ASPECTS OF NUMERICAL MODELLING – THE GAP BETWEEN PRACTICE AND RESEARCH

Tobias Hafner[1], Bernhard Schaipp[1] & Gabriele Schwaller[2]

[1] Bavarian State Ministry of the Environment and Public Health, 81925 Munich, Germany

[2]Bavarian Environment Agency, 86179 Augsburg, Germany

E-mail: tobias.hafner@stmug.bayern.de; bernhard.schaipp@stmug.bayern.de; gabriele.schwaller@lfu.bayern.de

Abstract

In the cleft between state-of-the-art science and practical use of complex numerical models in everyday life a great deal of knowledge is lost. Often hydraulic problems are faced with out-dated know-how, while adequate tools have existed for years and science has already closed this topic without realizing its shortcomings in terms of practical implementation.

The intention of this paper is to present certain aspects demonstrating the above-mentioned problem. It will highlight the need for a link connecting scientists and practitioners, which in case of numerical modelling is often the software company.

Secondary currents in 2D-models

Two-dimensional depth-averaged numerical models are standard working practice for hydraulic calculations. Water levels or flood hazards, in particular, are in most cases calculated using these models. Morphological calculations with bed level evolution or with bank erosion processes are also increasingly carried out with two-dimensional models. While the effects of secondary currents in river bends are not usually as important in the context of hydraulic problems focusing on the water level, in morphological calculations these effects should not be neglected. Secondary effects should be considered in calculating the direction of bed load transport and in the depth-averaged flow equations themselves.

Secondary currents influence the direction of bed load transport

The vector of the depth-averaged velocity and so also the shear stress are orientated tangentially in a river bend. An important factor for the direction of the bed load transport is the flow situation near the bed which differs from the tangential direction because of the interaction between the transverse and tangential flow field. Two-dimensional models could take this into account with a deviation angle $\delta_{sec,}$ which transforms the vector of the "depth-averaged" shear stress for the following sediment calculations. A very common formula is shown in equation (1), where h is the flow depth and R the radius. The parameter A depends mainly on the velocity profiles and derivation used. It could be used as a constant calibration parameter in the numerical model with a typical range of about A = 7 ÷ 12 or calculated with formulas such as those of Rozovskii (1957), Engelund (1974), Jansen (1979) or Zimmermann & Naudascher (1979).

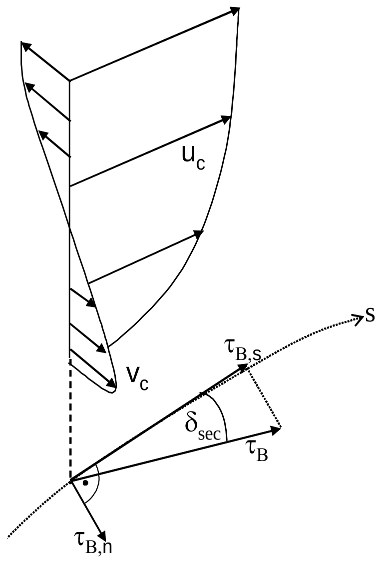

Figure 1: Flow distributions in a river bend - angle δ_{sec}

$$\tan\delta_{\text{sec}} = \frac{\tau_{B,n}}{\tau_{B,s}} \cong \frac{\tau_{B,n}}{\tau_B} = A\cdot\frac{h}{R} \tag{1}$$

Figure 2 gives an overview of the influence of formula (1) and the sensitivity of parameter A on cross-sectoral development in a river bend (I = 1,0 ‰, R = 300m, constant discharge, d_m=24 mm). The parameter A controls the percentage of the lateral bed load transport. The simulations with fixed banks show that A mainly influences the lateral slope in the bend and also the scour depth. In case of erodible banks, the parameter A mainly influences the lateral erosion.

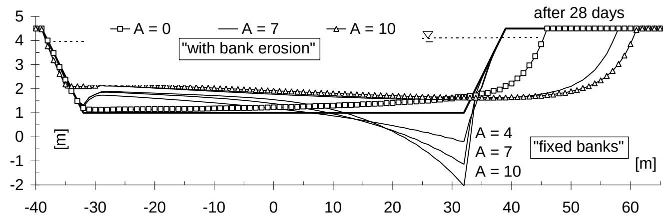

Figure 2: Sensitivity of parameter A

Secondary currents influence the velocity distribution over a cross-section

While formula (1) is integrated in most numerical 2D-models dealing with bed load transport, the effects of secondary currents on the depth-averaged velocity distribution in river bends are often neglected. These effects should be taken into account especially when bank erosion processes are simulated. This could be achieved with dispersion terms (formula 2), which include the deviation of the flow velocities over the flow depth from the depth-averaged value. These terms could be solved analytically by using established velocity profiles.

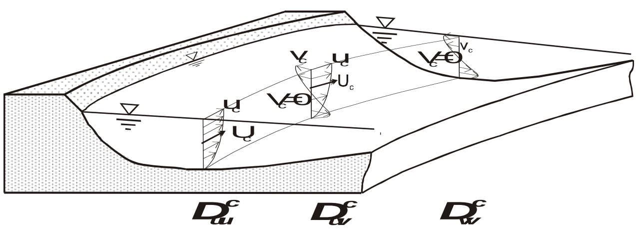

Figure 3: Dispersion terms

$$D_{uu}{}^{c} = K_1 \cdot \quad \rho U_c{}^{2}\, h$$
$$D_{uv}{}^{c} = K_2 \cdot \quad \rho U_c{}^{2}\, \frac{h^2}{R}$$
$$D_{vv}{}^{c} = K_3 \cdot \quad \rho U_c{}^{2}\, \frac{h^3}{R^2}$$

Parameters K_1, K_2, K_3 depend on the velocity profiles used and differ from author to author. (2)

Analytical solutions for formula (2) are given by Flokstra (1977), Duan (2004), Lien et al. (1999), Malcherek (2001), Kalkwijk & de Vriend (1980), Hafner (2008) and others. To use formula (3) in x-y-Cartesian coordinate systems, a coordinate transformation has to be conducted, as described by Yulistiyanto et al (1998) or Duan (2004). Figure 4 shows the effect of formula (2) in a river bend (R = 500m, I = 1,0‰, k_s = 0,1m). In Figure 4 the results of a 2D-model are compared with the results of the 3D-model SSIIM-3D (Olsen, 2003). By way of conclusion, it should be mentioned, that regardless of which author's formula is ultimately used, dispersion terms are a suitable way of including secondary effects in 2D-models and improving the velocity distribution. Compared to the influence of formula (2) – the bed load direction – the dispersion terms have little influence on morphological calculations.

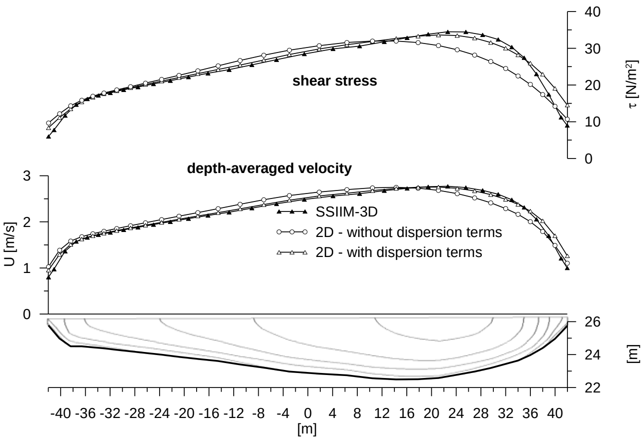

Figure 4: Comparison of 2D-results (with and without use of dispersion terms) with the 3D-model SSIIM-3D

Modelling roughness

In 2D-models usually an overall roughness is applied that represents the mean conditions, or – in the best case – one that is calibrated to observed events in an order of magnitude of the design event (frequently HQ100). For simple steady- state calculations this method is sufficient. The use of very high roughness coefficients calibrated at low water levels not only leads to problems in floodplains that are exposed to different levels of flooding, but also and in particular, in small, heavily overgrown channels. In the extreme range of a flood runoff this value is no longer valid. If, in addition to this, bed roughness parameters change significantly across the discharge spectrum (ripple and/or dune formation), or different hydrological phenomena have to be taken into account (flow-over or flow-through rigid/flexible vegetation), this method is not adequate. In the following, proposals on how an overall roughness could be appropriately "automated" are addressed: on the one hand, key issues from practice are to be covered, while on the other hand, however, largely avoiding complex algorithms for the determination of individual roughness parameters.

Bottom roughness and flow through roughness of plants

Most two-dimensional depth-averaged numerical models use the Manning's value n, Strickler value k_{st} or the sand roughness k. All these are bottom roughness parameters. Formulas for the effect of crop roughness like corn fields are not usually implemented. But especially in river sections with spacious floodplains the flow-through roughness of fields or wetland forests could be important. Constant bottom roughness values are often used, regardless of the flow depth. Bottom roughness flow formulas, like the Strickler formula (3), give in case of a rising flow depth h also a higher velocity. The velocity is proportional to $v \sim k_{st} \cdot h^{2/3}$. If a corn field is portrayed as a field of cylinders, it is obvious that with rising h the velocity stays constant. So in this case we need a roughness formula that will give a proportionality such as $v \sim k_{st}$. This could lead to underestimation of the flow depth in case of densely planted floodplains.

$$v = k_{St}\sqrt{J_e}h^{2/3} \qquad \text{with } k_{st} = 1/n \qquad (3)$$

There are a large number of formulas, which allows a conversion of flow-through roughness effects in bottom roughness parameters (for example: Lindner, 1982), but as said above these formulas are not usually implemented. A simple approach could be to give the user of a 2D-model the possibility to set a roughness parameter depending on the flow depth. Then the user is free to decide which roughness - flow depth correlation he wants to use.

In physical model tests in the Laboratory for Hydromechanics at the Technische Universität München genuine maize plants were set up over a length of 22 m with a typical plant spacing of 15 cm x 75 cm to investigate the roughness parameters k_{st} under practical conditions. The tests were carried out with a crosswise and streamwise flow direction and also with different flow depths and water surface slopes. The main objective of the experiment was to get a summarized flow depth–k_{St} diagram (Figure 5), which allows an adequate k_{st} value to be chosen for maize fields, depending on which range of flow depth is relevant in the practical hydraulic problem. Figure 5 also shows that the Lindner formula (1982) matches the physical results well.

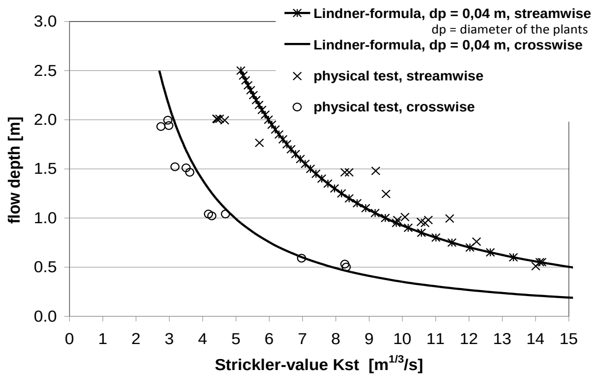

Figure 5: Flow depth – k_{St} diagram for a maize field, (see Rapp & Hafner, 2011)

In conclusion, it is clear that constant bottom roughness parameters for hydraulic problems in respect of densely planted areas are not satisfactory. Although suitable formulas do exist, they are not used in most numerical models.

Flexible and flowed-over vegetation

In research work over the past 3 decades there was an initial focus on the interactions of rigid vegetation. This led to a range of approaches of varying complexity that were to account for the effect of flow-inhibiting interactions in 1D calculations. For some 2 decades now, efforts have been made to include flexible vegetation in these calculations in a practice-oriented manner. For example, Indlekofer (2003) developed a system of formulas – with reference to the calculation method recommended by Schröder (1999) – that takes into account profile classification and vegetation growth (rigid and flexible) leading to an overall roughness. Disadvantage: to reach an overall roughness parameter, multiple, nested iterations have to be dealt with, among other things, and these make a numerical calculation more difficult and have a very negative impact on the speed of calculation. An “automation” of such complex interactions is not going to be possible in the foreseeable future.

In principle, it amounts to the overlapping of two hydraulic phenomena (compare extreme roughness): the flowing over or flowing through of roughness elements. The transition area between the two is difficult to determine, or rather, it very much depends on the hydraulic boundary conditions (is the turbulent dispersion “good” enough to enable an approximate depth-averaged approach to the problem).

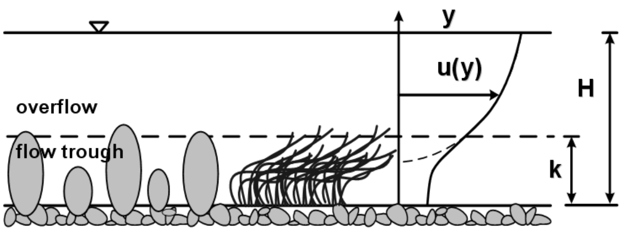

Figure 6: Flow areas in open channel, Stephan, 2001 modified)

Bed forms

Taking channel bed forms into account substantially improves 2D numerical modelling when a reliable determination of a river bed overall roughness is required as a function of discharge. Many approaches are known from reference literature. The following takes up an approach by Yalin that has been consistently refined over decades and, in the version of Valin & da Silva (2001), contains the option to calculate the length and height characteristics of the bed forms. When using the complex system of formulas it must, of course, not be overlooked that there is no such thing as “the” ripple or dune height/length that exactly matches a concrete flow depth, rather there is always a certain bandwidth of bed forms for a concrete discharge. This condition was also pointed out by Hentschel (2007), for example, based on extensive model experiments on the river Elbe. It is also to be observed that the adaptation of bed forms to discharge conditions does not take place as quickly as the change in the hydraulic parameters. Nevertheless, Yalin’s calculation concept is interesting for the modelling because, in addition to the grain roughness of the bed material, the resulting bed forms (ripples and dunes) can be determined with adequate accuracy from the flow conditions. Furthermore, the concept of roughness overlapping $1/C^2 = 1/C1^2 + 1/C2^2 + ... 1/Cn^2$ (C = bottom roughness, ripple roughness, dune roughness) offers the possibility to overlap other roughness types to provide an overall roughness.

Discharge with extreme bottom roughness

If the water depth is low in relation to the roughness, simple flow formulas, such as Strickler (1923) and the general flow formula (Type log or ln) also reach their limits. Extreme bottom roughness parameters are encountered in mountain torrents and in sections of rivers with very coarse river bed material, and in event of structures such as ramps. In technical references mostly area-modified flow equations are offered (quasi different levels of the roughness overflow) or flow formulas are recommended that are based on a “flowing through” of roughness elements. A cohesive approach is relatively rare. At the VAW hydraulics laboratory a flow formula, see Jäggi (1984), was developed in the nineteen eighties containing a gradient term that, with low relative overlapping of the bottom roughness, appropriately takes into account the increase in energy losses. This gradient term can be simply transferred into a term of type $1/C^2$ and, in this way, be dealt with as a component of overall roughness. A certain ambiguity is to be seen in the use of the parameter alpha that, as a function of the substrate, describes the interaction between shape and density of roughness-influencing bed elements.

As a pragmatic approach depth-dependent roughness parameters could be specified that have been defined in advance for the specific case, under concrete boundary conditions and using hand calculations. This method can help provide a rough estimate of the roughness of ramps or (flexible) vegetation, at a reasonable expenditure, for example. It can, however, quickly lead to implausible results if no correct assumptions for the areas of overflow and flow-through can be made.

Use of 2D-modelling in the Bavarian Water Management Authority

The Bavarian water management authority has been using the high-performance software tool HYDRO_AS-2d for many years. It has since been upgraded to cover the fractionated transport of suspended solids and bedload. Depending on the task, the modelling is carried out on a purely hydraulic basis (with fixed bed) or with the transport of solids (with moving bed).

Current projects based on 2D modelling that are being carried out across Bavaria, include the implementation of the EC Flood Risk Management Directive as well as the hydrological validation of rating curves at gauges in the extreme discharge range.

Hydraulic calculations serve as the basis for the preparation of flood hazard maps and flood risk maps. In Bavaria, specifications are provided for carrying out these calculations (Bayerisches Landesamt für Umwelt, 2012). In doing so, there is a particular focus on whether steady-state modelling or unsteady-state modelling of the channel sections is required. For instance, in very flat river basin areas or on alluvial cones in alpine regions, a flash flood event with brief, high peak discharge will flood smaller areas than a prolonged event. Because steady-state modelling considers a constant discharge over time, an excessively large flood area would then be determined for such areas. A steady-state calculation places fewer demands on the preparation of the hydrological input data, however, to achieve realistic results each area is individually assessed to determine whether an unsteady-state calculation is required.

Stage-discharge relationships (rating curves) at gauges provide an essential basis for flood forecasts. In the extreme range the discharge rating curves are usually only with inadequate measurements. Obtaining reliable discharge measurements in flood events is very difficult due to the high flow velocity and floating debris, and is often not possible. To achieve more accurate discharge rating curves for the extreme range, investigations are currently being carried out with hydraulic model calculations, in some cases also with moving channel bed. Up until now the calculations have been carried out with a constant roughness over the entire discharge spectrum. However, as indicated in the above, bottom roughness parameters or roughness parameters can vary substantially with the discharge and thus with the flow depth, particularly in floodplains. This means that the frequently very high roughness coefficients determined on the basis of calibration at low water levels, lead to problems in the modelling of flood runoffs. Not only in floodplains subject to different levels of flooding, but also and especially in small and overgrown channels, these values are no longer valid in the extreme range of a flood runoff. Today, a water-depth dependent roughness coefficient is desirable for many practical applications.

Some of the improvements mentioned have since been incorporated in the software HYDRO_AS-2d and are now available to users. In this connection, it will be most important to first gather experience on the sometimes complex interactions of the extended features to enable clear and straightforward model applications in the future and to ensure coordination of the calculated results with hydrological observations.

References

Bayerisches Landesamt für Umwelt (ed.) (2012): *Hochwassergefahren- und -risikokarten in Bayern. Ermittlung von Hochwassergefahrenflächen im VOF-Verfahren 2, Teil B Leistungsbeschreibung. München [not published]*

Engelund, F. (1974): *Flow and Bed Topography in Channel Bends*. Journal of Hydraulics Division, Vol. 100; HY11; 1631-1648

Engelund, F. (1976*): Closure - Flow and Bed Topography in Channel Bends*. Journal of Hydraulics Division, Vol. 102; HY3; 416-418

Flokstra, F. (1977): *The Closure Problem for Depth-Averaged Two-Dimensional Flow*. 17th IAHR Congress, Baden-Baden, Paper A106

Hafner, T. (2008), *Uferrückbau und eigendynamische Gewässerentwicklung*, Lehrstuhl für Wasserbau und Wasserwirtschaft, TU München; Bericht Nr. 117

Hentschel, B. (2007): *Hydraulische Flussmodelle mit beweglicher Sohle*, Mitteilungsblatt der Bundesanstalt für Wasserbau Nr. 90, 2007

Indlekofer H.M.F. (2003): *Abflussberechnung für Fließgewässer bei Rauheits- sowie Profilgliederung auf der Grundlage der Strickler-Formeln*, Wasserbau-Heft 5, FH Aachen, 2003

Indlekofer H.M.F. (2003): *Die Bestimmung des hydraulischen Einflusses von flexiblem Bewuchs auf die Abflusskapazität von Fließgewässern*, Wasserbau-Heft 7, FH Aachen, 2003

Jäggi, M. (1984): *Abflussberechnung in kiesführenden Flüssen*, Wasserwirtschaft 74 (1984) 5 S. 263-267

Jansen, P. Ph. (1979): *Principles of River Engineering, The non-tidal alluvial river*. Pitman, London, ISBN 0-273-01139-1

Kalkwijk, J.P.TH., de Vriend, H. J. (1980): *Computation of the Flow in Shallow River Bends*. Journal of Hydraulic Research, Vol. 18, No. 4, pp. 327-341

Lien, H. C., Hsieh, T. Y., Yang, J. C. Yeh, K. C. (1999): *Bend-Flow Simulation Using 2D Depth-Averaged Model*. Journal of Hydraulic Engineering, Vol. 125, No. 10; pp. 1097-1108

Lindner, K., (1982): *Der Strömungswiderstand von Pflanzenbeständen*, Mitteilungen, Heft 75 Leichtweiss-Institut für Wasserbau, Technische Universität Braunschweig

Malcherek, A. (2001): *Hydrodynamik der Oberflächengewässer*. Institut für Strömungsmechanik und elektronisches Rechnen der Universität Hannover. Nr. 61

Olsen, N., R., B. (2003): *A three-dimensional numerical model for simulation of sediment movements in water intakes with multiblock option – User´s manual*. Department of Hydraulic and Environmental Engineering – The Norwegian University of Science and Technology

Rapp, Ch & Hafner, T. (2011: *Experimentelle Bestimmung der Rauheit eines Maisfeldes mit echten Pflanzen.* WasserWirtschaft 12/2011 pp. 23-27

Rozovskii, I. L. (1957): *Flow of Water in Bends of Open Channels*. Academy of Sciences of the Ukrainian SSR, Institute of Hydrology and Hydraulic Engineering, Kiev - 1957

Schröder, W. (1999): *Grundlagen des Wasserbaus*. Hydraulik, Düsseldorf

Stephan, U. (2001): *Fließwiderstandsverhalten flexibler Vegetation*, Technische Universitaet Wien; Fakultät fuer Bauingenieurwesen; Institut für Hydraulik, Gewaesserkunde und Wasserwirtschaft

Strickler, A. (1923): *Beiträge zur Frage der Geschwindigkeitsformel und Rauhigkeitszahlen für Ströme, Kanäle und geschlossene Leitungen*, Mitteilungen d. Eidg. Amtes für Wasserwirtschaft, No. 16, Bern

Yalin, M.S.; da Silva, A.M.F: fluvial processes, IAHR, Delft, 2001

Yulistiyanto, B.; Zech, Y.; Graf, W. H. (1998): *Flow around a Cylinder: Shallow-Water Modelling with Diffusion-Dispersion*. Journal of Hydraulic Engineering, Vol. 124, No. 4; pp. 419-429

Zimmermann, C. & Naudascher, E. (1979): *Sohlausbildung und Sedimentbewegung in Krümmungen alluvialer Gerinne.* Wasserwirtschaft 69 (1979) 4, Seite 110-117