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ORIGINAL ARTICLE

Determination of the Manning roughness coefficient influenced by vegetation in the river Aa and Biebrza river

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Abstract The aim of this study was to investigate the variation of channel bed roughness in two rivers, as important parameter in hydraulic modelling especially with regard to flood control. The universities of Ghent (UG) and Antwerp (UA) are conducting scientific research in the river Aa in Belgium and the Biebrza river in Poland in order to better understand the phenomena involved and to come to a more accurate determination of the different parameters influencing flow. In this paper, the determination of the roughness coefficient '*n*' from the Manning equation is used. This coefficient is not easy to determine and is varying constantly. It is influenced by the meandering character of the river, the bed material and the average grain size, the channel bed forms, the channel obstructions, the geometry changes between sections and the vegetation in the channel. Furthermore, due to these parameters, the roughness of the channel is not equally distributed over the channel, the banks and the floodplains. So, using literature data does not always lead to satisfactory results, due to the different situation in the field (Werner et al. J Hydrol 314:139–157, 2005). Therefore, measurements are necessary to determine the variation of the Manning coefficient. The Manning coefficient is a function of the discharge, but will also vary over the time due to the mentioned influences. In a multidisciplinary research project on the fundamental exchange processes in river ecosystems, hydraulic measurements were performed on a regular base in the river

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Aa. During these measurement campaigns, velocity and discharge measurements were carried out in multiple cross-sections. Once a month, the discharge and the water levels were measured at the upstream and the downstream end of the test stretch. On the river Biebrza, similar intensive measurement campaigns took place along a 6 km stretch in the upstream part of the river. An accurate determination of the Manning coefficient according a seasonal variation is an important tool in hydraulic modelling.

Keywords Ecohydraulics · Environmental engineering · Hydraulic measurements · Manning roughness coefficient · Vegetated rivers

1 Introduction

Knowledge of the movement of water is essential as water flow is the driving factor for all other water related processes. Measurements of discharge and water level depict the actual situation, but hydraulic modelling allows to evaluate parameter influence and future prospects. Hydraulic modelling is of big concern with respect to water resources management, strategic planning and crises management.

A well calibrated hydraulic model provides reliable information on different aspects of the real situation. The numerical model is used to simulate the actual behaviour of the river, but it is also an important tool to produce a forecast on possible floodings, peak discharges, low water levels, etc. For that, a representative model, with determination of the topography of the river and river banks and registration of the discharges and water levels, is necessary. A parameter of main importance is the roughness of the river channel and the banks [9]. Here, the Manning coefficient is used as roughness parameter.

The channel roughness is affected by a lot of factors which are difficult to translate into a single value. Green [13] stated that aquatic macrophytes are often the dominant factor influencing flow conditions within the channels they occupy. Furthermore, it is more difficult to determine the Manning coefficient for vegetated streams than for open channel flow [4]. Also Watson [25] showed that seasonal variations in the aquatic vegetation have an important influence on the flow resistance. It is possible to estimate the value, but the deviation from reality may be large. Therefore, in flood analysis, a conservative evaluation is advisable. The scope of formulas, experiences, tables, pictures or other techniques to estimate the friction factor is wide and therefore, a case specific analysis is interesting [12].

Lowland rivers often contain extensive stands of aquatic macrophytes which can increase channel resistance and water stage, while reducing average flow velocities [13]. Flow resistance of vegetated channels can typically be an order of magnitude greater than that of unvegetated channels [7,8]. So, macrophytes can contribute to local flooding, and their removement is part of the water management strategy. Mowing of the grasses in the river channel and the removal of the aquatic vegetation is another important water management related topic [2]. Study of the influence of different mowing patterns is done in [24], but is not seen in the field. On the one hand, the presence of vegetation in the river leads to a wealthy ecosystem with habitats for different fish and other species. On the other hand, the flooding risk is big, especially during the growing season. Presence of vegetation in water courses has a lot of advantages from ecological point of view, so the mowed area has to be limited [22]. Next to a low percentage of mowing, also a the avoidance of specific trajectories of the water is ecologically important [22]. This can be obtained by mowing following a 'chessboard' pattern which causes an important structural variation. As a result, erosion creates areas with high velocities next to areas with stationary water where sedimentation can take place. A classification of the mowing patterns is presented by the Flanders Hydraulics Lab [24]. A mowing pattern with a low roughness (Manning coefficient) has to be chosen to limit the backwater effect. Out of these patterns, the most ecologically friendly one is retained. According the environment, more or less attention is paid to a good drainage (living areas) or to an ecological development (green areas) [2]. Besides the mowing pattern, also the frequency of mowing, the time and the mowing method is important for the maintenance of the water course and for guaranteeing its ecological quality.

In a first phase, the importance of the roughness coefficient in two monitored river stretches is investigated, using the Manning equation and hydraulic modelling of surface water. The one-dimensional numerical model HEC-RAS [16] has been selected for the modelling. Field measurements have been carried out and flow characteristics have been collected. Based on these data, the Manning coefficient is calculated as a function of time, distance and water level. Further, this coefficient is also determined for studying the effect of vegetation on the drainage of the river.

2 Study area's: the Biebrza river and the river Aa

Two study areas are compared: the river Aa and the Biebrza river. Both of them are lowland rivers and highly influenced by vegetation growth in different periods over the year. They are both subject from extensive measurement campaigns from the past up till now. While the river Aa is situated in an urbanized region, the Bierbza river and its wetlands is part of an undisturbed peatland.

2.1 The river Aa

In Belgium, focus of the study is the downstream part of the river Aa. The catchment basin of the river Aa is situated in the region of Antwerp in Belgium and is hydrographically part of the Nete basin. The most important rivers of this basin are the Kleine Nete and the Grote Nete, both influenced by the tidal bore. More than 40% of the water in the Nete basin is carried by the river Aa, which is consequently the most important tributary of the Kleine Nete. The river Aa flows into the Kleine Nete near the city of Grobbendonk. The well of the river Aa is found in the northern part of the Kempic Plateau near the communities of Merksplas and Turnhout. It has a total length of 36.8 km and a drainage area of about 23,700 ha. The study area is focused on the downstream part of the Aa, near the village of Poederlee (Fig. 1), on a 1.4 km reach controlled by two weirs at the up- and downstream end.

The river Aa is a typical lowland river with low velocities, a small fall and a sinusoidal charactar. Over the years, the river has been straightened and the section was enlarged. The water inflow originates from drainage of rain water and seepage of ground water. The water is rather acid, without chalk and a low amount of minerals, not suitable for organisms. Living conditions for them are caused by food supply in the way of organic drainage of fertilizers from the fields of agriculture along the banks of the river.

The subsoil [11] is predominantly formed by coarse sand. One million year old tertiary sand (as the Formations of Diest, Kasterlee and Berchem) is covered by 10,000 years old quartaire sand. Under these permeable sandy soils, a less permeable clay layer, the Boomse Klei, is present [1].

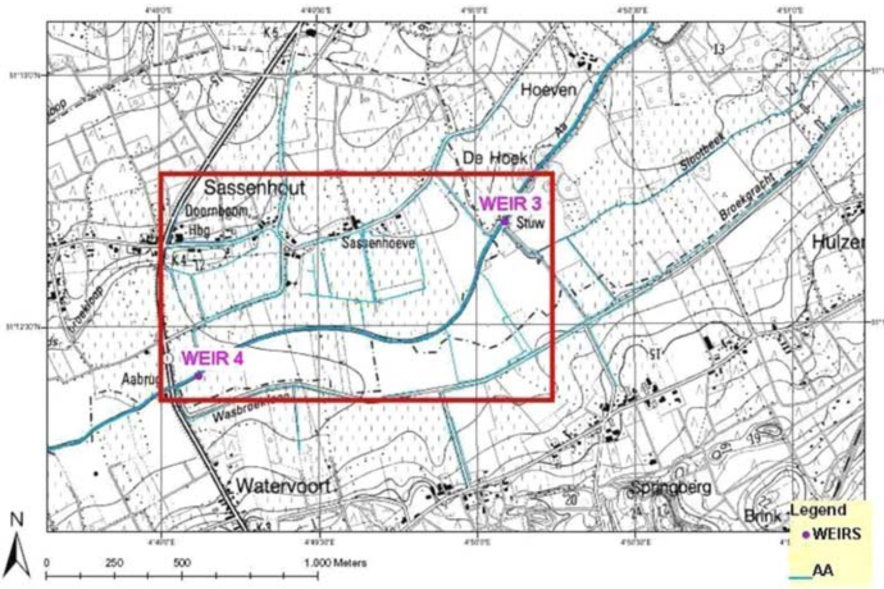

Fig. 1 Study area of the river Aa, Poederlee, province of Antwerp, Belgium

2.2 The river Biebrza

The Biebrza River and surrounding wetlands are situated in the northeastern part of Poland, in an ice-marginal valley, an area of 195,000 ha. This region forms the last extensive, fairly undisturbed river-marginal peatland in Europe, containing endangered plant and animal species in a large variety of ecosystems. There are three major basins [27], respectively identified as the Upper Basin reaching from the springs of Biebrza to the mouth of the Netta River; the Middle Basin covering the area from Netta to the mouth of Rudzki Channel and the Lower Basin situated in the southern part of the valley up to the alluvial cone of the recipient Narew River.

The Biebrza river, as a whole, is a typical lowland river. It has mild slopes (in average about 10 cm/ km) and a strong meandering character. It features varying cross-sections and an irregular longitudinal profile. The variability of the hydrological characteristics along the river is also typical. This is due to the fact that the valley intensively drains the surrounding plateau and the outwash plain into the river. The surface water system is quite complicated consisting of a complex drainage system, network of inundation fields and storage areas. The flow is highly influenced by the dense vegetation [23].

3 Methodology

3.1 Hydraulic measurements

Discharge measurements are carried out from a bridge and from a boat in different sections along the stretch of both the river Aa and Biebrza. The method used is the integration of the velocity field over the cross section as is explained in [14]. Velocities were measured at different depths on different verticals along each section.

Two systems are used for measuring the velocity of the water. In case of open water (no vegetation), hydrometric propellers (Type: OTT, C31 Universal Current Meter) are used. In locations where vegetation might hinder the mechanical functioning of the propeller an electromagnetic instrument (Type OTT, Nautilus C2000/SENSA Z300 and Valeport, Type 801) is applied. The latter instrument has no moving parts which can interfere with the macrophytes. The device is wear-resistant and maintenance free.

The accuracy of these electromagnetic devices is up to 0.5% [21] of the velocity while for the propellers the accuracy is 1% [19]. Furthermore, deviations are larger for the lower range of velocities. The flow characteristics and the precision of measuring water depths also influence the accuracy. Measurements over the year show an overall accuracy of 2–5% for the determination of the discharge. Accuracy calculation of the discharge is based on the measurement error on the velocity and the wetted cross section area, as is described in [10].

3.1.1 The river Aa, Belgium

Several measurement campaigns have been organised to collect hydraulic data (water levels and discharges). The discharge of the river Aa was also measured monthly upstream and downstream the selected stretch since September 2004. Water levels at the weirs on both sides of the stretch are registered continuously by the Hydrological Information Centre (HIC) of Flanders Hydraulics Research. Water levels are registered making use of levelled staff gauges (accuracy 0.5 cm).

In this study, the Manning coefficient for the river Aa is calculated according to three different approaches, in the following mentioned as ‘Approach 1’, ‘Approach 2’ and ‘Approach 3’. ‘Approach 1’ calculates the roughness coefficient directly using Manning’s equation. Second way (Approach 2) of calculating the Manning coefficient is by using the numerical model HEC-RAS solving the complete Saint-Venant equations (in steady state conditions known as the Bresse equation). Fitting allows to determine the roughness value. ‘Approach 3’ is similar to ‘Approach 2’ but is using a simplified geometry.

3.1.2 The river Biebrza, Poland

On the river Biebrza, several measurement campaigns were carried out in the period April–June from 1999 up to 2006. Spring is the period with a wealthy plant growth, so this period is the most interesting from both, ecological and hydraulical point of view.

In Fig. 2 the schematic plan of the Biebrza river shows the locations where measurements are carried out. A substantial contribution of the tributaries to the total discharge in the river and the importance of the groundwater inflow between the tributaries becomes clear.

3.2 Biomass determination

In the river Aa, macrophytes found are various leaved water-starwort (Callitriche platycarpa), rigid hornwort (Ceratohyllm demersum) and floatingleaf pondweed (Potamogeton natans). Sampling is carried out upstream, downstream and half way the stretch. In each of these

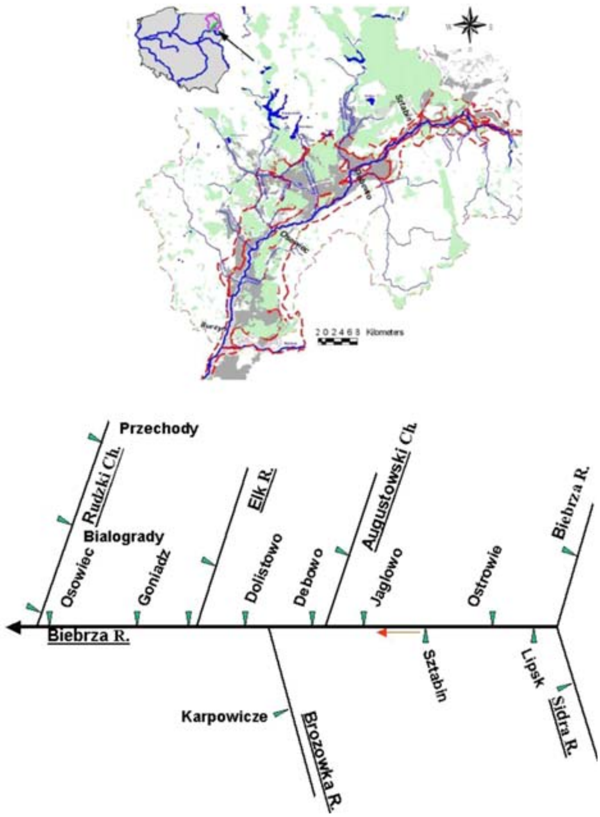

Fig. 2 Study area of the Biebrza river, Poland and schematic view, with indication of the measuring points

cross-sections, the amount of macrophytes is determined each meter, at the same position were the discharge measurements are carried out. First the fresh weight (g/m^2) of the plants is defined, afterward, also the dry weight (g/m^2) is postulated.

For the Bierbza river, the same procedure is followed, but plants occuring are sparganium (Sparganium), floatingleaf pondweed (Potamogeton natans), reed canarygrass (Phalaris a-rindinacea) and yellow pondlily (Nuphar luteum). The sampling of the macrphytes is carried out with a sampler as described in [18]. This instrument has no moving parts, its primary components are a cutting blade fixed to the base of a vertical shaft to shear off plant stems at the substrate surface, and a collection rake to allow retrieval of the freed vegetation. The sampler is well suited for the measurements in this study, because a large variety of macrophytes over a range of conditions can be sampled, while possessing the design features of prime importance: lightweight, low cost and easily used.

3.3 Quality of the measurements

3.3.1 The river Aa

It was necessary to check the sensitivity of the results to measurement errors, there small variation on the Manning coefficient has major implications on its use in hydraulic modelling [9]. Therefore, a comparative study of the variation of the Manning coefficient, based on the

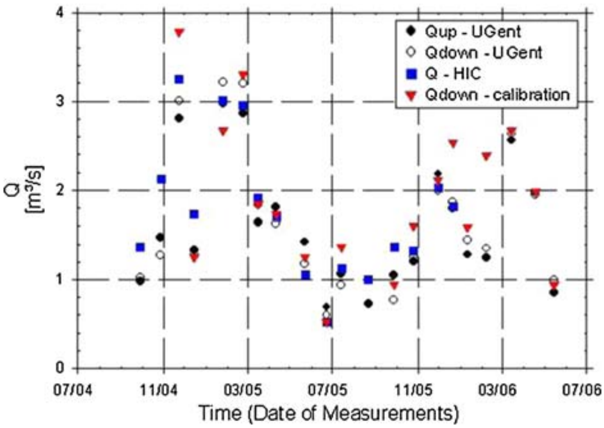

Fig. 3 Comparison of the discharges; measured by UG, calculated out of the calibration formula and calculated by HIC

measurements of Flanders Hydraulics Research, Hydrological Information Centre (HIC) and the measurements of UG is carried out. Furthermore, the discharge measurements of UG are compared to the values of HIC and to the values calculated out of the calibration formula of the downstream weir. Therefore, the water height over the flap of the weir is measured. Results for that are in the same range of the measured and registered values. For the comparison, river characteristics (as the wetted cross section and the river width) are used as measured by UG.

The Hydrological Information Centre (HIC) of Flanders Hydraulics Research has registered the water levels and the discharge in the studied stretch during 2004 and 2005. The Manning coefficient was calculated using the HEC-RAS model as this numerical approach gave the best results. For each of the monthly measured values, the upstream and downstream discharge is determined. There is only seen a small difference between both values (Fig. 3), due to groundwater inflow/outflow, to little tributary inflow between the sections and to inaccuracy of the measurements. Besides, also the discharge based on the calibration formula of the downstream weir, is calculated. In general, both values are in good agreement. The small deviations that sometimes occur can be explained by vegetation patches disturbing the free flow over the weir.

It should be mentioned that the values of HIC are estimated starting from the measurements in two neighbouring stations and taking into account the surface of the corresponding catchment areas. Due to this approximative determination of the discharges, differences can be remarked.

Three different curves, used for the calculation of the Manning coefficient, are presented in Fig. 4. First, the Manning coefficient calculated out of the measured values upstream of UG (UG measured), second, based on the downstream measured values of UG, third, the Manning coefficient based on the HIC-values registered at the same moment of the measurements of UG (HIC measured). All these values are calculated by the numerical model Hec-Ras.

The Manning coefficient is increasing from May until full summer, reaches the highest values in July and is decreasing from October–November on. This trend accompanies the vegetation growth in spring and summer. Maximum values of the Manning coefficient in 2005 are somewhat larger than 0.4 (UG) and 0.5 (HIC).

As can be seen, the deviations of the Manning coefficient based on the datasets of UG are rather small, result of good registration and measurement. Using the discharges estimated by

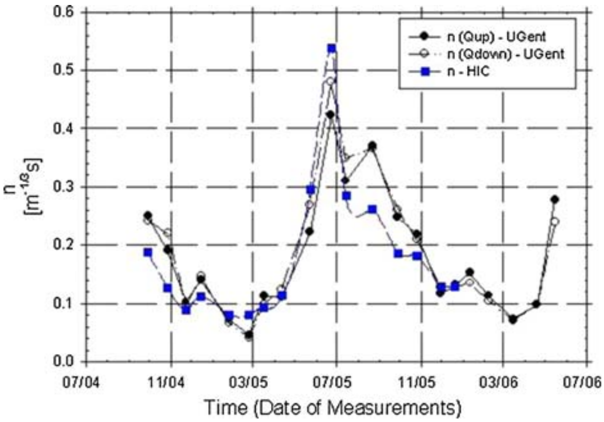

Fig. 4 Comparison of the Manning coefficients; calculations based on the measurements of UG and the registrations of HIC

HIC, the differences become bigger. The biggest deviations can be remarked from July 2005 to October 2005, probably due to the mentioned reason: difference in the discharges based on the estimations of HIC.

This comparison illustrates the importance of accurate information on hydraulic data with regard to the determination of the Manning coefficient as a key-value in numerical modelling.

It is clearly shown that presence of vegetation adds an extra roughness to the channel and influences the water levels. As there is a big variation in the amount of vegetation over the year, the roughness coefficient will change substantionaly.

3.3.2 The river Biebrza

Several intensive field-measuring campaigns have been developed in different seasons. In all these locations (3.1.2) discharges were recorded. Usually, the measurements were conducted twice in order to increase the measurement accuracy. The local water surface has been recorded in multiple, discrete cross-sections along the river leading to a fairly accurate recognition of the longitudinal water surface profile.

3.4 Determination of the Manning coefficient

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 open channel flow are based on the Saint-Venant equations [5]. These equations (continuity equation and momentum equation) are the one dimensional simplification of the Navier Stokes equations, which describe fluid flow in three dimensions. By calculation of the discharge and the water levels, the Saint-Venant equations allow for the calibration of the roughness of the channel (expressed by the roughness coefficient or friction factor) by comparing with field data. Here, this roughness is represented by the Manning coefficient n and is calculated from the energy slope.

For steady flow, the momentum equation is simplified and is known as the Bresse equation (Eq. 1).

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

with Q = discharge (m^3/s), A = wetted cross section (m^2), B = channel width (m), g = gravity (m/s^2), S_f = energy slope, S_0 = bottom slope (−), h (m) = water depth, s (m) = distance along the channel.

The Manning coefficient n ($m^{-1/3}s$) is easily linked to the Bresse equation (Eq. 1) and the expression for the energy slope S_f (Eq. 2) by the roughness coefficient of Darcy-Weisbach f [−] (Eq. 3):

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

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

with P = wetted perimeter (m), R = hydraulic radius (m) and n = Manning coefficient ($m^{-1/3}s$).

In steady state conditions and assuming uniform flow, the energy slope is equal to the bottom slope ($S_0 = S_f$) and discharge, water levels and Manning coefficient are linked directly by Manning's equation (Eq. 4) [5]. The roughness coefficient is determined out of the measurements of discharge and water levels by (Eq. 4). Further, channel flow is connected with the hydraulic and geometric characteristics of the channel.

Substituting Eq. 3 in Eq. 2 yields:

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

i.e. the Manning equation.

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.

In the Biebrza river, measurements have been carried out each year in spring, to measure the influence of the present vegetation. The campaigns started in 1999 and are still going on. Specific measurement points on the river are selected as is indicated on Fig. 2. Furthermore, in a specific stretch, the variation of the Manning coefficient over the distance is measured.

3.5 Roughness coefficient according different methods

Theoretical calculation of the Manning coefficient is difficult. The Manning formula is most used for expressing resistance [4]. It might be determined by empirical formula, e.g. [6] who splitted channel resistance into several parts, including the bed material, presence of vegetation in the river, meandering, etc.

$$n = (n_0 + n_1 + n_2 + n_3 + n_4)m \quad (5)$$

where

n_0 = basic value, for a straight, uniform channel,
n_1 = irregularities of the bottom,
n_2 = variations in the geometry of the channel,

n_3 = obstacles,
n_4 = vegetation,
m = correction factor for meandering

Important is to take into account not to double conditions that are already included in another parameter. The equation requires an estimate of separate n factors for different channel conditions.

However, the large variability of the coefficients involved leaves too many degrees of freedom to allow an accurate determination of the roughness coefficient. Another methodology is to use a set of pictures from literature which represent a comparable situation or to make use of graphs and tables [12]. One can find photographs and descriptive data of typical rivers for which the Manning coefficient is determined in [3], for United States rivers, and [15], for New Zealand rivers. Their main advantage derives from a wider range of bank vegetation types and density and multiple roughness values for each river calculated at different discharges. Using the books asks for a lot of experience in the field and looking for comparable rivers in the Flanders region as in the United States or New Zealand. As this research started from scratch, measurements over the year were carried out to have an idea of the roughness coefficient of the river. Next to these mentioned methods, also formulas to determine the roughness coefficient based on the bed material are published. [17] related the Manning coefficient to hydraulic radius and particle size on the basis of samples from 11 stream channels having bed material ranging from small gravel to medium-sized boulders. Analogous research, based on the characteristic bed material, is carried out by [20]. Using Cowan's formula for the river Aa leads to values from 0.04 $m^{-1/3}s$ for winter situations (low amount of vegetation) to $0.15\,m^{-1/3}s$ for summer situations (high amount of vegetation). Using the tables with Manning values mentioned in [4], leads to the same range. The calculated Manning coefficient, based on measurements of water level and velocity confirms these values for autumn and spring situations, but during summer, Manning coefficients are much higher and can reach values up 0.4 and even $0.5\,m^{-1/3}s$. Therefore, the Manning coefficient is considered as the result of the Bresse equation.

Channel roughness is influenced by grain size of the bed material, the surface irregularities of the channel, the channel bed forms (such as ripples and dunes), erosion and deposition characteristics, meandering tendencies, channel obstructions (downed trees, exposed root wads, debris, etc.), geometry changes between channel sections, vegetation along the bankline and in the channel, etc. [12].

One single value of the roughness coefficient has to include all these parameters (cf. Bresse equation, where the roughness is presented as f). Furthermore, as vegetation is strongly dependent on the season, the roughness coefficient can be fairly different for summer and winter conditions.

As different approaches show great variability of n, they do not guarantee accurate values for the roughness coefficient and a determination of the roughness starting from measurements is recommended [26]. Therefore, some assumptions are made: first, the bottom slope and the cross sections are supposed to be stable, so sediment transport and transformation of the channel bed are not included. Further, the friction factor or roughness coefficient (expressed by the Manning coefficient n) is set as a constant value in the channel and at the banks. The flow is regarded in a 1-dimensional way, with uniform velocity over the cross section. As mentioned in Sect. 3.4, the Manning coefficient n has been calculated in two ways: firstly, when uniform flow is supposed, the energy slope is equal to the bottom slope and n is obtained from the Manning equation. Secondly, when the Bresse equation is used, steady state flow is assumed and the roughness coefficient *n* is calculated from the energy slope.

Due to the wide range of factors influencing the Manning roughness coefficient, accurate measurement is difficult and very extensive, therefore, a well established model allows to compute Manning's coefficient for any discharge on any location.

The data from several measurement campaigns allow to determine the variation of the roughness coefficient [friction factor or Manning coefficient *n* ($m^{-1/3}s$)] as a function of time, type and density of vegetation, hydraulic parameters, etc.

The importance of the use of a correct Manning coefficient for the river is clearly illustrated by this example, representing the variation of a flood wave along a 25 km long trapezoidal shaped river stretch, increasing the roughness coefficient by a factor 2, causes a large reduction of the discharge. While a Manning coefficient of 0.02 $m^{-1/3}s$ reduces the peak discharge of the inflow hydrogram after 12 km with 17%, a Manning coefficient of 0.04 $m^{-1/3}s$ reduces the value with 23%. So, accurate knowledge of the Manning coefficient is necessary to guarantee reliable predictions.

4 Results and discussion

4.1 Manning coefficient as a function of time

The variation of the Manning coefficient as a function of time has been investigated in the river Aa. The three calculation methods (cf. Sect. 3.1.1) for the Manning coefficient are applied and calculations are carried out separately for both the discharges measured up- and downstream.

For each of the monthly measurements, the Manning coefficient is plotted in Fig. 5. The different calculation methods are indicated with a different symbol. Using the same approach, the Manning values based on both the up and downstream discharge values are very similar.

For the measurements of November 2005, January and February 2006, differences in the Manning coefficient are negligible. The scatter is larger for the measurements of September, May and June, which is probably due to the larger amount of vegetation. During winter, the presence of vegetation remains rather small and constant, while during spring and summer, the Manning coefficient increases rapidly with the amount of vegetation.

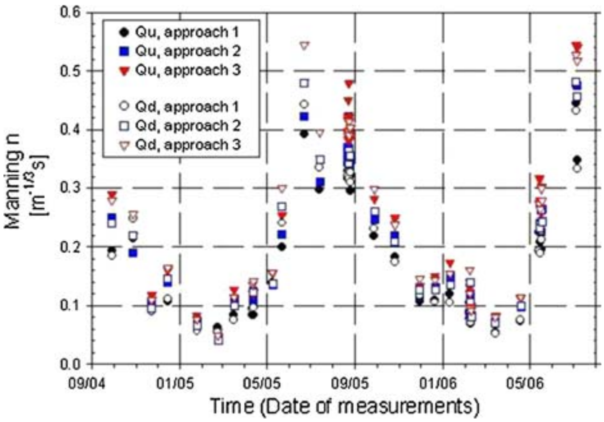

Fig. 5 Manning coefficient *n* for the upstream (Qu) and downstream (Qd) value of Q: comparison of the values calculated using three approaches: Manning's equation given by Eq. 2 (1), fitting based on the Saint-Venant (Bresse) equations (HEC-RAS) (2), and fitting using an average section (3)

Table 1 Values of the correlation coefficient for the fitted curve and the measured values, calculated for each of the 'Approaches' [Manning's equation given by Eq. 2 (1), fitting based on the Saint-Venant (Bresse) equations (HEC-RAS) (2), and fitting using an average section (3)] for both the upstream and downstream discharge

R^2	Qupstream	Qdownstream
Approach 1	0.8903	0.8725
Approach 2	0.8993	0.8895
Approach 3	0.8980	0.8884

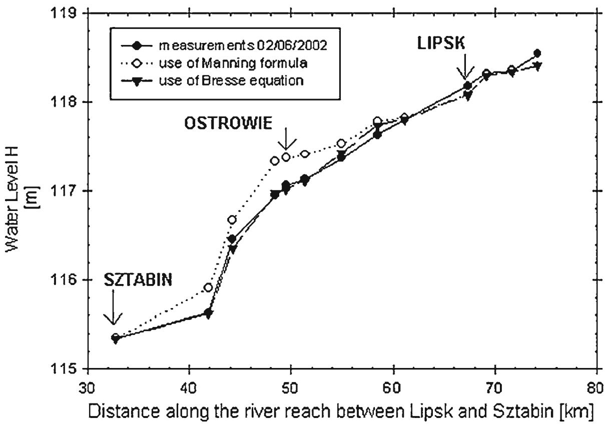

Fig. 6 Comparison between measured water levels and the values (calculated using the Manning coefficient *n*) obtained from Mannings and Bresse's equation

From this, a seasonal trend is observed in the value of the Manning coefficient with low values appearing in January, February (winter), a slight increase in March and April and a fast rise in May and June. Then, the resistance remains high during summer. During winter, most plants have disappeared, yielding lower flow resistance and a decreasing roughness coefficient.

As can be seen, during spring, Manning coefficients are up to 10 times higher than the values during winter.

Based on the results in Fig. 5, a curve is fitted to the trend in the *n*-values. The best fit is obtained using a polynomial function (power 6). Six curves are calculated , for each of the 'Approaches'. For each of the curves, the correlation coefficient is calculated and shown in Table 1. As can be seen, the correlation is slightly better for the upstream discharges. Besides, the numerical approach (Hec-Ras model [16], based on the Bresse equation for uniform flow) turns into the best fit, so, this method will be used for all further calculations. This corresponds also with the findings of Fig. 6, where larger deviations are noticed for the results of the simplified Manning equation.

From the findings in Table 1, one can also conclude that using a simplified geometry doesn't affect very much the accuracy of the calculations.

From Fig. 5, some variation over the season '04-'05 and '05-'06 can be seen, but the difference in these two years is not remarkable.

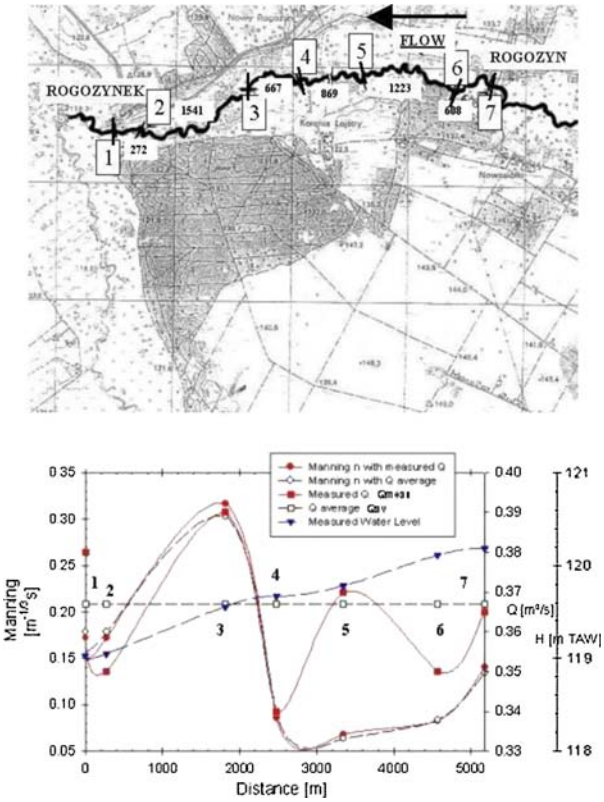

Fig. 7 Measured discharge Q, measured water level H and calculated Manning coefficients *n*

4.2 Manning coefficient as a function of distance and water level

In Fig. 6, the calculation of the Manning coefficient is carried out for the upstream part of the river Biebrza, from Lipsk to Sztabin. The resulting water levels between Lipsk and Sztabin obtained from Bresses equation correspond very well with the measurements, while these obtained from Manning formula return larger values of the water levels in the downstream part (neighbourhood of Sztabin) of the stretch. The results using Bresse's equation are much more accurate than those from the Manning equation.

Using the Manning formula, the Manning coefficient is $0.16\,m^{-1/3}s$ upstream Lipsk, for Lipsk to Ostrowie, this value is $0.27\,m^{-1/3}s$ and for the downstream part, the Manning coefficient is $0.65\,m^{-1/3}s$. Use of the Bresse equation, has resulted in more accurate values for the downstream part; in the neighbourhood of Sztabin (last two points), the Manning coefficient was $0.4\,m^{-1/3}s$, while this value was $0.5\,m^{-1/3}s$ for the other points between Sztabin and Ostrowie.

As the roughness is strongly dependant on the vegetation density, the Manning coefficient varies with distance due to the various amount of vegetation through the river. This variation was investigated on the river Biebrza (Poland) in the stretch between Rogozynek and Rogozyn, more than 5 km long, where the Manning coefficient is calculated in seven sections (Fig. 7). In each of the cross sections, the water level H and the discharge Q have been measured in June 2005 during a steady flow situation. The results are shown in Table 2 and Fig. 7.

Table 2 Stretch Rogozynek (downstream)–Rogozyn (upstream) of Biebrza River: measured water levels H and discharges Q in June 2005 as a function of distance from the upstream boundary, and calculated Manning coefficients *n*

	Water level H (m TAW)	Distance (m)	Q (m^3/s)	n (Qmeas) ($m^{-1/3}s$)	n (Qav) ($m^{-1/3}s$)
1	119.029		0.380		
2	119.105	272	0.350	0.172	0.178
3	119.557	1541	0.390	0.317	0.303
4	119.667	667	0.340	0.085	0.090
5	119.780	869	0.370	0.068	0.063
6	120.114	1223	0.350	0.082	0.083
7	120.190	608	0.365	0.140	0.134

The Manning coefficient is calculated based on the Manning formula, once with the discharge (Qmeas) measured in each section, once with the average discharge (Qav $=$ $0.367 m^3/s$) of all sections. Water levels to calculate the energy slope S_f are measured in each section. The average discharge is used to look at the deviations due to the influence of the accuracy of the discharge measurement. Because of the comparable discharges in each section, the deviations are small. In spite of the constant discharge, the Manning coefficient differs from one location to another. The smaller influence of the different discharges is also clear when the values for the Manning coefficient under the different calculations (i.e. with different discharge values) are compared. The Manning coefficient value is very similar in both cases. The big rise in Manning coefficient between Sects. 2 and 3 is due to an obstruction, a piece of wood, in the river. It proves that these natural and temporal situations can have a big influence on the calculation results.

4.3 Manning coefficient in relation to biomass

The relation between biomass and Manning coefficient has been investigated in the river Aa as in correspondence with the discharge measurements, also the biomass has been determined. For most of the plant species it is obvious that a denser vegetation, results in a lower velocity in the stretch occupied by macrophytes. Floating plants cause a reduction of the surface velocity, while submerged plants influence the complete vertical velocity distribution. A wealthy plant growth causes an obstruction of the drainage because of the reduction of the section, which is a problem especially for small discharges (low velocities). For higher discharges (high velocities), the plants are pushed down, by this reducing their influence.

For emerged plants (as reed), certainly higher discharges can cause problems if the plants, that in normal conditions can be seen above the water, are pushed into the water and cause a reduction of the cross section. During peak growth of the vegetation (April–June), the biomass as well as the Manning coefficient are inversely proportional to the flow velocity in the water course [24].

Figure 8 shows the variation of the biomass over the year and the relation between the biomass and Manning coefficient *n* measured at the river Aa during 2005. The biomass is the amount of vegetation in the channel and is expressed in g/m^2 (horizontal surface). Manning's coefficient is linked to the biomass and by this the biomass is a good parameter for the

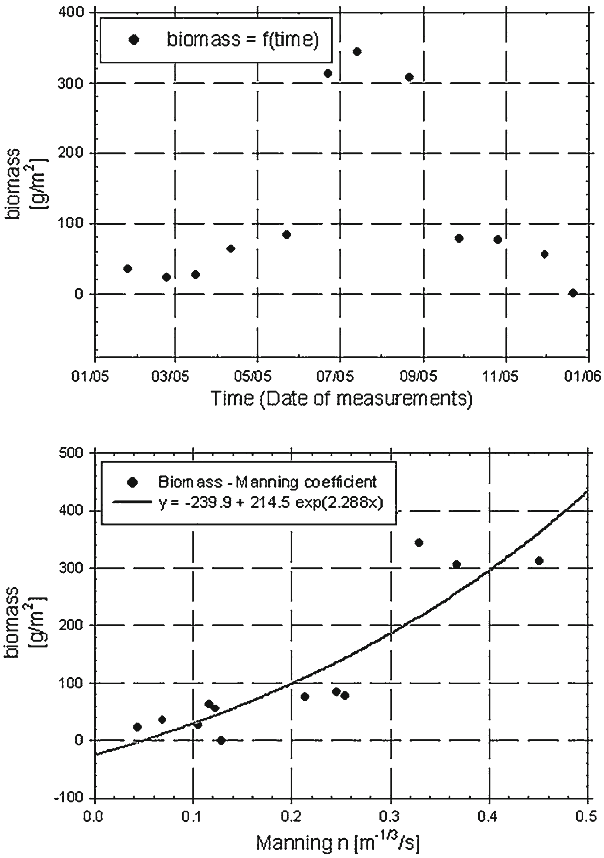

Fig. 8 The measured biomass in the river Aa as a function of time (*left*) and the relation between Manning coefficient and biomass (*right*)

added roughness of the channel. A positive correlation between the biomass and the Manning coefficient was found by Brooker and mentioned in [24] and is also shown in Fig. 8.

As can be seen, more biomass results in a higher Manning coefficient. An exponential curve is fitted to the values in Fig. 8. Similar results and curves have been presented in [7] for the Grote Kaliebeek and the Desselse Nete.

For low values of the biomass ($<100\,g/m^2$), the Manning coefficient is varying between 0.04 and $0.14\,m^{-1/3}s$. This variation is due to different discharges. The lowest values of the Manning coefficient correspond with a zero level of biomass.

It becomes evident again that the Manning coefficient is strongly increasing in spring, due to explosive vegetation growth (Fig. 8). During summer, the roughness reaches a peak value. After dying out of the plants, the Manning coefficient is also decreasing. This cycle is almost the same for each year (Fig. 5). A sudden fall in the roughness during the vegetation period can be due to the wash away or flattening of a vegetation patch with large discharges. The roughness decreases when the discharge increases. Hence, the variation of the Manning coefficient is influenced by both discharge and vegetation.

Figure 9 shows that lower discharges correspond with higher Manning coefficients. A larger amount of vegetation, reduces the cross sections open to flow so that less water can pass in a given time period. Discharges are varying between 0.6 and $3.2\,m^3/s$. Manning

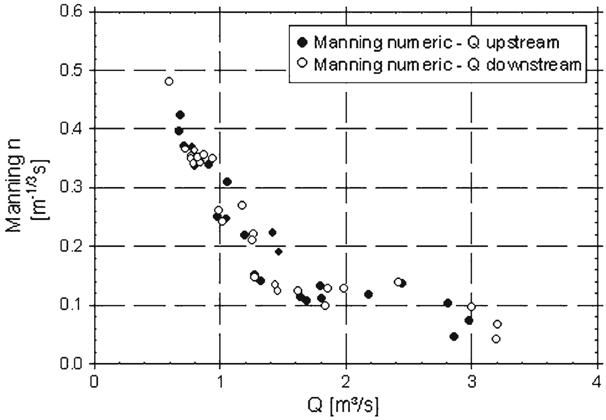

Fig. 9 Relation between Manning coefficient *n* and upstream and downstream discharge Q

values range from 0.05 to 0.5 m$^{-1/3}$s. The trend follows Eq. 4 and is the same for upstream and downstream measured discharges.

Due to vegetation and the consequential influence of backwater, the friction slope S_f of a river stretch can vary extremely. Figure 10a shows the situation in the stretch of the river Aa. Two cases are considered, a Manning coefficient of 0.046 m$^{-1/3}$s, which was calculated with the Manning formula (Eq. 4) and the measurements of February '05 and a Manning coefficient of 0.423 m$^{-1/3}$s (June '05). The Manning coefficient is 9 times higher in June when there is a wealthy vegetation. Starting from the same downstream water level and using a discharge of 1 m^3/s, the upstream water level is calculated for both values of n. In June, a value of 10.83 m for the upstream water level is calculated, while 10.20 m is obtained in February; this is a difference of more than 0.60 m due to the presence of vegetation.

Figure 10b shows the influence of the discharge on the energy slope S_f. For three different values of the discharge, the water surface profile is calculated. The Manning coefficient does not change. It seems that tripling the discharge results in an increase of the water level of only 0.35 m. So, the impact of the vegetation on S_f is much bigger and explains why a dangerous situation may occur with regard to inundation during summer floods.

5 Conclusions

For the river Aa (Belgium), as well as for the Biebrza river (Poland), an intensive study on the importance of the roughness coefficient is carried out. Hydraulic measurements are performed to set up a data set for implementation in and calibration of numerical models.

For the determination of a correct roughness coefficient, the most important parameter is the accuracy of the hydraulic measurements, using the Manning or Bresse equation. The more simplified Manning equation gives worse results if compared with the more general Bresse equations. A simplified geometry of the river is of less importance.

The Manning coefficient is depending on time, distance and biomass. Also the discharge plays an important role in the determination of the Manning coefficient.

The Manning coefficient is dependent on the time, and shows a seasonal variety (with factor 10). The change over the years is rather small.

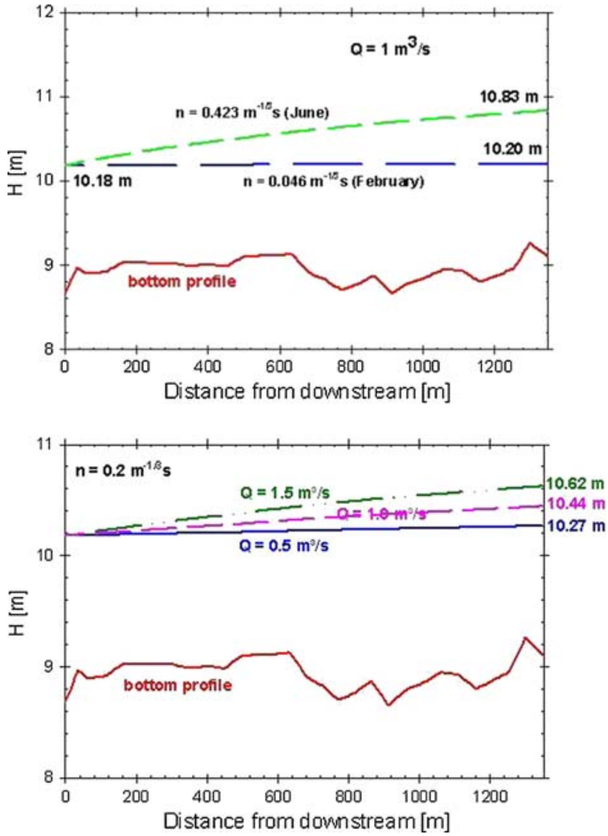

Fig. 10 Influence of backwater of the Manning coefficient on the water level for a given discharge (**a**, *left*) and Backwater influence of the Manning coefficient on the discharge for a given amount of vegetation (**b**, *right*)

Also over the length of the river a variation of the Manning coefficient is seen. This is due to different aspects of the river at different places. Also accidential obstacles have a major influence on the Manning coefficient.

The biomass in the river, so the amount of vegetation, is of major importance for the Manning coefficient. Higher biomass results in higher Manning coefficient. The seasonal variation is due to vegetation growth and die-off over the year. Difference of the Manning coefficient related to distance can also be due to more or other vegetation in the river. This also shows the importance of the mowing patterns in rivers.

Higher discharges corresponds with lower Manning coefficient, and thus lower roughness. This is due to the flattening of the vegetation with a good flow of the water over the vegetation and occurs for most of the vegetation.

A good determination of the Manning coefficient is important as the influence of the Manning coefficient on the water level in the river is rather extreme. Higher Manning results in higher upstream water levels, which causes a higher risk on flooding.

Finally, the importance of a correct determination of the Manning coefficient for modelling stream flow has been shown.

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The overall objective is to study the physical and biological exchange processes in margins and inundation areas of water courses and how their interactions determine the exchange of water, dissolved compounds and particulate matter. Thanks to Mr. Martin Van Daele and Mr. Stefaan Bliki for their assistance with the discharge measurements. The authors also acknowledge the Hydrological Information Centre of Flanders Hydraulics Research (HIC, Mr. E. Cornet) for providing the discharge and water level data of the river Aa.

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