Case Study: Bed Resistance of Rhine River during 1998 Flood

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Abstract: Detailed field measurements during the 1998 flood of the Rhine River in The Netherlands show that both Manning *n* and Darcy–Weisbach friction factor *f* increase with discharge. The changes in bedform roughness height and friction factors are attributed to the increased dune height during floods. There is a near-peak hysteresis in the dune height measurements. At a given discharge, dunes are significantly larger after than before the peak discharge. The trend is most apparent for the Bovenrijn with weaker variations for the Waal. The methods of Engelund and Vanoni–Hwang provide similar estimates of form drag. When combined with van Rijn's method to estimate grain resistance, both methods tend to overpredict the measured bed friction factor after the peak discharge. These methods perform best when field bedform measurements are available to estimate form drag. The composite effect of primary and secondary dunes should be considered in the analysis of resistance to flow.

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Introduction

The protection of densely populated communities against floods is one of the primary concerns and duties of river engineers. This concern is particularly acute in The Netherlands where dykes and levees protect living communities below sea level. The height of dykes and levees is determined from the flood stage expected at a given period of return. This flood stage depends among other things on: (1) the aggradation or degradation trend; (2) the loop-rating effects due to the dynamic terms of the equation of motion; and (3) changes in bed form configuration during floods. The latter two effects are considered in this paper.

Resistance to flow parameters are normally written either in terms of the Darcy–Weisbach friction factor *f* or the Manning coefficient *n*. The Chézy coefficient *C* is a discharge coefficient and varies inversely with friction factors. It is often assumed that Manning *n* does not change with discharge, and computer models are often calibrated with average flow conditions and extrapolated to flood flows.

The values of friction factors in sand bed rivers depend primarily on bedform configuration which may change from plane bed, to ripples and dunes, to upper-regime plane bed and antidunes. In some cases, alluvial rivers like the Rio Grande are known to plane out with a corresponding decrease in resistance to flow during floods. The specific effects of bedforms in terms of classification characteristics and resistance to flow can be found in Chabert and Chauvin (1963); Simons and Richardson (1963, 1966); Guy et al. (1966); Engelund and Hansen (1967); Alam and Kennedy (1969); Van den Berg and Van Gelder (1993); and Julien and Raslan (1998). Specific studies on the geometry of sand dunes and resistance to flow can be found in Vanoni and Hwang (1967); Engelund (1977); Van Rijn (1982, 1984); Wijbenga and Klaassen (1983); Yalin (1985); Ogink (1989); Wiberg and Nelson (1992); Nelson et al. (1993); and Raudkivi (1997). Studies on the properties of bedform height and wavelength have been pursued by De Leeuw (1985); Moll (1985); Moll et al. (1987); Lai (1998); and Zedler and Street (2001). Field investigations on bedforms and properties of large alluvial channels include Peters (1978); Shen et al. (1978); Klaassen et al. (1988); Raslan (1991); and Julien and Wargadalam (1995). Many other references on this subject could also be cited.

The Rhine River branches have been studied for a long time, and the recent literature on bedform characteristics and sediment transport includes Klaassen (1981, 1987); Van Urk (1982); Ogink (1984); Adriaanse (1986); Termes (1986, 1989); Brilhuis (1988); Kamphuis (1990a, 1990b); Wijbenga (1990, 1991); Julien (1992, 1995); Julien and Klaassen (1995); Kleinhans (1996, 1997); Ten Brinke (1997); Ten Brinke et al. (1999); Wilbers (1997, 1998a, 1998b); and Klaassen et al. (1999). In the analysis of bedform geometry in large rivers, Julien (1992) and Julien and Klaassen (1995) showed that the beforms of the Rhine River branches generally grew in amplitude and length during the floods and decayed after the floods. These observations were confirmed with more recent measurements by Ten Brinke et al. (1999) and Wilbers and Ten Brinke (1999). Specific measurements in the Rhine River branches during the February–March 1997 flood documented the growth, decay, and migration rates of dunes during a large magnitude flood. Dunes were omnipresent but were particularly significant a couple days before and after peak discharge in the sand-gravel bed sections and during the entire period in sand-bed sections. Dunes in the sand-bed section reached 1.2 m in ampli-

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tude and 52–59 m in length, with smaller dunes of 0.5 m in height and 15 m in length superposed on the large ones. From the results of laboratory experiments at Delft Hydraulics, simulating conditions in the Dutch Rhine, it has been inferred that upper-regime plane bed may not be reached during conditions such as the 1998 flood (Termes 1986; also in Julien and Klaassen 1995).

As dunes grow and decay during floods, it seems relevant to question whether bed resistance to flow is affected by changes in dune geometry. The complexity of resistance to flow analysis stems from the fact that resistance to flow in rivers is a composite of bed resistance and flood plain resistance. In the case of the Rhine River branches, there is also additional resistance caused by groynes or spur dykes built on both river banks to control ice formation and maintain a constant navigation channel width. The presence of bedforms should only affect bed resistance without affecting groynes and floodplain resistance. Hence, the forthcoming analysis focuses exclusively on the effect of changes in dune geometry on bed resistance to flow.

Bed resistance to flow can be divided into two components: (1) grain shear refers to resistance to flow due to the shear stress applied on individual grains on the river bed; and (2) form drag refers to resistance to flow due to the pressure differential and energy loss in the large eddy located on the lee side of dunes and ripples. There are methods to calculate form drag and bed resistance to flow as a function of bedform height, bedform length and flow depth. Examples of methods include the procedures developed by van Rijn, Vanoni–Hwang, and Engelund. In general, one expects from these methods that an increase in dune height increases resistance to flow. Conversely, longer dunes decrease bed resistance. The problem is also exacerbated by the fact that dunes do not have homogeneous properties and small dunes are often superposed on top of large dunes. In this paper, a distinction is made between primary and secondary dunes. The primary dunes are the large dunes that dominate the bedform population during the rising stage of the flood hydrograph. These dunes typically have wavelengths in excess of 20 m and increase 2–3 times in length during the floods. The secondary dunes generally develop on top of large dunes during the falling stage of the hydrograph. Secondary dunes typically measure less than 15 m in length.

Objectives

The primary objective of this study is to determine the changes in bed resistance to flow during the 1998 flood of the Rhine River. A reach of the Rhine and Waal Rivers near the bifurcation with the Pannerdensch Kanaal is selected because of the very high quality of the hydraulic and sediment data collected on a daily basis during the flood of October and November 1998. As a second objective, existing methods to predict bed resistance to flow are applied and tested with field measurements. The analysis will specifically determine whether the methods of van Rijn, Engelund, and Vanoni–Hwang appropriately predict the changes in resistance to flow during both the rising and falling stages of the 1998 flood.

Study Location and Field Measurements

The Rhine River originates in the Alps and flows through Switzerland and Germany to the Netherlands. The average discharge of the Rhine River near the Dutch–German border is 2,300 m^3/s and varies as a function of rainfall and snowmelt. In 1993–1995, the Rhine River experienced maximum discharges of 11,000 and 12,000 m^3/s, among the highest discharges ever recorded. A peak discharge in excess of 7,000 m^3/s is experienced on average every 4 years. With respect to these discharges, the peak value of 9,464 m^3/s in 1998 also figures among the largest floods.

In the Netherlands, the Rhine River is relatively straight with an average sinuosity of 1.1 and flows from right to left as shown in Fig. 1. The bifurcation point identified as Pannerdensche Kop at river Kilometer 867.2 divides the flow into the Waal River to the west and the Pannerdensch Kanaal flowing to the north. The discharge ratio between these branches is approximately two thirds to the Waal and one third to the Pannerdensche Kanaal.

Two cross sections are considered: (1) one cross section of the Bovenrijn approximately 1 km upstream of the bifurcation with the Pannerdensch Kanaal at river kilometer 866.2; and (2) one cross section of the Waal River located a few kilometers downstream of the bifurcation at river kilometer 870.5 (Fig. 1). At each cross section, the three verticals of particular interest are: (1) the centerline vertical; (2) the vertical located 67 m to the left, south, of the centerline; and (3) the vertical located 67 m to the right, north, of the centerline.

The period of record extended from October 29 until November 19 and the peak discharge of 9,464 m^3/s was measured on the Bovenrijn at Lobith on November 4, 1998. Fig. 2 illustrates the variability in the main parameters in terms of discharge, flow depth, and flow velocity for the Bovenrijn in Fig. 2(a) and the Waal in Fig. 2(b).

Stage Measurements

Regular stations measured the water surface elevation called river stage with reference to the Dutch Ordinance Datum (NAP). Hourly measurements were available at: (1) Lobith located at river kilometer 862.18; (2) Pannerdensche Kop located at river kilometer 867.22; and (3) Nijmegen located at river kilometer 884.87. The slope of the Bovenrijn was determined by taking the difference in water surface elevation between Lobith and Pannerdensche Kop. Similarly, the slope of the Waal was determined by taking the difference in water surface elevation between Pannerdensche Kop and Nijmegen. The river gradient is approximately 1.1×10^{-4}. Near the flood peak on November 5, more detailed laser altimetry data were available to determine the local water surface slope of the Bovenrijn–Waal in the reach between river kilometers 866 and 869.

Bathymetry

Longitudinal and cross-sectional profiles of the bed elevation were obtained from single and multibeam echosounding. Echosounding records were made available on a daily basis from October 29 until November 19. The measurements set included data from: (1) a single-beam echosounder ATLAS DESO 25 for 3 days; (2) a multibeam echosounder SEABAT 8101 with a large number of beams and a wide band width for 2 days; and (3) a multibeam echosounder SEABAT 9001 with a relatively small number of beams and hence relatively small total band width used all other days of the campaign. The survey vessel was equipped with a two-dimensional horizontal positioning system called the differential global positioning system controlled by a desk-top computer. With the multibeam echosounder, the river bed was scanned over a width equal to 3–5 times the flow depth, depending on the type of echosounder in use. The absolute combined accuracy in the vertical measurements range from a few centimeters (multibeam) up to 20 cm (single beam). Multibeam soundings are far more accurate owing to the high density of the measurements, up to 15–20 flow depth measurements per square

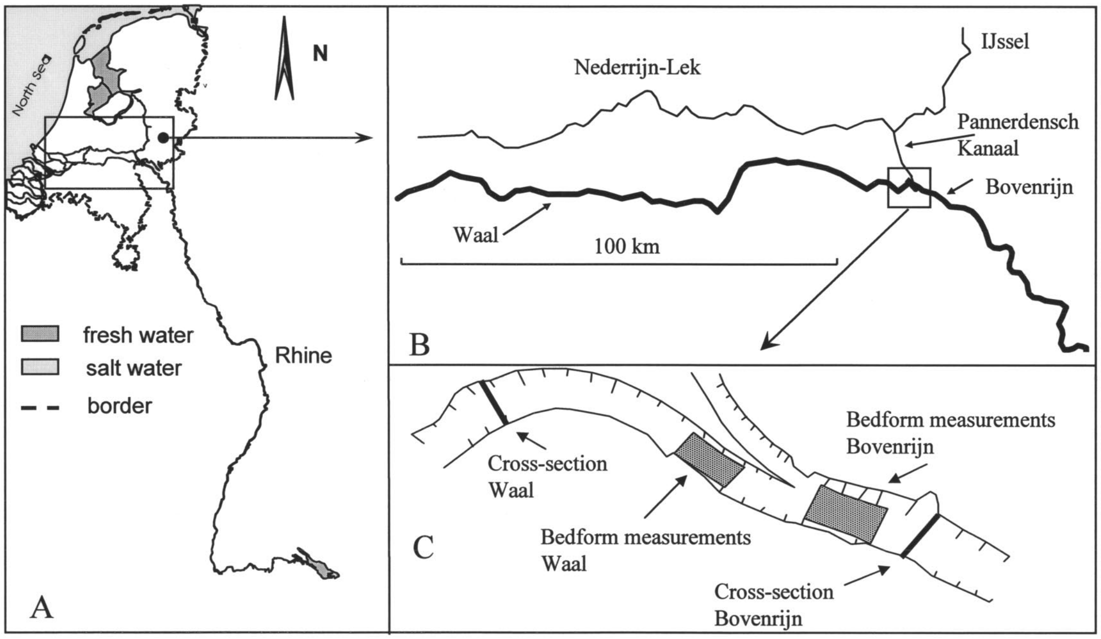

Fig. 1. Study area: (a) Rhine River; (b) Dutch Rhine River; and (c) study area

meter. All single and multibeam soundings were recorded along tracks parallel to the river banks.

Acoustic Doppler Current Profiler Velocity Measurements

Acoustic doppler current profiler (ADCP) velocity measurements were available for 6 days of the 1998 flood. The ADCP survey period extended from November 3–6 with additional measurements on November 9 and 11. Since the peak discharge was observed on November 5, the survey period covered the near-peak and falling stage of the flood hydrograph. Each transect was surveyed daily and flow velocities were also measured at numerous verticals along the cross section.

Bed Material

The bed material was sampled at a spacing of 1 km along the entire river reach. Particle size distributions were obtained at the three aforementioned verticals. The data set included median grain sizes d_{50} as well as d_{10} and d_{90}. There was a lot of variability in the field measurements and the bed material consisted of a well-graded mixture of sand and gravel. Median grain diameter d_{50} varied between 0.75 and 3.8 mm, the average finer fraction described by the d_{10} was approximately 0.4 mm and the coarser fraction described by d_{90} was as large as 15 mm. A typical gradation coefficient was thus approximately 5 and values of grain size $d_{10}=0.4$ mm, $d_{50}=2.5$ mm, and $d_{90}=12$ mm were considered representative of bed material samples.

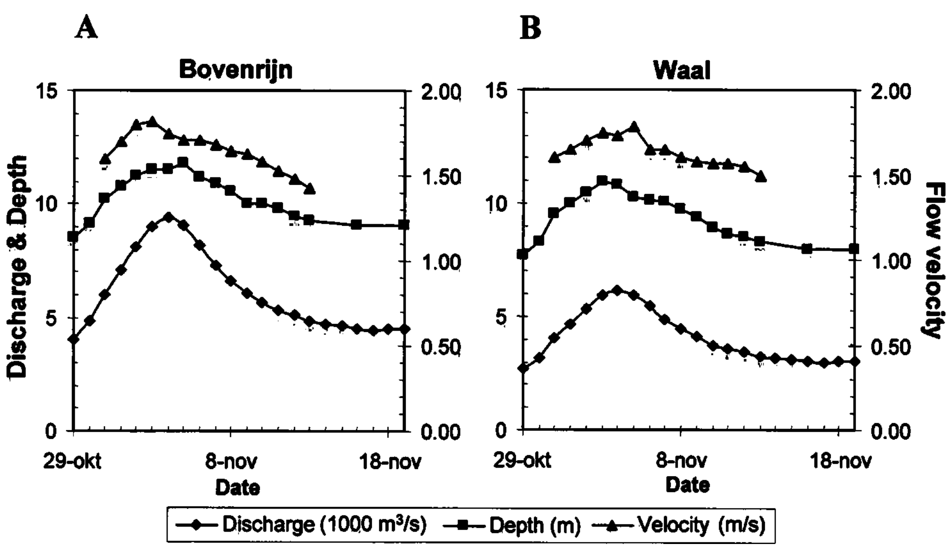

Fig. 2. Flood discharge, flow depth, and velocity: (a) Bovenrijn and (b) Waal

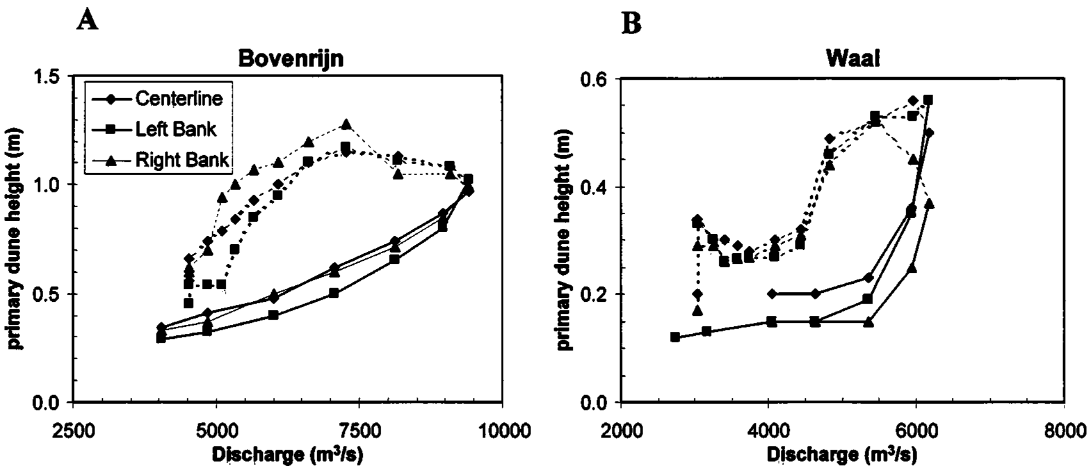

Fig. 3. Primary dune height versus discharge: (a) Bovenrijn and (b) Waal (dashed lines represent falling stage)

Bedform Measurements

Bedform data were recorded about twice per day during the period from October 29 to November 7 and measured about every 3 days thereafter until November 19. The dune properties of the Bovenrijn were measured between river kilometers 866.5 and 867, thus slightly downstream of the cross section and the ADCP measurements (Fig. 1). In the case of the Waal River, the dune properties were measured between river kilometers 868 and 868.5. The south section −67 m contained the average data measured between sections −83 and −50 m. The centerline section was effectively the average of the dune measurements between −16 and +16 m from the centerline. The north section +67 represented the average of the data contained between +50 and +83 m. The data were processed and classified into primary and secondary dunes using the procedure described by Ten Brinke et al. (1999). Bedform measurements of the Bovenrijn show that the primary dune length gradually increased from 8 to 40 m during the flood. The primary dune amplitude increased from 0.34 to 1.15 m on November 7 and then decreased to about 0.5 m after the flood. As the flood receded, the primary dunes elongated and decreased in amplitude and the secondary dunes formed. The secondary dunes formed after November 12 with a wavelength of about 7 m and an amplitude of about 0.25–0.3 m. The primary dunes of the Waal were considerably smaller with a maximum amplitude of 0.56 m on November 5 before disappearing after November 7. Starting November 6, secondary dunes formed on the primary dunes and were the only dunes left after November 7. The length of primary dunes of the Waal ranged from 6 to 18 m with a maximum wavelength measured on November 6 and 7.

A comparative plot of the field measurements in Figs. 3(a and b), respectively, shows the changes in primary dune height with discharge for the Bovenrijn and the Waal. There is a significant counterclockwise hysteresis effect with larger dunes observed during the falling stages of the hydrograph. The height of primary dunes of the Waal is about half the size of the height of the primary dunes of the Bovenrijn. For comparison, the roughness height k_s calculated using Eqs. (4) and (3) represents the size of bed roughness elements as determined from the velocity, depth and slope measurements. As shown in Figs. 4(a and b), the roughness height clearly increases with discharge, especially for the Bovenrijn. When comparing with Figs. 3(a and b), the hysteresis effect is much less pronounced for roughness height than for dune height. The roughness height is found to be approximately one half of the primary dune height. The results at the centerline compare very well with those on both sides of the channel. The lateral variability in hydraulic roughness characteristics is therefore not a factor in this analysis.

Resistance to Flow Analysis

Three parameters describing resistance to flow are calculated from the measured hydraulic and sediment parameters: (1) Manning n; (2) Chézy C; and (3) Darcy–Weisbach f. Calculations of local values of Manning n are based on the field measurements of depth-averaged velocity V, the local flow depth h, and the reach-averaged slope S, as per the formula

$$n = \frac{1}{V} h^{2/3} S^{1/2} \tag{1}$$

The local Chézy coefficient C in $m^{1/2}/s$ corresponds to a local value describing bed conveyance based on field measurements of depth-averaged flow velocity V, local flow depth h, and reach-averaged slope S according to

$$C = \frac{V}{h^{1/2} S^{1/2}} \tag{2}$$

The Darcy–Weisbach friction factor f corresponds to a local value describing bed resistance to flow. Calculations are based on measurements of the depth-averaged flow velocity V, the local flow depth h, the reach-averaged slope S, and the gravitational acceleration $g = 9.81\ m/s^2$

$$f = \frac{8ghS}{V^2} \tag{3}$$

where the Darcy–Weisbach friction factor f refers to a local value that describes solely bed resistance to flow.

The bed resistance as depicted by the Darcy–Weisbach friction factor in Figs. 5(a and b) changes more with discharge for the Bovenrijn than the Waal. The variability in local Manning n with discharge in Figs. 6(a and b) is less pronounced than the Darcy–Weisbach friction factor. In all cases, the cross-sectional variability is very small compared with the changes taking place in the downstream direction. Although the bedform properties of the Waal were collected upstream of the flow measurements, it was considered that the spatial variability at this scale was acceptable

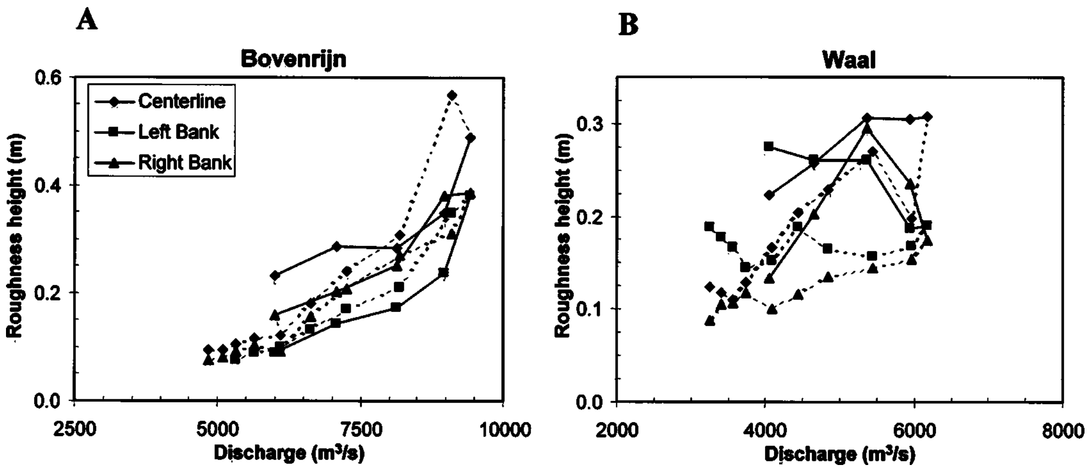

Fig. 4. Roughness height versus discharge: (a) Bovenrijn; and (b) Waal (dashed lines correspond to falling stage)

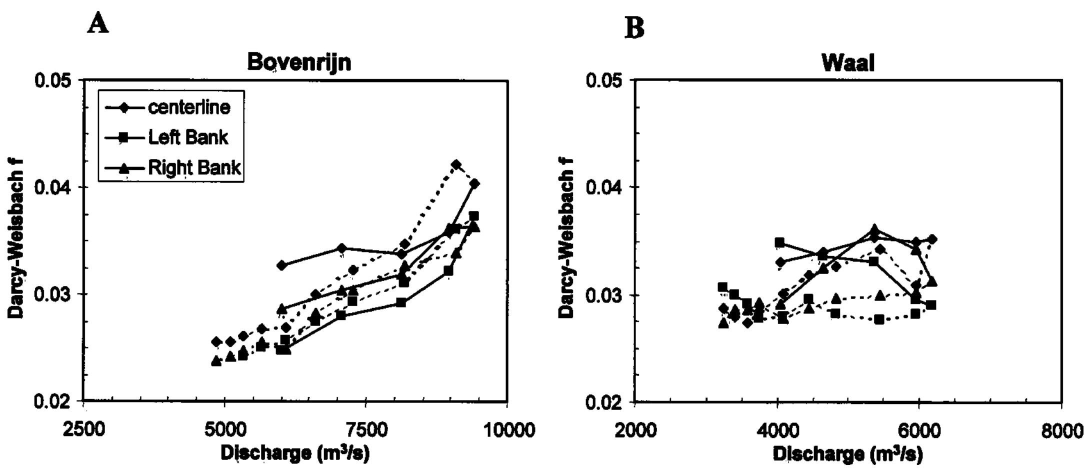

Fig. 5. Darcy–Weisbach *f* versus discharge: (a) Bovenrijn and (b) Waal (dashed lines correspond to falling stage)

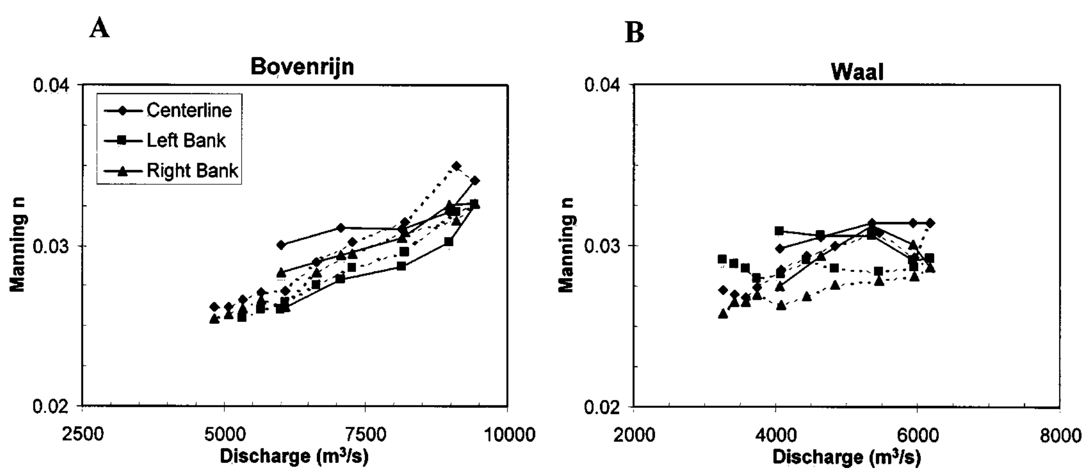

Fig. 6. Manning *n* versus discharge: (a) Bovenrijn and (b) Waal (dashed lines correspond to falling stage)

(Ten Brinke and Wilbers 1999). It is nevertheless considered that the data in the straight reach of the Bovenrijn is of better quality than the measurements of the Waal River bend.

The flow resistance parameters vary with stage or discharge in the following manner: (1) the measured Manning *n* varies from 0.03 to a peak value of 0.035 on November 5 and then gradually decreases to about 0.026 after the flood; and (2) the measured Darcy–Weisbach friction factor *f* also increases from 0.03 to 0.04 during peak discharge and then decreases to about 0.022 after the flood. By definition, the values of the Chézy *C* show the opposite trend as the Darcy–Weisbach *f* values with a minimum value of about 44 during the peak discharge and a value up to 55 after the flood. All the results clearly point to an increase in bed resistance that can be attributed to the changes in bedform geometry during

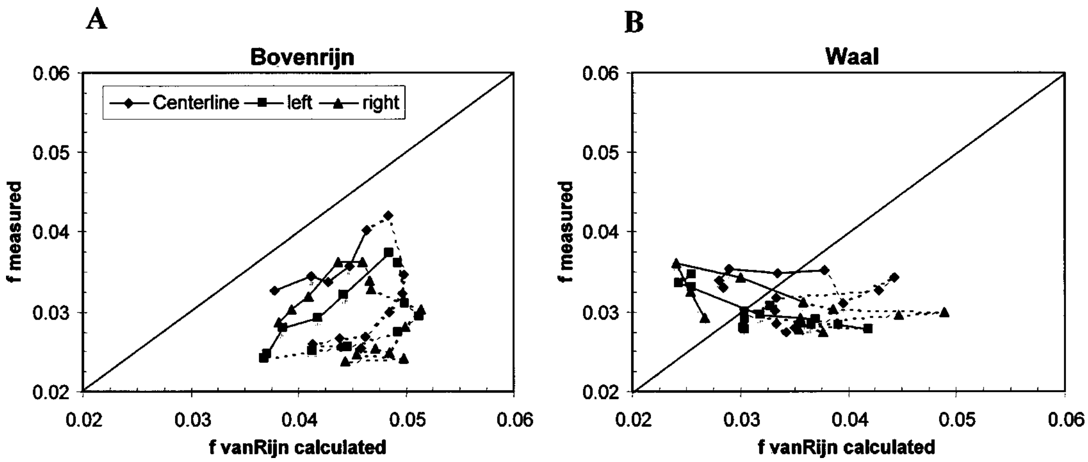

Fig. 7. Bed resistance from van Rijn versus field measurements: (a) Bovenrijn and (b) Waal (dashed lines correspond to falling stage)

the flood. The increase in bed resistance of the Bovenrijn is more apparent than that of the Waal because the dunes of the Bovenrijn are larger than the dunes of the Waal.

Modified van Rijn Approach

The method of van Rijn can be used to determine bed resistance to flow as a function of bedform geometry. In terms of resistance to flow, the Darcy–Weisbach friction factor f is calculated from Eq. (3) from the field measurements of flow depth h, slope S, and mean flow velocity V.

$$\frac{1}{\sqrt{f}}=2.03\log\frac{12.2h}{k_s} \tag{4}$$

Values of the roughness height k_s can thus be determined from field measurements of the flow depth h and the Darcy–Weisbach friction factor f.

The procedure proposed by van Rijn is consistent with other formulations whereby resistance to flow can be divided into two components: (1) a grain shear friction factor f' due to the bed shear stress applied on the grains; and (2) a form drag friction factor f'' due to the local energy loss on the lee side of bedforms like ripples and dunes. The grain friction factor f' cannot be measured but must be calculated assuming the applicability of resistance relationships for hydraulically rough plane surfaces. Accordingly, the grain resistance factor f'_{vR} from van Rijn's approach is calculated from

$$\frac{1}{\sqrt{f'_{vR}}}=2.03\log\frac{12.2h}{d_{90}} \tag{5}$$

The grain roughness height thus corresponds to $k_s=k'_s=d_{90}$, which is slightly different from $k'_s=3d_{90}$ suggested in Van Rijn (1984). The formulation in Eq. (5) is preferred to the original formulation because it stems from recent research by Van Rijn (1993) and Kleinhans and Van Rijn (2002).

The total roughness height k_s is determined as follows from the grain roughness d_{90} and the ratio ζ of dune height Δ to dune length Λ for primary dunes $\zeta_p=\Delta_p/\Lambda_p$ and secondary dunes $\zeta_s=\Delta_s/\Lambda_s$

$$k_s=k'_s+k''_{\mathrm{sp}}+k''_{\mathrm{ss}} \tag{6}$$

where

$$k'_s=d_{90} \tag{6a}$$

$$k''_{\mathrm{sp}}=1.1\Delta_p(1-e^{-25\zeta_p}) \tag{6b}$$

and

$$k''_{\mathrm{ss}}=1.1\Delta_s(1-e^{-25\zeta_s}) \tag{6c}$$

The last term specified in Eq. (6*c*) accounts for the roughness from the secondary dunes and constitutes a modification of the original Van Rijn method. Eq. (6) provides calculated values of the roughness height that approach the dune height for short dunes and approach grain roughness when the dunes length approaches infinity.

Using the Van Rijn approach, the values of the Darcy–Weisbach friction factor f calculated from the measured bedform dimensions vary like the measured values. With reference to Fig. 7, the calculated values for the Bovenrijn are systematically higher and show an hysteresis effect that reflects the hysteresis of primary dunes with a maximum calculated value of the Darcy–Weisbach friction factor of 0.05. The grain resistance parameter f' calculated using the modified van Rijn approach remains fairly constant during the entire flood at about $f'=0.021$. On the Waal, the modified Van Rijn approach provides reasonably good agreement with field measurements of resistance to flow as long as the dune characteristics measured in the field are used in the calculations.

Vanoni–Hwang Approach

The Vanoni–Hwang (1967) approach is based on the energy losses due to form drag. The main parameter to determine the form friction factor f''_{VH} is the ratio of dune length times the flow depth divided by the square of the dune height. The form drag friction factor of Vanoni–Hwang f''_{VH} is calculated from the measured values of flow depth h, dune height Δ, and dune length Λ

$$\frac{1}{\sqrt{f''_{\mathrm{VH}}}}=3.3\log\frac{\Lambda h}{\Delta^2}-2.3 \tag{7}$$

Both primary and secondary dunes are considered separately and the sum is then used for comparison with field measurements. From the characteristics of primary dunes, the values of f'' range from 0.015 to 0.035, which seems reasonable. In the case of secondary dunes, the values are very small considering that there are

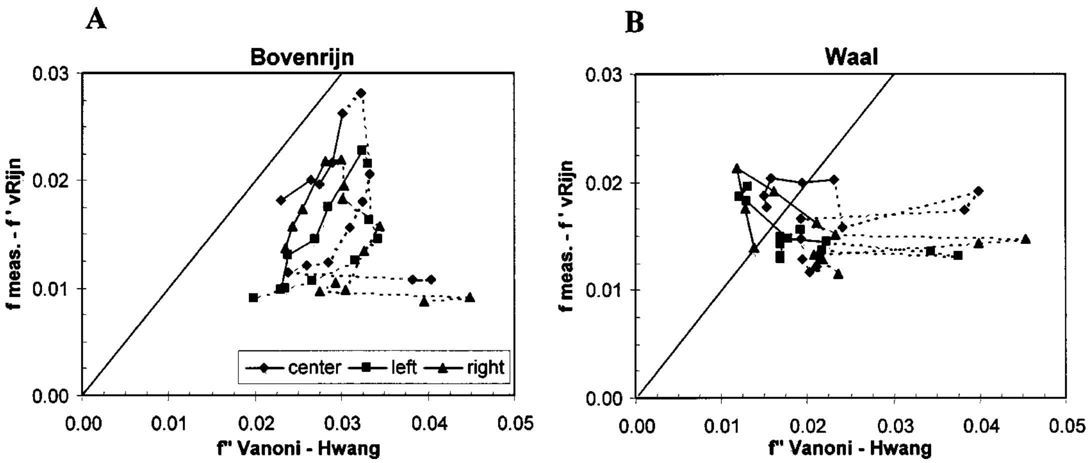

Fig. 8. Bed form resistance from Vanoni–Hwang versus field estimates: (a) Bovenrijn and (b) Waal (dashed lines correspond to falling stage)

no measurements until the flood wave recedes. Values of about 0.017 are then calculated as the secondary dunes appear on the river bed long after the peak discharge. It is difficult to compare form drag with any measurement because form drag cannot be measured in the field. At best, it can be assumed that the calculated grain resistance factor f' can be subtracted from the total friction factor f determined directly from field measurements. In doing so, the calculated values of form drag f'' in Fig. 8 turn out to range between 0.015 and 0.045. The estimated values of form drag from the difference between measured total and calculated grain resistance is less than 0.025.

Engelund Approach

The Engelund approach differs from Vanoni–Hwang in that the form drag friction factor is calculated from a decreasing exponential of dune height to flow depth. The form drag friction factor f''_E also involves the parameter $\Lambda h/\Delta^2$ previously defined in the Vanoni–Hwang approach.

The Engelund formula used to calculate the form drag friction factor is

$$f''_E = 10\frac{\Delta^2}{h\Lambda}e^{-2.5\Delta/h} \tag{8}$$

The sum of the two contributions for primary and secondary dunes is compared to the measured value of the total resistance minus Van Rijn's grain resistance. As shown in Figs. 8 and 9, the results of the calculations using Engelund's method are close to those of the Vanoni–Hwang method during high discharge. It is only long after the peak that the calculations using the Engelund method become smaller than those calculated with the Vanoni–Hwang method. Although the form of the equations of Vanoni–Hwang and Engelund is quite different, it is interesting to find out that both methods based on laboratory data yield comparable results when extrapolated to field data.

Finally, regarding which procedure should be recommended for the determination of bed resistance to flow. First, only the total bed resistance to flow should be considered rather than the individual parts due to grain roughness and form drag. In this regard, the bed resistance to flow seems overall fairly well predicted by the modified Van Rijn method as long as the calculations are based on field measurements of dune properties. An alternative approach would be to examine the dune properties in terms of height and length at different discharges during the course of several floods, and empirically determine the relationship between bed resistance and discharge. In this regard, the approach of Wilbers and Ten Brinke (1999) seems promising.

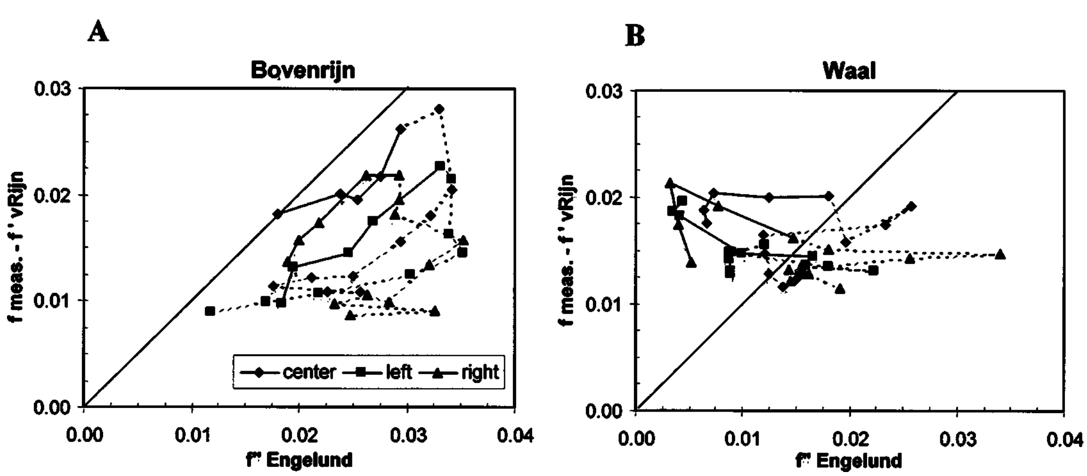

Fig. 9. Bed form resistance from Engelund versus field estimates: (a) Bovenrijn and (b) Waal (dashed lines correspond to falling stage)

Summary and Conclusions

The extensive data base used in this analysis includes high-quality field measurements on a daily basis for flow velocity, flow depth, dune properties, stage and reach-averaged slope, and flow discharge. This data set of the Dutch Rhine River allowed the direct determination of bed resistance to flow from measurements of flow depth, flow velocity and water surface slope during the rising and falling stages of the 1998 flood. The analysis was repeated at two cross sections with three vertical measurements at each cross section. The field observations in 1998 indicate clearly that dunes in the Dutch Rhine River system generally grow in amplitude during large magnitude floods and decay in amplitude as the flood recedes. These results corroborate the findings of earlier studies, e.g., Julien and Klaassen (1995), and show that some rivers do not necessarily plane out during floods.

In the case of the 1998 flood of the Dutch Rhine, both the Darcy–Weisbach friction factor f and Manning n clearly increase with discharge. The increase in bed resistance is attributed to the increase in bed form height during the flood. The increases in bedform roughness height and roughness factors f and n with discharge are most apparent for the Bovenrijn. For the Waal, a weak variation in bedform roughness height with discharge is reflected in similar weak variations in friction factors f and n during the flood.

A modified Van Rijn approach was used to examine bed resistance and grain resistance, and the methods of Engelund and Vanoni–Hwang were examined to calculate form drag for both primary and secondary dunes. It can be concluded that the modified Van Rijn approach corresponds fairly well to the bed resistance measurements. There is a noticeable hysteresis effect of the dune height versus discharge with maximum values of dune height observed a couple of days after the peak in discharge values. The methods of Engelund and Vanoni–Hwang yield comparable form drag calculations. Yet, these three methods perform best when field measurements of the bedform properties are available, but tend to overpredict resistance to flow after the peak discharge. Finally, a composite analysis of primary and secondary dunes is recommended for future studies on resistance to flow.

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Notation

The following symbols are used in this paper:

C = Chézy coefficient, $m^{1/2}/s$;
d_{10} = grain diameter, 10% finer by weight, m;
d_{50} = median grain diameter, 50% finer by weight, m;
d_{90} = grain diameter, 90% finer by weight, m;
f = Darcy–Weisbach bed friction factor;
f_{vR} = bed friction factor from van Rijn;
f' = grain bed friction factor;
f'_{vR} = grain friction factor from van Rijn;
f'' = bed form friction factor;
f''_E = bed form friction factor from Engelund;
f''_{VH} = bed form friction factor from Vanoni–Hwang;
g = gravitational acceleration, m/s^2;
h = flow depth, m;
k_s = bed roughness height, m;
k'_s = grain roughness height, m;
k''_{sp} = roughness height of primary dunes, m;
k''_{ss} = roughness height for secondary dunes, m;
n = Manning n, $s/m^{1/3}$;
S = slope,
V = depth-averaged flow velocity, m/s;
Δ = dune height, m;
Δ_p = primary dune height, m;
Δ_s = secondary dune height, m;
$\zeta_p = \Delta_p / \Lambda_p$ = primary dune height to dune length ratio;
$\zeta_s = \Delta_s / \Lambda_s$ = secondary dune height to dune length ratio;
Λ = dune length, m;
Λ_p = primary dune length, m; and
Λ_s = secondary dune length, m.

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