

**BED RESISTANCE TO FLOW  
OF THE BOVENRIJN-WAAL RIVERS  
DURING THE 1998 FLOOD**

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## **ABSTRACT**

During the 1998 flood of the Rhine River in the Netherlands, daily measurements of hydraulic and sediment characteristics aimed at a direct determination of the changes in bed resistance to flow during floods. Hourly stream gauge measurements at regular stations complemented a local laser altimetry survey near the peak discharge. The migration of bedforms could be tracked on a daily basis with complete bathymetric profiles measured from single- and multibeam echosounders. The observed growth and decay of dunes during the rise, peak and fall of the flood hydrograph confirmed earlier studies on the change in bedform geometry during the floods of the Rhine river branches.

Field measurements of flow depth, flow velocity and water surface slope clearly show that bed resistance in terms of the Darcy-Weisbach friction factor  $f$  and Manning  $n$  increases with discharge. The increase in bed friction factor is attributed to the increased dune height during floods. The method of van Rijn provides reasonably good estimates of the bed friction factor as long as field measurements of large dune height and wavelength are considered. The methods of Engelund and Vanoni-Hwang provide similar and realistic estimates of form drag. When combined with van Rijn's method to estimate grain resistance, however, both methods overpredict the measured bed friction factor. There is also a near-peak hysteresis effect with a calculated peak bed friction factor occurring two days after the measured peak.

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## NOTATION

Symbol	Description		Unit
C	Chezy coefficient		$m^{1/2}/s$
$d_{50}$	median grain diameter	m	
$d_{90}$	grain diameter, 90% finer by weight		m
f	Darcy-Weisbach bed friction factor		-
$f_{vR}$	bed friction factor from van Rijn		-
$f_{fl}$	grain bed resistance friction factor		-
$f_{flvR}$	grain friction factor from van Rijn		-
$f_0$	bed form friction factor	-	
$f_{0E}$	bed form friction factor from Engelund	-	
$f_{0VH}$	bed form friction factor from Vanoni-Hwang	-	
g	gravitational acceleration		$m/s^2$
h	flow depth		m
H	dune height		m
$H_l$	large dune height		m
$H_s$	small dune height		m
$k_s$	bed roughness height		m
L	dune length		m
$L_l$	large dune length		m
$L_s$	small dune length		m
n	Manning n		$s/m^{1/3}$
S	slope		-
T	van Rijn's transport-stage parameter		-
$u^*$	shear velocity		m/s
V	depth-averaged flow velocity		m/s
?	dune height calculated with van Rijn's method	m	
$?_{vR}$	dune height from van Rijn		m

# 1. INTRODUCTION

The protection of densely populated communities against floods is one of the primary concerns and duties of river engineers. Flood protection is particularly important in The Netherlands where the construction of dykes and levees protects surrounding land often below sea level. Considering that the volume of material for dyke construction is proportional to the square of the structure height, an accurate determination of the height of dykes and levees becomes essential in order to reduce construction costs.

The height of dykes and levees is determined from the maximum water elevation or stage reached during the historical flood record. The design discharge depends on the past hydrologic record and the frequency of discharge at a given location. It also depends on the relative stability of the river in the reach considered. Among other things, it depends on the aggradation or degradation trend of the river as a result of the changes in sediment transport of the river in the downstream direction. During a single flood, the calculations of flood stage prediction for a given flood hydrograph is determined from the stage-discharge relationship which determines at what elevation the water surface will rise at a given peak flow discharge. This stage-discharge relationship is in turn dependent on resistance to flow. Resistance to flow parameters are written either in terms of the Darcy-Weisbach friction factor  $f$ , the Chezy coefficient  $C$ , or the value of the Manning coefficient  $n$ . It is often assumed that Manning  $n$  does not change with discharge, and the determination of flood stage is often obtained after extrapolating average flow conditions to flood characteristics.

The value of the resistance parameter is also known to depend on bedform configuration which may change from plane bed to ripples and dunes in sand bed rivers. Early studies on sediment transport include Duboys (1879), Gilbert (1914), Einstein (1942), Kalinske (1942), Vanoni (1946), Einstein and Barbarossa (1952), Liu (1957), Shinohara and Tsubaki (1959), Vanoni and Nomicos (1960), and Brooks (1962). General references on the mechanics of movable bed channels can be found in Yalin (1972), Vanoni (1977), Jansen (1979) and Julien (1995). The specific effects of bedforms in terms of classification, characteristics and resistance to flow can be found in Simons and Richardson (1963, 1966), Chabert and Chauvin (1963), Guy et al. (1966), Engelund and Hansen (1967), Alam and Kennedy (1969), Southard and Boguchwal (1990), 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), Gill (1971), Ranga-Raju and Soni (1976), Engelund (1977), White et al. (1979), van Rijn (1982 and 1984), Wijbenga and Klaassen (1983), Yalin (1985), Ogink (1989), Wiberg and Nelson (1992), and Raudkivi (1997). Studies on the properties of bedform height and wavelength have been pursued by Nordin and Algert (1972), Shen and Cheong (1977), de Leeuw (1985), Moll (1985), Moll et al. (1987), and Lai (1998). Field investigations on bedforms and properties of large alluvial channels include Taylor (1971), Shen et al. (1978), Peters, (1978), Klaassen et al. (1988), Raslan (1991), Julien and Wargadalam (1995). Finally detailed studies on the bedform characteristics and on sediment transport in the Rhine River branches have been reported by van Urk (1982), Ogink (1984), Adriaanse (1986), Termes (1986, 1989), Brillhuis (1988), Kamphuis (1990 a

and b), Wijbenga (1990 and 1991), Julien (1992), Julien and Klaassen (1995), Kleinhans (1996 and 1997), ten Brinke (1997), ten Brinke et al. (1999), Wilbers (1997 and 1998), Klaassen (1987) and Klaassen et al. (1999) also reported on the changes in river bed composition during floods in armoured rivers.

Earlier research by Julien (1992) and Julien and Klaassen (1995) on the changes in bedform geometry in large rivers showed that the bedforms of the Rhine River branches generally grow in amplitude and length during the floods and decay after the floods. These observations were confirmed with more recent measurements by ten Brinke et al. (1999). Specific measurements in the Rivers Rhine and Waal and the Pannerdensch Kanaal during the February-March 1997 flood document the growth, decay and migration rates of dunes during a large magnitude flood. Dunes covered the bed for a couple days before and after peak discharge in the sand-gravel bed sections and for the entire period in sand-bed sections. Dunes in the sand-bed section reached 1.2 m in amplitude 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.

### ***1.1 Objectives***

As dunes grow and decay during floods, it seems relevant to question whether resistance to flow is affected by the changes in dune geometry during floods. This has been the primary subject of focus of this sabbatical research program. The complexity of the problem stems from the fact that resistance to flow of a river is a composite of bed resistance and flood plain resistance during floods. 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 maintain a 260 m wide navigation channel. The presence of bedforms would only affect bed resistance without affecting groynes and floodplain resistance. Hence, the forthcoming analysis focuses exclusively on the effect of the changes of dune geometry on the bed resistance to flow. An increase in bedform geometry should affect directly the flow velocity of during the flood.

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. These methods will be described later in this report. Bedforms such as dunes and ripples impact form resistance and the question as to whether the growth and decay of dunes also affects bed resistance to flow during floods is at the center stage of this investigation. In general, one expects from these methods that an increase in dune height should result in an increase in resistance to flow. Therefore, if the methods are correct, one may intuitively expect bed resistance to flow to increase during floods and decay thereafter. The length of bedforms also affects resistance to flow and one would expect that an increase in dune wavelength during floods would decrease resistance to flow, as opposed to the increase cause by an increase in dune height. The problem is also exacerbated by the fact that dunes do not have homogeneous

properties and small dunes are often superposed on top of larger dunes. The composite effect of large and small dunes also deserves consideration.

Results on dune properties during floods in the eighties and the nineties show that dune height, length and steepness vary with discharge for both the sand and sand-gravel bed reaches of the Bovenrijn and the Waal River. For the sand-gravel bed reaches, an increase of the dune properties is observed over the entire discharge range from 2,000 to 12,000 m<sup>3</sup>/s, which corresponds to the largest discharges observed in the last century. For sand-bed reaches, the dune properties increase up to a certain discharge and then stay the same (Wilbers and ten Brinke, 1999). Dune properties at different stages during a flood need to be related to energy conditions such as friction slope and flow velocity. This study has been undertaken in order to substantiate the present formulations for bed roughness in the presence of bedforms observed in the Dutch rivers.

The primary objective of this study is to determine how bed resistance to flow changes during floods. As a second objective, existing methods to predict bed resistance to flow are evaluated in order to suggest or develop a procedure to determine bed resistance to flow during floods.

The expected results from this analysis include an appraisal as to whether total resistance to flow increases or decreases with discharge, during the 1998 flood. It is also expected that the amplitude and length of dunes increase with discharge. The study aims at determining whether the bedform geometry measurements are in agreement with the calculations using van Rijn's procedure. In terms of resistance to flow, the analysis will determine whether the methods of Engelund and Vanoni-Hwang can correctly predict the form drag changes caused by changes in bedform geometry during the 1998 flood.

A reach of the Rhine and Waal Rivers near the bifurcation with the Pannerdensch Kanaal has been selected for the analysis 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.

## **2. STUDY LOCATION AND FIELD DATA**

The Rhine River originates in the Alps and flows through Switzerland and Germany to the Netherlands. In the Netherlands, the Rhine River bifurcates into the Waal, the Nederrijn-Lek and the IJssel River branches. The discharge ratio between these branches is approximately 6:2:1. The average discharge of the Rhine River near the Dutch-German border is 2,300 m<sup>3</sup>/s and varies as a function of rainfall and snowmelt. In 1993-95, the Rhine River experienced maximum discharges of 11,000 and 12,000 m<sup>3</sup>/s, among the highest discharges ever recorded. With respect to these discharges, the peak value of 9,464 m<sup>3</sup>/s in 1998 also figures among the largest floods. A peak discharge in excess of 7,000 m<sup>3</sup>/s is experienced on average every 4 years. The Rhine River branches in The Netherlands are generally sandy with a median grain size of about 0.5-4 mm. The gradient of the river is approximately  $1.1 \times 10^{-4}$ . This research was carried out near the bifurcation of the Rhine into the Waal and Pannerdensch Kanaal and the bed consists of a mixture of sand and gravel. The river is relatively straight with an average sinuosity of 1.1.

## **2.1 Study Area**

The study focuses on the data set collected during the 1998 flood of the Bovenrijn-Waal. The data set near the bifurcation of the Bovenrijn into the Waal and the Pannerdensch Kanaal is particularly interesting due to the combination of measurements on bedforms, sediment transport, sediment composition, flow depth, flow velocity and water surface slope.

The study reach illustrated in Figure 1 shows the Bovenrijn flowing from right to left just upstream of the bifurcation. The transect of the Bovenrijn is going through Millingen a/d Rijn at the river kilometer 866.2. The bifurcation with the Pannerdensch Kanaal corresponds to river km 867.22 and is referred to as Pannerdensche Kop. The Waal River is located downstream of the bifurcation. The cross-section of the Waal River is located at river km 870.5. The Pannerdensch Kanaal flows to the North from the Pannerdensche Kop.

A peak discharge of 9,464 m<sup>3</sup>/s was measured at Lobith on November 4, 1998, and the period of record extends from October 29 until November 19. The main parameters illustrated in Figure 2 include discharge, stage, flow depth, flow velocity and water surface slope. The results of the Bovenrijn are shown on Figure 2a and the Waal on Figure 2b. A better description on how each parameter was measured follows.

## **2.2 Stage Measurements**

Regular stations measure the water surface elevation called river stage with reference to the Dutch Ordnance Datum (NAP). Hourly measurements are available at: 1) Lobith located at river km 862.18; 2) Pannerdensche Kop located at river km 867.22; and 3) Nijmegen located at river km 884.87. The slope of the Bovenrijn is determined by taking the difference in water surface elevation between Lobith and Pannerdensche Kop. The water slope of the Waal River is determined by taking the difference in water surface elevation between Pannerdensche Kop and Nijmegen. During the flood, the water surface elevation was determined from visual measurements at some extra water gages located between the regular stations. These visual readings provide more information on the spatial scale but these data are available only once or twice a day. These visual readings were used to check whether the regular stations provided sufficiently accurate measurements of surface slope. The reach averaged-values of surface slope were found to be sufficiently accurate and therefore only the data collected at regular stations was used in this study. Near the flood peak on November 5, more detailed laser altimetry data was available to determine the local water surface slope of the Bovenrijn-Waal in the reach between river km 866 and 869. The results are shown in Figure 3 where the slope decreases rapidly in the downstream direction. This variability is attributed to the front of the flood wave propagating in the downstream direction.

## **2.3 Bathymetry**

Longitudinal and cross-sectional profiles of the bed elevation were obtained from single and multibeam echosounding. Echosounding records started on October 29 until November 19. During this period, three types of echosounder were used as detailed in Table 1. The data set includes data from: 1) a single-beam echosounder ATLAS DESO 25 for three days; 2) a multi-beam echosounder SEABAT 8101 with a large number of beams and a wide band width for two days; and 3) a multi-beam 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 DGPS (Differential Global Positioning System) controlled by a desk-top computer. The actual position and the water depth data are stored on tape aboard the survey vessel and processed later on a computer at the office. With the multi-beam 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 combined position and elevation accuracy of the bed topography is about 20 cm. All single and multi-beam soundings were recorded along tracks parallel to the river banks. The procedure detailed in ten Brinke et al. (1999) has been used to determine the pattern and planform geometry of dunes. A GIS-based software has been developed to determine dune height and length, bedload transport from dune tracking and dune migration over time.

Two cross-sections have been considered; 1) one cross section of the Bovenrijn approximately 1 km upstream of the bifurcation with the Pannerdensch Kanaal at river km 866.2; and 2) one cross-section of the Waal River located a few kilometers downstream of the bifurcation at river km 870.5. At each cross-section, three verticals are of particular interest: 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 three verticals are considered in order to examine the spatial variability in the measurements. Detailed cross-sectional profiles are available at both cross-sections from November 4 until November 11. Surveys were repeated, though not necessarily at the exact same location. Cross-sections profiles during the flood are presented in Figures 4a and 4b for the Bovenrijn and Waal respectively.

#### **2.4 *ADCP Velocity Measurements***

Acoustic Doppler Current Profiler ADCP velocity measurements are available during six days of the 1998 flood. For each day, the geometry of each transect has been measured repeatedly during the flood. The depth-averaged flow velocities are also available at numerous verticals along the cross-section during the same period. These ADCP flow measurements were depth-integrated for the analysis. Detailed velocity profiles are also available and some were examined during this investigation. The ADCP survey period extends from November 3-6 with additional measurements on November 9 and 11. Since the peak discharge was observed on November 5, this survey period corresponds essentially to the near-peak and falling stage of the flood hydrograph. Figure 5a and b show the velocity profiles across the river for the Bovenrijn and the Waal River respectively.

#### **2.5 *Bed Material***

The bed material data is also available along the entire river at a spacing of 1 km. There is also a survey of the particle sizes distributions at the three aforementioned verticals. The data set includes median grain sizes  $d_{50}$  as well as  $d_{10}$  and  $d_{90}$ . Some data is missing but the data set closer to the left bank is remarkably complete. There is a lot of variability in the field measurements between fairly uniform sands and well-graded gravels. Additional surveys have been sought and Maarten Kleinhans at Utrecht University provided additional data.

A summary table of particle size distribution representative of the bed material is presented in Table 2. It is noticed that the bed material consists of a well-graded mixture of sand and gravel. The median grain diameter varies between 0.75 and 3.8 mm, the average finer fraction described by the  $d_{10}$  is approximately 0.4 mm and the coarser fraction described by  $d_{90}$  is as large as 15 mm. The gradation coefficient is thus approximately 5 and values of grain size  $d_{10} = 0.4$  mm,  $d_{50} = 2$  mm and  $d_{90} = 20$  mm are considered representative of bed material samples.

As part of a pilot study, a new technique developed at the Nuclear Geophysics Division at the University of Groningen was developed and tested for the determination of bed grain sizes by means of natural radioactivity measurements. The approach is based on the hypothesis that the amount of radioactivity of a sediment sample varies with grain size. A detector is towed over the river bed and the radioactivity is measured. In the laboratory, a calibration curve is determined between the grain size and the radio-activity level for a few selected isotopes. A combination of the Uranium 238 and Thorium 232 isotopes is used for correlation with the fraction of coarse particles in the bed. Unfortunately, when compared with field samples measured during this campaign, the calculated coarse fraction did not really correspond to the sieve curves of the field samples. The Uranium counts seemed better than the Thorium counts. Accordingly, the average value of the median grain size is between 2.67 and 2.89 mm for the Bovenrijn, and between 2.6 and 3.09 mm for the Waal River. The value of  $d_{90}$  is between 11.65 and 11.93 mm for the Bovenrijn and between 11.53 and 12.06 mm for the Waal River.

## **2.6 Bedform Data**

Bedform data is also available on a daily basis during the entire flood as per the detailed bathymetric surveys previously described. The data is processed and classified into large and small dunes using the same procedure that was used in ten Brinke et al. (1999). Both the average dune height and dune length are reported on a daily basis. The south section -67 m contains the average data measured between sections -83 and -50 m. The centerline section is 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 dune properties of the Bovenrijn correspond to measurements between river km 866.5 and 867.7 which is located slightly downstream of the cross-section and ADCP measurements. In the case of the Waal River, the dune properties correspond to measurements between river km 868 and 868.5. It is assumed that the bedform properties of the Waal River are fairly uniform and correspond to flow conditions measured at river km

870.4. Measurements were recorded about twice per day during the period from October 29 til November 7 and measured about every three days thereafter until November 19.

### **3. METHODS AND ANALYSES**

The approach used for the analysis consists of preparing a spreadsheet with the daily values of the hydraulic and sediment characteristics. The calculation of the resistance parameters then follows from the measured hydraulic and sediment characteristics. The file was subdivided into two parts: 1) file of the Bovenrijn with the characteristics upstream of the Pannerdensche Kop; and 2) a file of the Waal River just downstream of the Kop. For each of the two files, the measured data is highlighted with yellow. Because this file contains some missing data that affects the calculations, the data set has been subject to interpolation and extrapolation around the measured values. This enlarged data file provides a larger data bases of calculated parameters and expands the analysis based strictly on measured data.

Each of the two files is subdivided into three parts corresponding respectively to the centerline, the left side located 67 m south of the river centerline and the right side located 67 m north of the river centerline. The entire spreadsheet is included in Appendix A for the Bovenrijn and in Appendix B for the Waal. Some graphics also illustrate the key calculations for this analysis of resistance to flow.

#### **3.1 Measured data**

The following description refers directly to the spreadsheets and pertains to the raw data and the detailed algorithms used in the calculation of flow resistance parameters. The date is found in column A. The average daily discharge measured at Lobith in the case of the Bovenrijn is given in column B. The stage measured at the Pannerdensche Kop is given in column C. The flow depth measured at the given vertical is presented in column D followed with depth-averaged velocity measurements from the ADCP in column E. The reach-averaged slope was calculated from the difference in water surface elevation between Lobith and Pannerdensche Kop for the Bovenrijn and between Pannerdensche Kop and Nijmegen for the Waal River. The reach-averaged slopes are listed in column F of the spreadsheet.

The dune properties described in columns G-L are separated into large dunes in columns G-I and small dunes in columns J-L. The large dune length  $L_l$  is found in column G, the large dune height  $H_l$  in column H and the aspect ratio or large dune steepness calculated from the ratio of  $H_l/L_l$  is given in column I. The same approach was used for the small dunes with length  $L_s$  in column J, small dune height  $H_s$  in column K and small dune steepness  $H_s/L_s$  in column L. Large dunes were essentially observed all the time but small dunes were only present near and after the peak. For the calculations, it was assumed that small dunes, about 10 m in length and very small amplitude, 0.001 m in height, were present at all times. The average ratio of dune height to dune length given from the sum of large dune height and small dune height to the large dune length is given in column V.

The particle size distribution of the bed material is presented respectively for  $d_{90}$ , the median grain size  $d_{50}$  and  $d_{10}$  in columns M-O. There was a large variability in the particle size distribution of the bed material and no direct measurements were specifically available during the 1998 flood. It was therefore assumed in all calculations that the sand-gravel bed mixture does not change during the flood. Different values were thereafter assumed in a sensitivity analysis of possible changes in particle size distribution of the bed material during the flood.

### 3.2 *Resistance to Flow*

The parameters relative to resistance to flow were then calculated from the measured hydraulic and sediment parameters described in the previous section. The Manning  $n$  listed in column P is a local value corresponding to bed resistance. Calculations of local values of Manning  $n$  are based on the depth-averaged velocity  $V$ , the local flow depth  $h$  and the reach-averaged-slope  $S$ , as per the formula:

$$n = \frac{1}{V} h^{2/3} S^{1/2} \quad (1)$$

The local Chezy coefficient  $C$  in  $m^{1/2}/s$  listed in column Q also corresponds to a local value describing bed conveyance based on the depth-averaged flow velocity  $V$ , local flow depth  $h$  and reach-averaged slope  $S$  according to:

$$C = \frac{V}{h^{1/2} S^{1/2}} \quad (2)$$

The Darcy-Weisbach friction factor  $f$  listed in column R also corresponds to a local value describing bed resistance to flow. Calculations are based on the depth-averaged flow velocity  $V$ , the local flow depth  $h$ , the reach-averaged slope  $S$  and the gravitational acceleration  $g = 9.81 \text{ m/s}^2$ . The Darcy-Weisbach friction factor  $f$  is calculated with:

$$f = \frac{8ghS}{V^2} \quad (3)$$

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

### 3.3 *van Rijn Approach*

The following eight columns S-Z refer to the procedure developed by van Rijn (1984). The method of van Rijn can be used to determine both resistance to flow as well as a prediction of bedform geometry.

In terms of resistance to flow, both the total and grain resistance can be separately calculated. Accordingly, the Darcy-Weisbach friction factor  $f_{vR}$  presented in column S is calculated from the flow depth  $h$ , the coarse grain diameter of the bed material  $d_{90}$ , the measured large dune height  $H_l$  and the measured large dune length  $L_l$  as per the following formula:

$$\sqrt{f_{vR}} = \frac{1}{2.03 \log \frac{12h}{3d_{90} \left( 1 + 1.1 H_l / L_l \right)^{0.25}}} \quad (4)$$

Notice that the van Rijn friction factor is here calculated from the field measurements of dune height and dune length and not from the dune height and length calculated from van Rijn's method.

The estimated Darcy-Weisbach friction factor describing bed resistance  $f = f' + f''$  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.

The procedure proposed by van Rijn is consistent with other formulations whereby resistance to flow depends on the ratio of grain size to flow depth. The formulation of van Rijn presented in column T of the spreadsheet calculates  $f'_{vR}$  from the field measurements of flow depth and bed material size as:

$$\sqrt{f'_{vR}} = \frac{1}{2.03 \log \frac{12h}{3d_{90}}} \quad (5)$$

The value of grain friction factor cannot be measured in the field and can only be estimated by assuming that part of the roughness is due to surface shear stress applied directly on the grains as if the river bed would have a plane rough surface.

In column U, the total roughness height  $k_s$  may be considered as a measured parameter because it stems directly from measured parameters and the definition of roughness height. In this case, it is determined from solving the following equation given the depth-averaged flow velocity  $V$  and the shear velocity  $u_* = (g h S)^{0.5}$  calculated from field measurements of flow depth and slope as:

$$\frac{V}{u_*} = 5.75 \log \frac{12h}{k_s} \quad (6)$$

Equation 6 is therefore used for the determination of the total bed roughness  $k_s$  from the field measurements of flow depth, flow velocity, and shear velocity from flow depth and reach-average slope measurements.

The reader will notice that for grain roughness in Equation 5, the grain roughness height corresponds to  $k_s' = 3 d_{90}$ . In the presence of dunes, the total roughness should therefore be expected to be closer to the size of dunes as opposed to grain size. The relative roughness height representing the ratio of the total roughness height  $k_s$  to the characteristic dune height  $\lambda$  is listed in column W. It may be worth mention that the dune height  $\lambda$  here is neither that of large or small dunes. It is only used to see if the roughness height is approximately equal to the dune height. The ratio refers to an estimated quantity of the ratio of roughness height to a characteristic dune height. The value of roughness height ratio according to van Rijn is only calculated here for comparison of the roughness height to a typical dune height. The calculations leading to the roughness ratio in column X are provided from field measurements of the dune properties:

$$\frac{k_s}{\lambda} = 3d_{90} \left[ 1 + e^{\frac{25(H_L H_s)}{(L_L L_s)}} \right] \quad (7)$$

Equation 7 only provides values of the roughness ratio that would be less than 1.1 and approach grain roughness when the dunes are becoming infinitely long.

The following equations refer to van Rijn's procedure to determine bedform geometry based on the transport-stage parameter. The transport-stage parameter T represents the ratio of the grain shear stress in excess of the critical shear stress for beginning of motion, then divided by the critical shear stress. Given that for gravels, the critical shear stress for the beginning of motion in Pascals is approximately 0.7 times the median grain diameter in mm, the transport-stage parameter T in column Y is estimated from:

$$T = \frac{V^2}{0.7d_{50} (5.75 \log \frac{4h}{d_{90}})} \quad (8)$$

Values of T are calculated to determine whether there is a lot of sediment in transport. Values of  $T < 0$  are below incipient motion, values of  $T = 0$  correspond to beginning of motion, values of  $T = 1$  correspond to twice the incipient motion, and according to van Rijn,  $T = 25$  corresponds to upper regime plane bed.

Based on the transport-stage parameter, van Rijn proposed a method to estimate the dune height. The calculated dune height  $\eta_{vR}$  in column Z according to van Rijn's method is calculated from:

$$\eta_{vR} = 0.11 h \left( \frac{d_{50}}{h} \right)^{0.3} (1 + e^{-0.5T}) \quad (9)$$

The value of dune height calculated with van Rijn method can be compared with the field measurements. Van Rijn does not specify whether this dune height compares with either large or small dunes. This value of the van Rijn dune height is calculated for comparison with the height of large dunes measured during the flood. The effects of hysteresis describing a time lag between the hydraulic conditions and the real dune height that natural bedforms can attain during the flood can be assessed from these calculations.

### 3.4 Vanoni-Hwang Approach

The Vanoni-Hwang approach is based on the energy losses due to form drag. The main parameter to determine the form friction factor is the ratio of dune length times the flow depth divided by the square of the dune height. The corresponding values of this ratio from the field measurements are specifically listed for large and small dunes in column AA and AB. The form drag friction factor of Vanoni-Hwang  $f_{0VH}$  is calculated from the measured values of flow depth  $h$ , dune height  $H$  and dune length  $L$ .

$$\frac{1}{\sqrt{f_{0VH}}} = 3.3 \log \frac{Lh}{H^2} + 2.3 \quad (10)$$

The form drag friction factor  $f_{0V}$  calculated respectively for large dune and small dune data are listed in columns AC and AD respectively. The sum of the form drag friction factors for large and small dunes is then listed in column AE. Column AF provides the value of the form drag friction factor  $f_0 = f - f_{vR}$  obtained from subtracting the grain friction factor calculated with van Rijn's method  $f_{vR}$  from the measured bed friction factor  $f$ . The corresponding value of the inverse of the square root of  $f_0$  is listed in column AG.

### 3.5 Engelund Approach

The Engelund approach is also quite comparable to that of Vanoni-Hwang in that the form drag friction factor is calculated from the measured values of dune height and length. The form drag friction factor  $f_E$  is calculated from the parameter previously defined in the Vanoni-Hwang approach  $hL/H^2$  listed in columns AA and AB. It also depends on the ratio of dune height  $H$  to flow depth  $h$ . The formula used to calculate the form drag friction factor is:

$$f_E^{))} = 10 \frac{H^2}{hL} e^{-\frac{2.5H}{h}} \quad (11)$$

The values of the calculated form drag friction factor obtained from the dune measurements in the field are listed in columns AH and AI, respectively for large and small dunes. The sum of the two contributions for large and small dunes is given in column AJ, and the value of the total resistance measured minus the grain resistance calculated from van Rijn's method is finally given in column AK. Although the form of the equations of Vanoni-Hwang and Engelund are quite different, it will be interesting to see if both methods based on laboratory data yield comparable results when used with field data.

## 4. RESULTS AND DISCUSSION

The results of this analysis essentially focus on the changes in the measured and calculated properties during the flood. The results at the channel centerline for both the Bovenrijn and the Waal River are considered most relevant and provide an information on the changes in conditions in the downstream direction. Comparatively, the results near the left and right side of the channel provide indication on the variability at a given cross-section. The reader is referred to the spreadsheets where several figures illustrate the analysis of the data at each cross-section. The figures to the right-hand side of the file refer to results at a specific vertical. The figures presented at the bottom of the spreadsheet refer to the cumulative data at the entire cross-section.

### 4.1 *Characteristics of the data set*

The peak discharge occurred on November 4 but was still near the peak on November 5. The stage varied by about 3 m during the flood and the flow velocity gradually decreased after November 3. As shown in Figure 2, the reach-averaged slope ranged from 8 to 13 cm/km and this shows the significant dynamic effect of the flood wave propagation.

In the case of the Bovenrijn, the large dune length gradually increases from 8 to 40 m during the flood. The large dune amplitude increases from 0.34 to 1.15 m on November 7 and then decreases to about 0.5 m after the flood. As the large dunes elongate and decrease in amplitude after the flood, the small dunes form as the flood recedes. The small dunes form after November 12 with a wavelength of about 7 m and an amplitude of about 0.25-0.3 m. The large dunes of the Waal were considerably smaller with a maximum amplitude of 0.56 m on November 5 and decreased to 0.2 m before and after the peak. The length of large dunes of the Waal ranged from 6 to 18 m with the maximum wavelength measured on November 6 and 7.

The resistance to flow 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 Chezy  $C$  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.

Figures 6a and 6b respectively show the changes in large 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. One also will notice that the height of large dunes of the Waal are about half the size of the height of the large dunes of the Bovenrijn. The hysteresis effect is less pronounced in terms of roughness height versus discharge as shown in Figures 7a and 7b. The roughness height clearly increases with discharge and the results at the centerline and both sides compare very well. The lateral variability in hydraulic roughness characteristics is less than the variability in the downstream direction. One may consider that the roughness height is about one half of the large dune height. When compared with the Waal, the higher dunes of the Bovenrijn correspond to larger values of roughness height. The bed resistance as depicted by the Darcy-Weisbach friction factor in Figures 8a and 8b changes more with discharge for the Bovenrijn than the Waal. The variability in local Manning  $n$  with discharge in Figures 9a and 9b is also less pronounced than for the Darcy-Weisbach friction factor. In all cases, the variability along a cross-section is very small compared with the changes taking place in the downstream direction. It is considered that the data in the straight reach of the Bovenrijn is of better quality than the measurements of the Waal River bend. Nevertheless, all the results clearly point to an increase in bed resistance that can be attributed to the changes in bedform geometry during the flood. The increase in resistance to flow 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.

#### **4.2 Results of the van Rijn approach**

Using the van Rijn's approach, the calculated values of the Darcy-Weisbach friction factor  $f$  from the measured bedform dimensions varies very much like the measured values. With reference to Figure 10, the calculated values are systematically higher and show an hysteresis effect that reflects the hysteresis effect of large dunes with a maximum calculated value of the Darcy-Weisbach friction factor of 0.05 on November 6 and 7. The grain resistance parameter  $f_{\text{fl}}$  calculated using van Rijn's approach remains fairly constant during the entire flood at about  $f_{\text{fl}}=0.021$ . This is somewhat to be expected because the bed material was assumed to remain constant during the flood. The calculations nevertheless show that the change in flow depth during the flood does not significantly affect grain resistance. It is worth noting that the grain resistance parameter depends thus primarily on the size of the bed material. However, it is possible that this river bed composed of a well-graded sand-gravel mixture becomes entirely covered with sand dunes or may become armoured during the flood. More research on the changes in bed roughness during the flood may warrant different results than what is assumed in this analysis.

Relative to the size of sand dunes during the flood, the van Rijn method gives values of the transport-stage parameter less than 5 which is near the beginning of motion. The maximum dune height calculated with the van Rijn method are about 1.7 m which far exceeds the measured amplitude of sand dunes in the river bed. On one-hand, a viable hypothesis is that the flood duration is too short to allow for the full formation of dunes in the river. However, van Rijn's method still predicts dune amplitude in excess of 1.3 m after the flood. If this hypothesis holds true, the dunes should still grow as the flood recedes and this is contrary to the field observations. On the other hand, the method of van Rijn provides reasonably good agreement with field measurements of resistance to flow as long as the dune characteristics are measured in the field and not calculated from the van Rijn method. In this regard, the method of van Rijn based on field dune properties seems partially appropriate. The order of magnitude of the parameters is reasonable but the method fails to predict the hysteresis effects and the calculated dune height far exceeds the field measurements.

### **4.3 Results of the Vanoni-Hwang and Engelund methods**

The method of Vanoni-Hwang provides estimates of the form drag calculated from the product of relative dune height  $H/h$  and dune steepness  $H/L$ . Both large and small dunes are considered separately and the sum is then used for comparison with field measurements. From the characteristics of large dunes, the values of  $f''$  range from 0.02 to 0.03 which seems reasonable. In the case of small dunes, the values are very small considering that there are no measurements until the flood wave recedes. Values of about 0.017 are then calculated as the small dunes appear on the river bed long after the peak discharge. The exact procedure to account for large and small dunes is still nebulous. Resistance to flow should normally increase when there are small dunes on the back of large dunes. It seems reasonable to add the resistance to flow caused by small dunes to the resistance to flow caused by the large dunes. Therefore, it is considered that the form drag is composed of the sum of two contributions: 1)  $f''$  caused by large dunes; and 2)  $f''$  caused by small dunes. It is difficult to compare form drag with any measurement because the form drag cannot be measured in the field. At best, one can assume that grain resistance is properly calculated and the value of  $f''$  can be subtracted from the total friction factor  $f$  determined directly from field measurements. In doing so as shown in Figure 11, the calculated values of form drag  $f''$  turn out to range between 0.025 and 0.04. The estimated values of form drag from the difference between measured total and calculated grain resistance vary between 0 and 0.02.

The calculations are somewhat too high and it seems that two effects may be affecting the data: 1) the grain resistance may be lower than effectively calculated by the van Rijn method; and 2) one may consider that adding resistance to flow for large and small dunes may effectively double the calculated resistance to flow. Regarding the first consideration, the grain resistance may effectively be smaller if the bed is covered with dunes during part of the flood. It is almost impossible to pursue further along this line of discussion without field data on the possible changes in bed material composition during the floods. Regarding the second consideration, the form drag added from the small dunes is quite small during most of the flood. It is only after the flood that the value of form drag from small dunes becomes

as large as the form drag contribution from large dunes. It is therefore most likely that the grain resistance remains less than calculated. This can in turn be attributed to either: 1) a finer bed material during the flood than assumed in the calculations; or 2) an overestimate of grain resistance calculation when using van Rijn's approach. It is impossible to examine the question further without field data on bed material composition during the flood. This is a recommendation for future field survey programs.

The method of Engelund is also considered in the same manner in terms of adding the respective contributions for large and small dunes. As shown in Figure 12, the results of the calculations using Engelund's method are remarkably comparable 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. Overall, the same comments relative to field comparisons and to the determination of grain resistance apply as per the above discussion of the Vanoni-Hwang method.

#### **4.4 Discussion**

It has been discussed during the preparation of this report that there seems to be a sediment imbalance during the flood. One hypothesis by ten Brinke and Kleinhans (pers. comm.) suggests a mechanism of winnowing of the river bed during the flood. Accordingly, the fine sediment would be winnowed out of the gravel bed during the major floods and would significantly contribute to local formation of bedforms to increase resistance to flow during and after the floods. This mechanism would explain the increased suspended sediment transport that was observed during the falling stages of the 1998 flood.

An alternative hypothesis is herewith suggested in an effort to possibly explain why bedforms change during the flood. It is considered that sand dunes may form on top of a gravel-bed during floods. At low stage, the river bed may primarily be made of stable gravel with low sediment transport and possible armouring at very low flows. Floods may provide a supply of sand that tends to deposit on the river bed during the flood. Sand dunes could start forming during the flood as a result of the exchange of sand material between the suspension and the bed. As the flood recedes, the sand supply decreases and the river has a sufficient transport capacity to gradually clear the sand dunes and transport the material further downstream or between the groynes. At low flows, there may be more gravel than sand on the river bed while the bed is mostly covered with sand dunes during floods. The source of sand may be from sand in suspension supplied from the upper river reaches, although according to ten Brinke and Kleinhans (pers. comm.) This does not seem to be supported by field measurements. It is the author's opinion that there may also be an exchange of sediment between the bed and the river banks during floods. At low stage, the river may clean the river bed and deposit sand near the banks between the groynes. When the flow overtops the groynes during floods, the sand deposits between the groynes may be remobilized and supplied to the suspended load. The sand would then be brought into suspension and in continuous exchange with the river bed this would form sand dunes during floods. As to gravel sizes, the coarser gravel fractions may not be mobilized at low flow. There should be gravel in transport as bed load during floods depending on the discharge magnitude.

As per the discussion regarding resistance to flow, it is clear that bed resistance to flow increases with discharge. Both the Vanoni-Hwang and the Engelund method yield calculation results similar to form drag friction factors based on field dune measurements. The relative change in the calculated values of the form drag friction factor during the flood of about 0.015 is approximately the same as the measured change in bed resistance during the flood. However, the calculated form drag friction factor depends solely on the dune properties, which peak on November 6 compared with the maximum value of the measured friction factor on November 4. There is therefore a hysteresis effect in the large dune height which is much less in terms of roughness height. It is possible that local properties of surface slope which vary near the flood peak could explain the noticed differences. Regarding grain resistance to flow, it is clear that by changing the coarse grain size from 20 to 1 mm, the calculated grain resistance parameter decreases from about 0.022 to about 0.01. It is therefore possible that the presence of sand dunes could reduce the grain resistance during floods. However, it is noticed that resistance to flow increases during floods, which is simply the opposite effect. If this is a viable hypothesis, it would imply that the decrease in grain resistance associated with a finer bed material is counteracted by a more important increase in form drag due to the formation of dunes. This seems to be an unlikely hypothesis.

The alternative in which grain resistance calculated by van Rijn's formulation may be overestimated seems more viable. In this regard, since van Rijn's method was essentially developed to describe sand dunes, its application to well-graded gravel-bed streams may not be warranted. The basic question regarding all resistance equations is: which bed particle diameter should be used? This question may not be too important when dealing with uniform particle size distributions in sand-bed channels. In the case of the Bovenrijn-Waal, the well-graded mixture would lead to different results whether the median grain size or the coarser fractions are used. Perhaps the grain resistance to flow of a sand-gravel mixture is not as high as calculated with van Rijn's method based on  $d_{90}$ . This is a general research question and if van Rijn's method seems to overestimate grain resistance to flow, a final statement cannot be determined without direct measurements of bed material distributions during floods.

Relative to form drag friction factors, the values calculated using the Engelund and Vanoni-Hwang approaches are in-line with the field measurements. It is still debatable whether one should sum up the contributions of large and small dunes. In this study, the small dunes were only present during the receding part of the flood hydrograph. On one hand, it is essential to determine form drag based on field measurements of dune properties. On the other hand, the calculation of form drag friction factors in practice is more difficult than anticipated due to the simultaneous presence of large and small dunes and the intricacies surrounding separate calculations. It also seems impractical to measure dune properties and process the data to separate large from small dunes before calculations. It is difficult to say whether they should be applied to the calculation of bed resistance to flow in the Rhine river branches because it depends on which algorithm is used for the calculation of grain roughness. In this study, the combination of either the Engelund or Vanoni-Hwang method for form drag with van Rijn's method for grain resistance yields overestimates of bed resistance to flow, and this approach seems impractical.

Finally, regarding which procedure should be recommended for the determination of bed resistance to flow. First, one should be concerned with the total bed resistance to flow rather than the individual parts due to grain roughness and form drag. In that regard, the bed resistance to flow seems overall fairly well predicted by van Rijn's method as long as the calculations are based on field measurements of dune properties rather than using the van Rijn approach to determine the dune height and wavelength. This seems impractical in the view that direct field measurements of dune properties during each flood are probably not part of regular field programs. The data also needs to be processed to separate large from small dunes. Perhaps a better approach would be to examine the dune properties in terms of height and length, etc. as a function of stage or discharge during the course of several floods. In this regard, the approach of Wilbers and ten Brinke (1999) seems promising. From these average properties, the van Rijn method could then be applied to calculate the bed resistance. This could lead to simple and practical estimates of bed resistance as a function of stage or discharge.

The best recommendation would be to plot the Darcy-Weisbach bed friction factor or Manning  $n$  directly as a function of discharge as plotted in Figures 8 and 9. It may be recommended to test the results of these two figures for different floods. A last comment is that for flood stage determination, besides bed resistance, one would also have to determine resistance due to groynes and resistance to flow on the flood plain whenever appropriate.

## **5. SUMMARY AND CONCLUSIONS**

This study has been undertaken with the primary objective to determine how bed resistance to flow changes during the 1998 flood of the Rhine-Waal River. As a second objective, existing methods to predict bed resistance to flow were evaluated in order to suggest or develop a procedure to determine bed resistance to flow during floods.

The data base for the analysis includes high quality field measurements on a daily basis for flow velocity, flow depth, dune properties, stage and reach-averaged slope measurements, and flow discharge. Particle size distributions were not measured during the 1998 flood but could be estimated from numerous field measurements prior to the flood. The data set allowed the determination of bed resistance to flow from direct measurements of flow depth, flow velocity and water surface slope on a daily basis during the 1998 flood. The analysis was repeated at two cross-sections with three vertical measurements at each cross-section. The field observations indicate clearly that dunes generally grow in amplitude during the flood and tend to wash away after the flood. These results corroborate the findings of earlier studies. As far as bed resistance to flow is concerned, the analysis clearly shows that the Darcy-Weisbach friction factor  $f$  and Manning  $n$  increase with discharge during the flood. The increase in bed resistance is attributed to the increase in bed form height during the flood.

The method of van Rijn was used to examine bed resistance and grain resistance, and the methods of Engelund and Vanoni-Hwang were examined for form drag. It can be concluded that the approach of

van Rijn based on field measurements of the dune properties corresponds fairly well to the bed resistance measurements. The van Rijn approach needs to be combined with field measurements of dune properties because the calculated dune heights exceed the field measurements. The calculations are slightly overestimated compared to the measurements and there is a noticeable hysteresis effect of the dune height versus discharge with maximum values of dune height occurring a couple days after the peak in measured values. The methods of Engelund and Vanoni-Hwang yield comparable results but are difficult to apply considering that field measurements are required for the analysis. Also, large and small dunes should be considered separately and direct comparisons with field measurements are not possible.

In future studies, it may be recommended to seek direct field measurements of the bed material composition during the flood as it is suspected that there may be changes in the bed composition between sand and gravel during the course of a single flood. It may also be interesting to examine several floods and to determine directly how the bed resistance factor changes with discharge. It may become the most practical way to determine the expected changes in bed resistance during major floods. Finally, the interaction between different components of resistance to flow during floods may be examined. For instance, if the resistance to flow caused by groynes increases with stage or discharge, it is possible that the added turbulence behind groynes may cause resuspension of sand deposited between groynes and may contribute to an added source of sand available for dune formation during floods.

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## **APPENDIX A.            Data set of the Bovenrijn**

1. Measured parameters (centerline and left side)
2. Measured parameters (right side) and Figure total bed resistance parameter
3. Calculated van Rijn resistance (centerline and left side)
4. Calculated van Rijn resistance (right side) and Figure Vanoni-Hwang
5. Calculated Vanoni-Hwang and Engelund resistance (centerline and left side)
6. Calculated Vanoni-Hwang and Engelund resistance (right side) and Figure Engelund
7. Figure summary for left side, centerline and right side
8. Bovenrijn flood characteristics

## **APPENDIX B.           Data set of the Waal**

1.     Measured parameters (centerline and left side)
2.     Measured parameters (right side) and Figure total bed resistance parameter
3.     Calculated van Rijn resistance (centerline and left side)
4.     Calculated van Rijn resistance (right side) and Figure Vanoni-Hwang
5.     Calculated Vanoni-Hwang and Engelund resistance (centerline and left side)
6.     Calculated Vanoni-Hwang and Engelund resistance (right side) and Figure Engelund
7.     Figure summary for left side, centerline and right side
8.     Waal flood characteristics