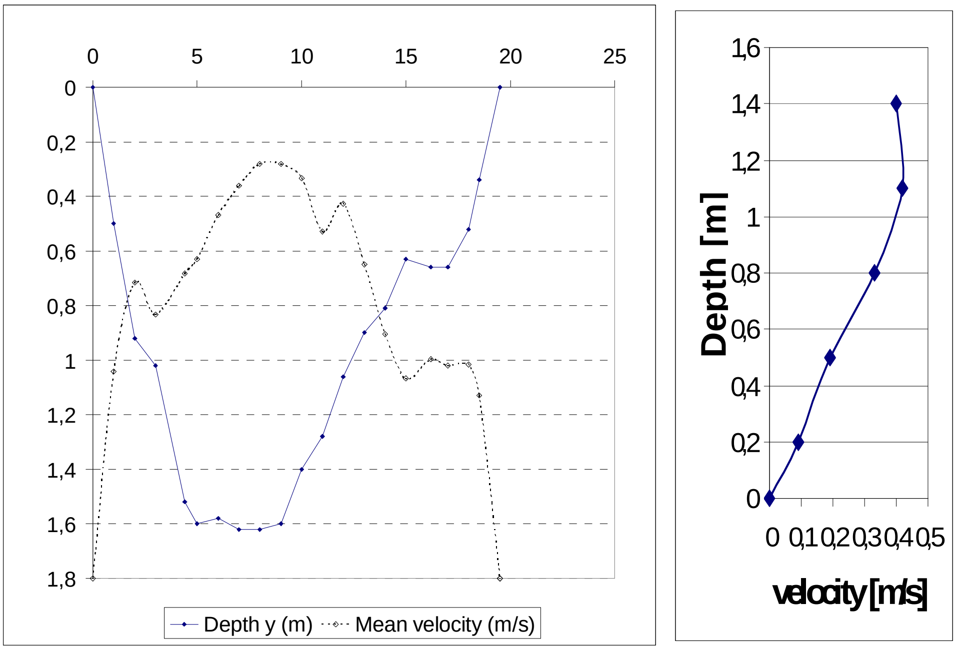

Figure 3: Horizontal and vertical velocity profile in a river with irregular cross-section

Good guidelines on the number of verticals and the depths on each vertical to be gauged are found in international normalisation guidelines. They apply to big rivers with well-developed regular flow patterns. In smaller rivers one mostly needs to increase the number of gauging points in order to assure sufficient accuracy of the final result. Indeed, figure 3 gives an example of a measurement where the horizontal velocity distribution is not parabolic at all, while also the vertical velocity profile doesn't fit the Prandtl – von Karman velocity law.

Vegetation certainly causes major problems to this kind of measurements. In principle the measurement section should always be cleaned from vegetation. In deeper water this can be rather problematic and turbidity of the water can hide its presence. Interruption of the propeller meters signal may reveal the presence of plants, but when the revolution speed decreases due to contact with leaves, errors slip into the measurement. And even if the section is cleaned and acoustic or electromagnetic instruments are used, big leaves or plants in front of the gauging device may cause periodic velocity fluctuation and reduction.

Figure 4: Discharge measurement from a boat, connected to a cable

Big stones or rocks and irregularities in the longitudinal profile may increase turbulence or lead to local velocity drop which is not representative for the area under concern. A soft bottom layer affects the accuracy of the depth gauging. When measuring from a boat fixed to a cable, wind will disturb the velocity measurement (Figure 4).

From all these possible influences one can conclude that making accurate discharge measurements is not a that evident business.

In figure 5, the results from 2 discharge measurement campaigns in the upper and middle Biebrza basin in the North-east of Poland are shown. The year 2000 campaign was performed in early June with dense vegetation in the river, while the 2003 campaign was hold in late April, before plants started to develop. Although the water stages in the upper basin where almost exactly the same during both campaigns, discharges where much bigger in 2003 than in 2000. From both figures one can conclude that in 2003 the continuity principle was much better fulfilled at the confluences than in 2000. This leads to the conclusion that in the year 2000, notwithstanding all efforts made to clean the measurement sections, vegetation was badly influencing the accuracy and quality of the discharge measurements.

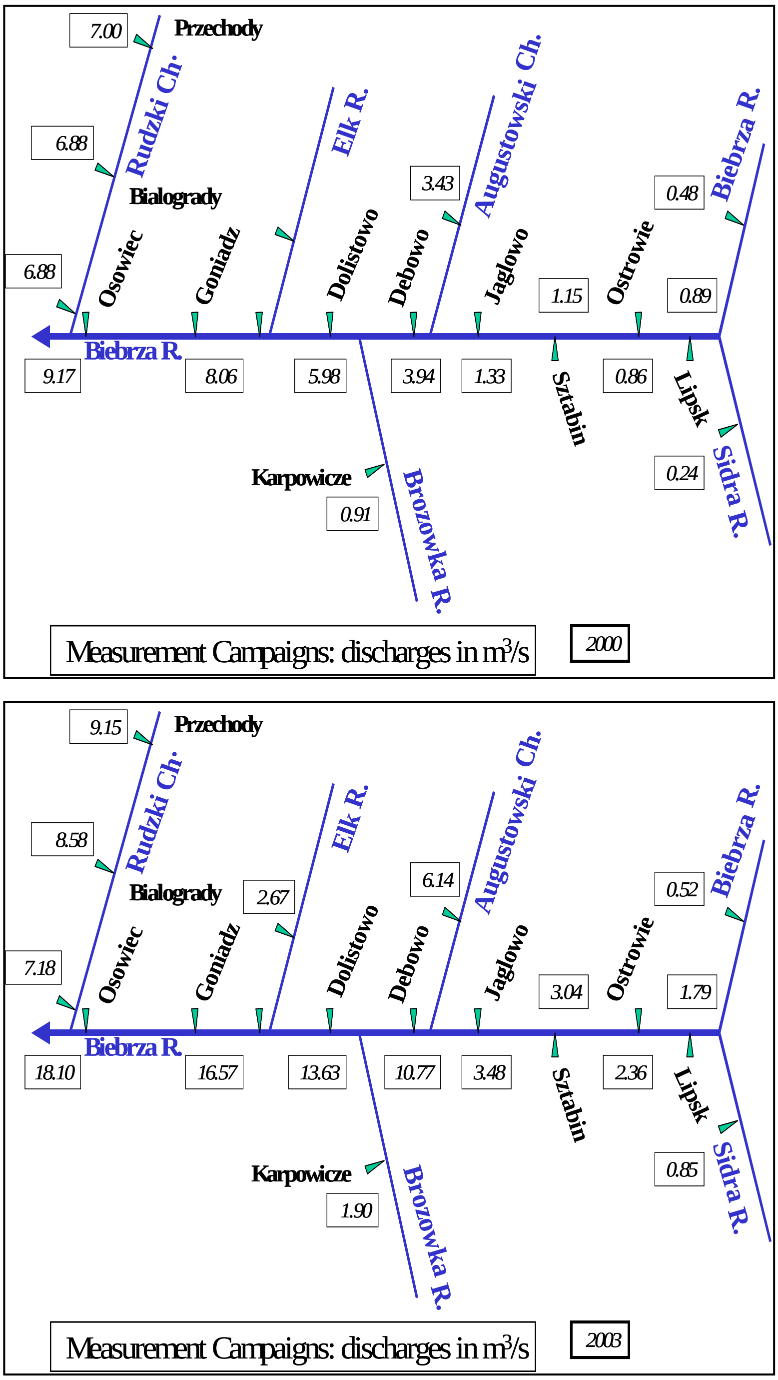

Figure 5: Discharge measurement in 2000 and 2003

INPUT DATA PROCESSING

Definition of cross-section

The definition of the cross-section of the river perpendicular to the thalweg is quite evident in normal flow periods (cfr. Figure 2). Figure 6a, shows that during peak flow, the velocity distribution over the cross-section might change drastically, and defining the section becomes much more tricky. This problem can be solved by keeping the flood plain areas separated from the main river in the numerical simulation scheme. In those cases where the flood plain flow contributes substantially to the total transport, a network structure should be used.
In case of a river with very irregular profiles, it is important to define the theoretical section as an average of the collected data, with the same 'averaged' wet area, wet perimeter and hydraulic radius. One will understand that in these cases, calibration of the friction factor becomes very important, as the theoretical section is much smoother than the natural one (Figure 6b).

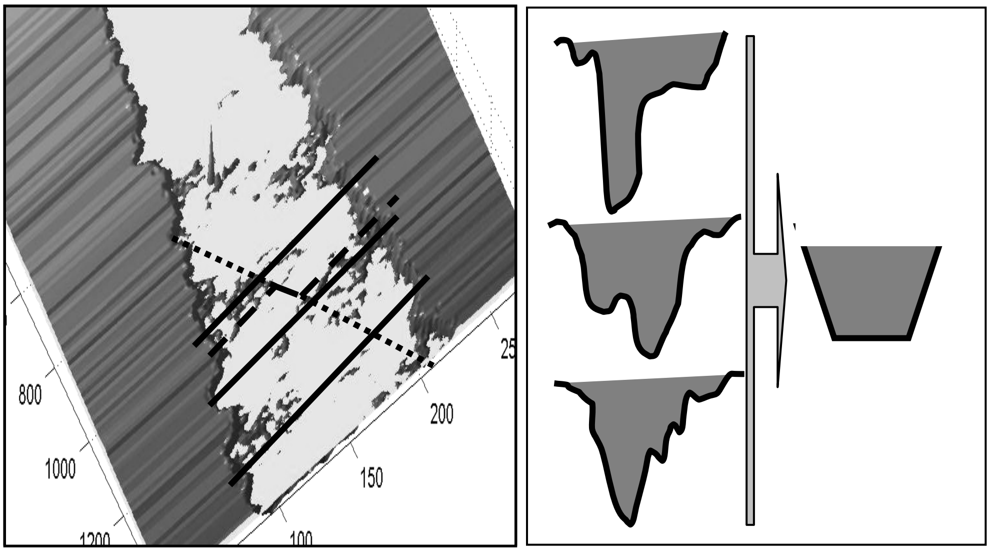

Figure 6:
a. Cross sections during peak flow   b. Determination of cross-section

Longitudinal profile

In figure 7a, it is shown that the definition of the longitudinal profile will depend on the way how the cross-sections have been determined. The same remarks as made in the section above are also valid here. Especially in case the straight line is used to determine the longitudinal profile, the effect of friction again needs to be compensated.

Figure 7: a. Determination of longitudinal profile

If the natural thalweg profile is irregular (Figure 7 b) the bottom slope will strongly depend on the choice of the river stretches and by this influence the development of the water surface profile.

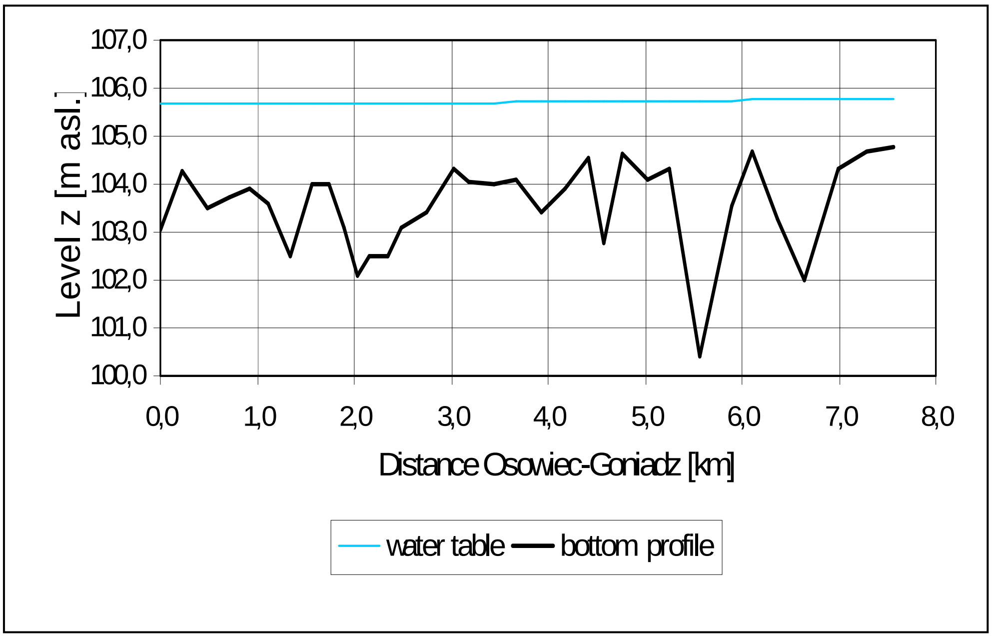

Figure 7: b. Impact of choice of stretches

Friction coefficient

Friction in a river is influenced by many parameters such as bottom roughness, shape of the cross-section, vegetation, obstacles, meanders, velocity distribution etc. By this, the value of the friction coefficient varies in space and time. Although many attempts have been made to theoretically calculate the value of the coefficient, it seems that only determination from measurements is able to deliver appropriate information on the values to be used for modelling.

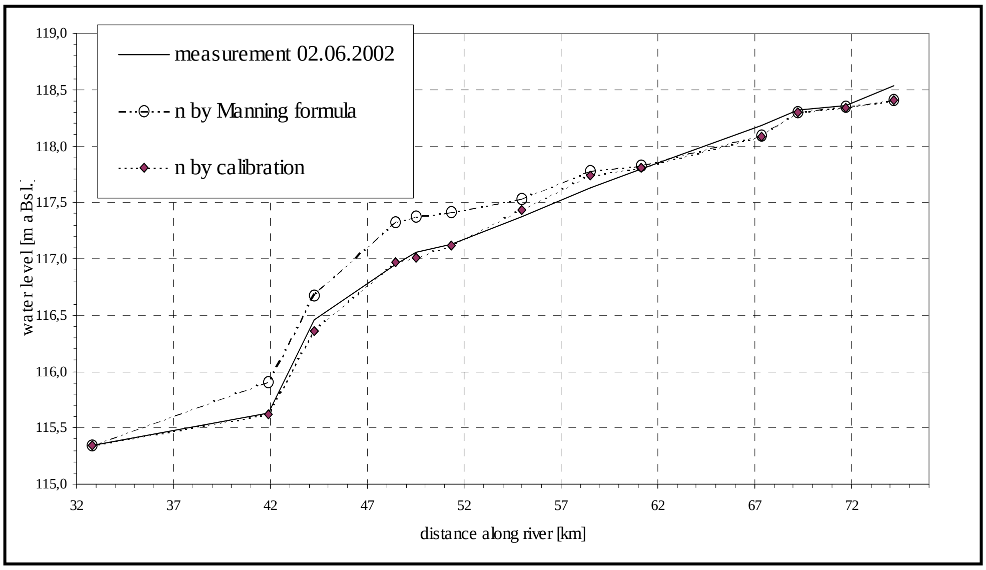

Figure 8: Determination of friction coefficient

For the numerical simulation discussed in the next section, friction coefficients have been determined in 2 different ways. First the coefficients where calculated for every stretch, starting from the results of the discharges measurements and supposing the flow to be uniform. Secondly the coefficients where determined by fitting the water surface profile obtained from Bresses equation to the measured water stages. It Is clearly shown that the second method delivers much more reliable results than the first one.

NUMERICAL SIMULATION

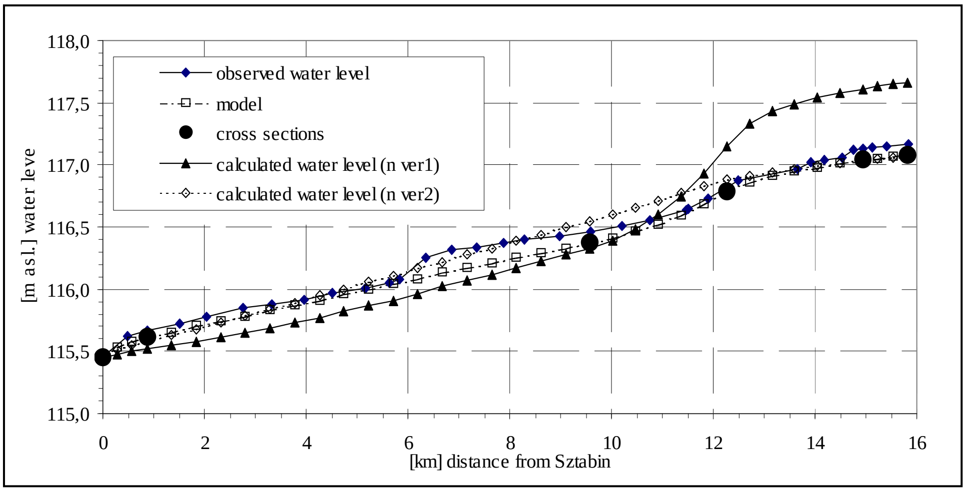

Figure 9: Comparison between recorded and simulated water levels in the Biebrza upper basin.

Notwithstanding all withdrawals discussed in the previous sections it is possible to develop reliable numerical models, able to generate accurate simulations of the natural situation. The approaches as suggested above where applied to the elaboration of the simulation model of the upper and middle basin of the Biebrza basin. Figures 9 and 10 illustrate the quality of some flow simulation results by comparison with field measurements and recorded data. In figure 9 comparison is made between the observed water levels in the upper basin and the results of different simulation approaches. The 'model' line shows the results from a calculation using all information on the cross-sections, that were recorded every 400 m. Both other lines ('n ver1' and 'n ver2') give the results as obtained from a simulation in which only the information on the representative cross-sections, indicated by a thick full dot was used. It can be seen that the approach with n determined from the Manning formula ('n ver1') applied over the full length of every reach, delivers less reliable results than a calculation using n values that are fit to the observation of the local water surface slope in each cross-section used for the simulation ('n ver2').

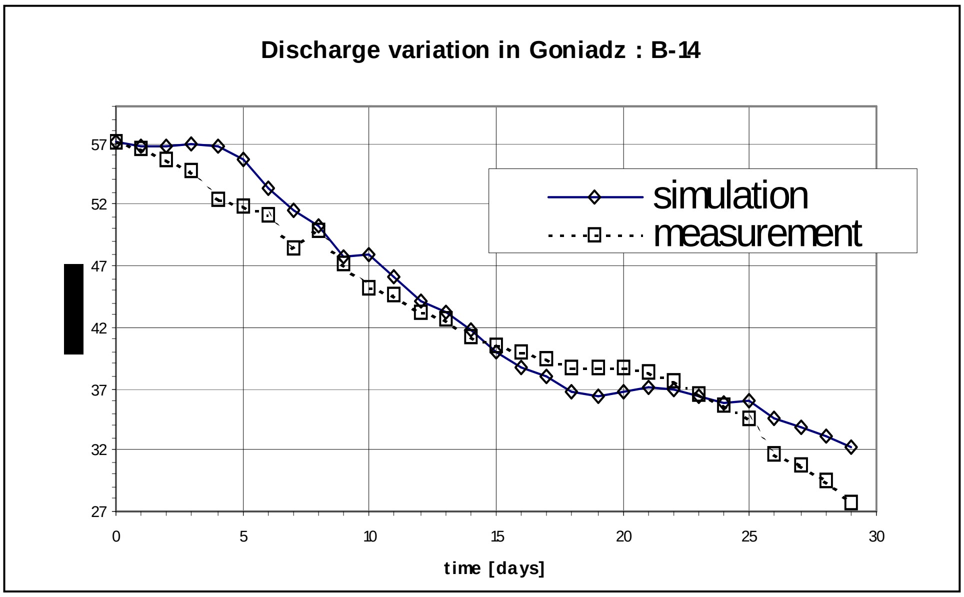

Figure 10: Comparison of calculated and measured discharges at Goniadz

Figure 10 shows the comparison between recorded and calculated water levels during a flood event at Goniadz, situated at the downstream end of the middle basin. The Manning n coefficient was determined by steady state calibration, using the Bresse equation. Although little topographical information was available and the longitudinal profile is very irregular (see Figure 7b), again it is clear that thanks to careful calibration of the friction factor, the choice of representative cross-sections and a well considered determination of the model stretches (fitting of bottom slopes) good simulation results can be obtained. Needless to remark that the more topographical and hydraulic data become available, the better the topography of the model can be defined and the higher the quality of the simulations will be.

CONCLUSIONS

Although the flood routing theory is quite simple and numerical solution methods are well developed, practical implementation is in many aspects confronted with serious obstacles. In this paper it is shown how a sound definition of the cross-sections and the longitudinal profile in combination with a well considered calibration of the friction coefficients enables the elaboration of reliable and accurate numerical simulation models. It is shown that a correct determination of the friction factor is an issue of major importance. As vegetation is substantially influencing the value of the friction factor, its variation in time is a main topic for further research.

REFERENCES

Huygens M., Okruszko T., Batelaan O., Verhoeven R., Chormanski J., Meyus Y., Van Poucke L., Swiatek D., De Smedt F. - *Field monitoring in the Upper basin of the Biebrza wetlands,* Int. Conf. on Monitoring and Modelling Catchment Water Quantity and Quality, Gent; 27-29/09/2000; pp 263-266

Verhoeven R. - *Hydrometry*, lecture notes – Ghent University