AMBIO (2011) 40:370–376
DOI 10.1007/s13280-010-0120-6

REPORT

The Influence of Floodplain Vegetation Succession on Hydraulic Roughness: Is Ecosystem Rehabilitation in Dutch Embanked Floodplains Compatible with Flood Safety Standards?

Bart Makaske, Gilbert J. Maas, Claus van den Brink, Henk P. Wolfert

Received: 7 July 2010 / Revised: 26 September 2010 / Accepted: 15 December 2010 / Published online: 21 January 2011

Abstract Here, we show for one of the Dutch Rhine River branches that large-scale riverine ecosystem rehabilitation and related vegetation succession may lead to up to 0.6 m higher river flood levels, because of increased hydraulic roughness. We hydraulically modeled future succession stages of embanked floodplain vegetation, following from present ecosystem rehabilitation plans for the 124-km-long river IJssel, and found flood levels exceeding the safety levels (related to dike heights). Our models take into account river engineering measures that are presently carried out, aimed at enhancing the river discharge capacity in order to meet required safety standards. Our study shows that there is a pressing need for integrated hydraulic-ecological evaluation of river engineering measures and ecosystem rehabilitation plans in the Rhine embanked floodplains. An important conclusion also is that hydraulic evaluation of planned vegetation goals only is inadequate, because flow resistance of preceding succession stages may be higher.

Keywords Ecosystem rehabilitation · Flood safety · Hydraulic roughness · River floodplains · River management · Vegetation succession

INTRODUCTION

Vegetation on river floodplains imposes hydraulic roughness to overbank flows causing flood water-levels to be raised with respect to a non-vegetated smooth situation (Cowan 1956; Klaassen and Van der Zwaard 1974). The hydraulic roughness of floodplain vegetation depends on the type of vegetation and the flow depth (Fathi-Maghadam and Kouwen 1997; Wu et al. 1999; Stone and Shen 2002). Along the lower courses of many rivers in densely populated areas, dikes protect large parts of the original floodplain. Flooding is only allowed in the relatively narrow embanked floodplain. In this situation, the embanked floodplain serves as a flood corridor, with a significant discharge function.

In the Netherlands, there is a government policy to strengthen the ecological function of the embanked floodplains, partly to meet the directives of the EU (European Commission 2007, 2010) underlying the planned Natura 2000 network of nature conservation areas (European Commission 2002). However, the effects of the expected vegetation development on flood levels in the embanked floodplains are poorly studied.

The embanked floodplains along the Dutch Rhine distributaries (Fig. 1) have been largely in agricultural use for centuries, mainly as production grasslands (Wolfert 2001). In the beginning of the 1990s, plans were made to allow a more natural vegetation of flood forests in limited areas. Since then, ecosystem rehabilitation plans have been developed at a larger scale and presently extensive parts of the embanked floodplains are planned to be incorporated in a national ecological network (LNV 2000) and the EU Natura 2000 network.

At the same time, government policy in the Netherlands aims at reinforcing the discharge function of the embanked floodplains, partly to accommodate the higher peak discharges that are expected because of climate change (Pfister et al. 2004). In January 1995, over 250,000 people were preventively evacuated from the Rhine floodplains just before Rhine discharge peaked at 12,000 $m^3\ s^{-1}$—the second highest discharge on record. Although the dikes bounding the embanked floodplains did not breach, awareness was raised that the Netherlands should be prepared for more frequent extreme discharge events in the future. The Room for the River project (Project Organisation Room for

Fig. 1 Aerial view of an embanked floodplain with a mosaic of woodlands and grasslands along a Rhine distributary in the Netherlands. View looking upstream. The winding road on the *foreground* and the *extreme right* marks the dike. The monumental city on the opposite river bank in the *left background* restricts the width of the embanked floodplain on that side (Photo: H. de Jong)

the River 2007) that is presently carried out involves river engineering measures—such as floodplain stripping, digging of secondary channels, and embanked floodplain widening—to facilitate a discharge of 16,000 $m^3 s^{-1}$. To cope with the expected effects of climate change in 2100, additional adaptation measures are under study in order to increase the discharge capacity of the Dutch Rhine to 18,000 $m^3 s^{-1}$.

Ecosystem rehabilitation in embanked floodplains leads to vegetation succession and an increase of hydraulic roughness during floods and therefore counteracts the engineering measures designed to improve the discharge capacity of the embanked floodplains. To assess the potential effects of the vegetation succession resulting from the present riverine ecosystem rehabilitation policy we carried out hydraulic calculations for one of the Dutch Rhine distributaries—the IJssel River (Fig. 2). These calculations comprise a series of future succession stages following from an embanked floodplain management change aimed at realization of the national ecological network, as described in governmental plans. The results show the development of flood water-levels over time, relative to flood safety levels, as a function of floodplain vegetation succession. In our calculations, we used a 2DH hydraulic model that meets all requirements of the Dutch Directorate-General for Public Works and Water Management (Rijkswaterstaat) (2006).

METHODS

Scenario-building

We have built scenarios of future floodplain vegetation for 12,000 ha of embanked floodplains along the entire 124-km-long IJssel River from the point where it branches off the Nederrijn upstream, to where it debouches into the lake Ketelmeer downstream (Fig. 2). The scenarios include all river engineering measures that are planned and presently carried out in the context of the Room for the River

Fig. 2 The location of the IJssel River in the Netherlands. The IJssel is a major Rhine distributary ranking third in size after the Waal (labeled "*a*") and Nederrijn-Lek (labeled "*b*") distributaries

project[1] aimed at enlarging the discharge capacity of the river-floodplain system, including digging of secondary channels, floodplain stripping, and widening of the embanked floodplain by dike displacement. Scenarios were made as digital maps using standard GIS software. We used mapped vegetation units representing the situation of 1997 as a starting point and added geomorphologic information and the engineering measures. Target vegetation units for the future were defined by available digital maps of governmental (provincial) plans. These plans involve turning the entire embanked floodplain area into different semi-natural (managed) vegetation units. We defined for each present vegetation unit a management that leads to the target vegetation, through vegetation succession. Management types ranged from intensive (mowing, harvesting), through semi-natural (grazing) to natural (spontaneous succession). Based on field experience with recent projects, we defined succession pathways for each combination of management and vegetation type (Table 1). Then, we combined all spatial information to generate a suite of future floodplain vegetation maps (e.g., Fig. 3, left panel) representing the situation after, respectively, 2, 5, 10, 30, and 100 years. After 100 years, all target vegetations have been reached.

Hydraulic Modeling

GIS vegetation scenario maps were converted to hydraulic roughness maps (Fig. 3), using the handbook for vegetation roughness of the Dutch Directorate-General for Public Works and Water Management (Rijkswaterstaat) that provides theoretically derived and experimentally tested Nikuradse *k* values (Table 2) for all vegetation structure types occurring in the embanked floodplains (Van Velzen et al.

---

[1] Details of the Room for the River project are still subject to changes. For some locations along the IJssel alternative measures with roughly equal flood water-level effects are under study and definitive decisions on these measures still have to be taken. In our study we included some alternatives that we consider likely to be carried out. We included, for example, the 'Bypass Kampen', a flood diversion in the IJssel delta area, which is an alternative for channel deepening in this area. Such choices between alternative measures do not affect the conclusions reached.

Table 1 Example of vegetation succession pathways for different types of vegetation management

Time	Vegetation management type		
	Natural	Semi-natural	Intensive
$T = 0$	Production meadow	Production meadow	Production meadow
$T = 2$ years	Dry herbaceous vegetation	Dry herbaceous vegetation	Production meadow
$T = 5$ years	Softwood shrubs	Dry herbaceous vegetation	Rough meadow
$T = 10$ years	Softwood shrubs	Mixed softwood shrubs/dry herbaceous vegetation (50–50%)	Rough meadow
$T = 30$ years	Natural softwood forest	Mixed natural forest/dry herbaceous vegetation (50–50%)	Semi-natural meadow
$T = 100$ years	Natural softwood forest	Mixed natural forest/dry herbaceous vegetation (50–50%)	Semi-natural meadow

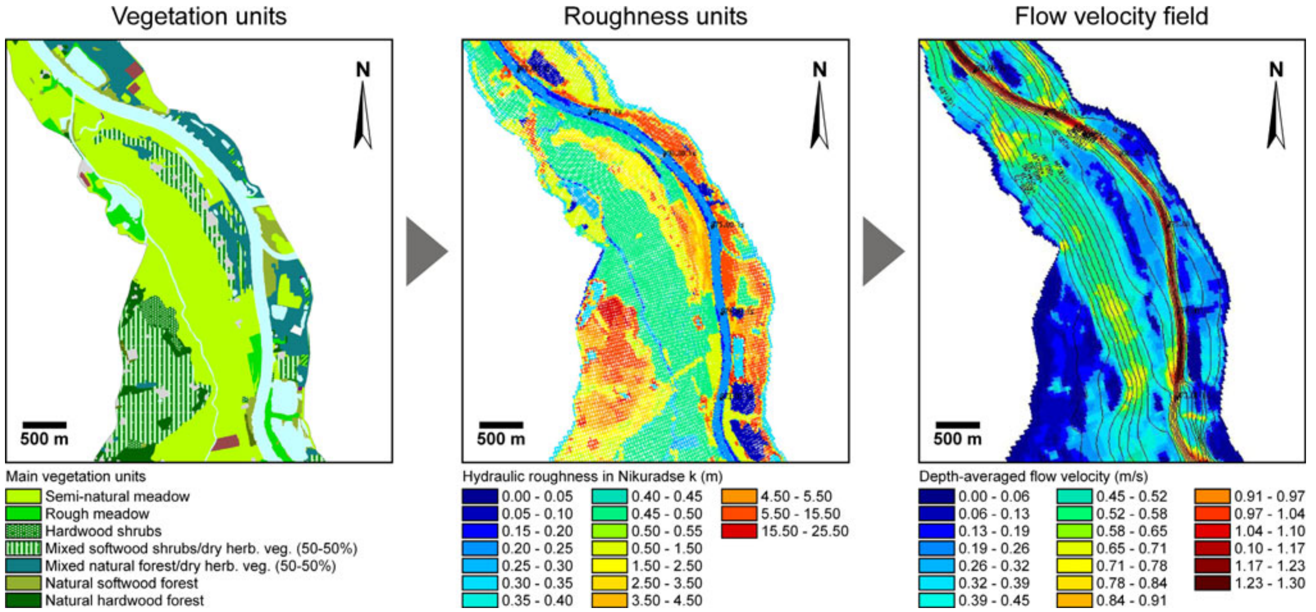

Fig. 3 Example of the modeling procedure for a part of the IJssel embanked floodplains. Area outside embanked floodplain is not shown. *Left panel* is a map of embanked floodplain vegetation units after 30 years of succession (*herb. veg.* herbaceous vegetation). These vegetation units were converted to hydraulic roughness units (*middle panel*) using information as given in Table 2. The roughness map was fed into the hydraulic model, which calculates a flow velocity field (*right panel*) and related water levels. Flow lines indicate flow direction (general flow direction is to the north, i.e., up in the panels) and are spaced such that 100 m^3/s passes between anyone pair of lines. Thus, spacing of flow lines largely reflects flow velocity (dense spacing is high velocity, wide spacing is low velocity)

2003a, b). This way of schematizing and modeling of vegetation roughness still requires rigorous field testing, but nevertheless represents the present official standard of river flood modeling in the Netherlands. The hydraulic roughness maps were fed into the WAQUA hydraulic model (Anonymous 2009; Vollebregt et al. 2003) for the IJssel River. This is a 2DH (two-dimensional depth-integrated) hydraulic model used by Rijkswaterstaat to asses the impact of engineering measures. The model calculates flow fields (Fig. 3) and water levels based on the Chézy flow resistance formula. We carried out our calculations for an imposed IJssel flood discharge of ~2460 $m^3\ s^{-1}$, which corresponds to a Rhine discharge (all distributaries summed) of 16,000 $m^3\ s^{-1}$, statistically representing the 1/1250 years flood event. This is the ‘design’ discharge used by river engineers to determine the required dimensions (especially dike heights) of the river system for a safe discharge function. The design of the river system is based on flood water-level predictions following from WAQUA calculations. With the 1/1250 year flood being far outside the range of discharges used for calibration and validation of the model the uncertainty range of the predicted flood water-levels is basically unknown.

RESULTS

We modeled the development of the hydraulic roughness of the floodplain vegetation over time as a result of a changed management designed to allow a vegetation succession towards various target biotopes. The changes in floodplain roughness lead to changes in flood water-levels

Table 2 The hydraulic roughness of embanked floodplain vegetation units. The roughness of vegetation is dependent on the water depth, which is taken into account in the hydraulic modeling by using vegetation-specific stage-roughness curves (Van Velzen et al. 2003a). Indicative roughness values given here are for a water depth of 4 m (a typical value for the modeled floods)

Vegetation unit	Nikuradse k (m)
Pioneer vegetation	0.28
Dry herbaceous vegetation	1.50
Wet herbaceous vegetation	0.50
Wet herbaceous vegetation with reed (>25%)	11.00
Reed	12.00
Arable land	0.20
Production meadow	0.295
Rough meadow	0.75
Semi-natural meadow	0.40
Hardwood shrubs	28.0
Softwood shrubs	25.0
Production forest	7.0
Natural softwood forest	13.0
Natural hardwood forest	12.0
Mixed natural forest/dry herbaceous vegetation (50–50%)	7.0
Mixed natural forest/dry herbaceous vegetation (75–25%)	9.0
Mixed hardwood shrubs/dry herbaceous vegetation (50–50%)	14.0
Mixed softwood shrubs/dry herbaceous vegetation (50–50%)	13.0
Mixed softwood shrubs/wet herbaceous vegetation (50–50%)	13.0
Mixed softwood shrubs/wet herbaceous vegetation with reed (50–50%)	18.0

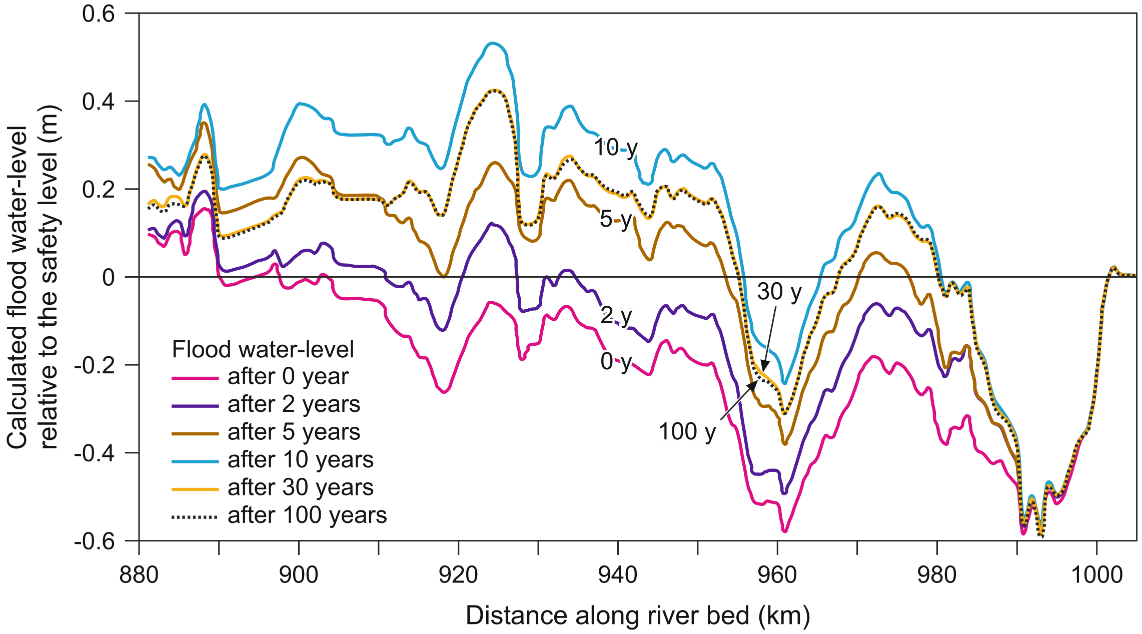

Fig. 4 Calculated flood water-levels for succession time steps relative to the safety level along the IJssel channel (flow direction is from *left* to *right*). The distance on the horizontal axis is given in the standard scale of river kilometers used by the Dutch Directorate-General for Public Works and Water Management (which starts at 880 km for the IJssel). The safety level (zero on the vertical axis) is used in the design of the flood protection infrastructure and generally represents the maximum flood level that can safely be accommodated by the river system at a certain location. Water levels above the safety level (positive values) indicate potentially unsafe conditions with risk of floodwaters overtopping the dike crest

that were calculated with our hydraulic model. In Fig. 4, along-stream flood water-levels for each succession time step are plotted relative to the safety level that is used in the design of the flood protection infrastructure. The safety level is closely related to dike heights, which means that positive values in Fig. 4 indicate a potentially unsafe situation with risk of floodwaters overtopping the dike crest and flooding of the inhabited floodplain. Negative values indicate a safe situation with flood water-levels (amply) below the dike crest.

After 2 years of changed management and consequent vegetation succession, calculated flood water-levels exceed the safety level in several reaches of the IJssel River (Fig. 4). This is due to the increase of roughness associated with the change from short vegetation in (mowed and grazed) production grasslands to taller vegetation in natural grasslands (Table 2). Further rise of the calculated water levels after 5 and 10 years of vegetation succession is caused by settlement of shrubs and small trees in combination with patches of remaining rough grasslands. This leads to a maximum in floodplain roughness and calculated water levels exceeding the safety levels over 76% of the study reach by up to ~0.5 m after 10 years. After 30 years, floodplain forests have developed in many places, replacing the hydraulically rougher shrubs and small trees. As a result, calculated flood water-levels are lower than after 10 years, but still water levels are above the safety level over 73% of the study reach, with a maximum of ~0.4 m. Because the final succession stage has been reached for most areas after 30 years, flood water-levels after 100 years are almost the same as after 30 years.

The longitudinal water-level graphs (Fig. 4) show peaks and troughs, which represent narrow and wide sections of the embanked floodplain, respectively. Narrow sections occur near major cities with monumental waterfronts on the river and floodplain-crossing infrastructure. Wide sections occur in between major population centers—partly as a result of engineering measures involving dike displacement. Flood water-levels are most sensitive to vegetation development in the narrow sections, which soon leads to critical situations with backwater effects raising flood water-levels far upstream of the constrictions.

DISCUSSION

The Netherlands is a densely populated country with limited space available for large-scale rehabilitation of natural ecosystems and development of ecological networks. In this context, the strong focus on the embanked floodplains in ecosystem rehabilitation plans is obvious: the embanked Rhine and Meuse floodplains represent wide corridors of uninhabited and extensively used land that is still dominated by natural abiotic processes (flooding, sedimentation). The embanked floodplains are planned to play an important role in the Dutch contribution to the EU Natura 2000 network. For riverine habitats there are few opportunities for rehabilitation elsewhere in the Netherlands. However, it seems that flood safety effects of large-scale floodplain ecosystem rehabilitation, so far have not been sufficiently taken into account in riverine ecosystem rehabilitation planning.

Our study illustrates the substantial hydraulic impact of vegetation succession on flood water-levels. Because of this, the evaluated ecosystem rehabilitation plans poorly fit within present and expected near-future flood safety margins. Our results indicate that relatively small changes over large areas, as a result of changed vegetation management (e.g. Fig. 4, after 2 years), already will lead to an unacceptable situation as to flood safety. It is a standard procedure in the Netherlands that the national authority for flood safety (Rijkswaterstaat) recurrently evaluates vegetation development in parts of the embanked floodplains and requests landowners to remove vegetation that is too rough according to their hydraulic model, i.e., the model also used in this study. Based on this study, we anticipate that the floodplain vegetation succession sketched in ambitious large-scale ecosystem rehabilitation plans will need to be aborted long before target vegetations are reached. Therefore, we feel that many of the goals formulated in the national and EU ecosystem rehabilitation plans for the Dutch embanked floodplains are unrealistic under the present circumstances and will not be reached. This especially holds for hydraulically rough vegetation types such as softwood floodplain forests, bushes, and marsh vegetations.

Optimization of hydraulic models remains important and it might be that the present model somewhat overestimates flood water-levels. However, given the magnitude of predicted flood water-level increase up to far above the safety level, it is unlikely that this increase fully results from errors and uncertainties in the hydraulic model. Accepting the model outcome as a realistic assessment, there are three strategies to combine ecosystem rehabilitation and flood safety in the future:

- realization of additional discharge capacity and flood-water storage capacity through river engineering measures (e.g., Klijn et al. 2004) to compensate for natural floodplain vegetation succession;
- lowering ecosystem rehabilitation ambitions and careful spatial planning of ecosystem rehabilitation projects as to minimize hydraulic obstruction;
- lowering ecosystem rehabilitation ambitions and careful temporal planning of ecosystem rehabilitation projects in order to prevent hydraulically rough succession stages to occur over large areas at the same time.

When combined with recurrent measures, such as removing mature vegetation and floodplain stripping, the third strategy is known in the Netherlands as ‘cyclic floodplain rejuvenation’ (Baptist et al. 2004). At present, the debate on which strategy to follow is still ongoing. Independent of ecosystem rehabilitation plans, a large number of measures is presently being studied in order to be able to accommodate higher Rhine discharges (up to 18,000 $m^3\ s^{-1}$) in the future. We recommend integrated planning and hydraulic evaluation of ecosystem rehabilitation projects and river engineering measures—taking into account long-term vegetation succession—to ensure that discharge capacity lost through vegetation development is compensated for by adequate measures. The results of our study indicate that hydraulic evaluation of planned vegetation goals only is inadequate, because flow resistance of preceding succession stages may be higher and give rise to critical situations.

Given the relatively large hydraulic impact of floodplain vegetation development found in this study, we expect similar conflicts between floodplain ecosystem rehabilitation and flood safety in other countries in northwestern Europe with embanked rivers—such as Belgium, France, Germany, and Poland—which face the same expected climate-change-induced river regime changes and have to implement the EU nature policy and legislation.

Acknowledgments This work was funded by the Netherlands Environmental Assessment Agency (PBL).

REFERENCES

Anonymous. 2009. *User's guide WAQUA, version 10.54*. Directorate-General for Public Works and Water Management, The Netherlands. http://www.helpdeskwater.nl/Extra_applicaties/Simona/release/doc/usedoc.html. Accessed 2 July 2010.

Baptist, M.J., W.E. Penning, H. Duel, A.J.M. Smits, G.W. Geerling, G.E.M. van der Lee, and J.S.L. van Alphen. 2004. Assessment of the effects of cyclic floodplain rejuvenation on flood levels and biodiversity along the Rhine River. *River Research and Applications* 20: 285–297.

Cowan, W.L. 1956. Estimating hydraulic roughness coefficients. *Agricultural Engineering* 37: 473–475.

Directorate-General for Public Works and Water Management. 2006. *Tentative river management review standard for interventions in the Rhine branches, version 10 April 2006*. Arnhem, The Netherlands: Rijkswaterstaat DON (in Dutch).

European Commission. 2002. Commission working document on Natura 2000. http://ec.europa.eu/environment/nature/natura2000/index_en.htm. Accessed 2 July 2010.

European Commission. 2007. Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora. Consolidated version 1.1.2007. http://ec.europa.eu/environment/nature/legislation/habitatsdirective/index_en.htm. Accessed 2 July 2010.

European Commission. 2010. Directive 2009/147/EC of the European Parliament and of the Council of 30 November 2009 on the conservation of wild birds (codified version). http://ec.europa.eu/environment/nature/legislation/birdsdirective/index_en.htm. Accessed 2 July 2010.

Fathi-Maghadam, M., and N. Kouwen. 1997. Nonrigid, nonsubmerged, vegetative roughness on floodplains. *Journal of Hydraulic Engineering* 123: 51–57.

Klaassen, G.J., and J.J. van der Zwaard. 1974. Roughness coefficients of vegetated flood plains. *Journal of Hydraulic Research* 12: 43–63.

Klijn, F., M. van Buren, and S.A.M. van Rooij. 2004. Flood-risk management strategies for an uncertain future: Living with Rhine River floods in The Netherlands? *AMBIO* 33: 141–147.

LNV. 2000. *Nature for People, People for Nature; Policy Document for Nature, Forest and Landscape in the 21st Century*. The Hague: Ministry of Agriculture, Nature Management and Fisheries, 87 pp.

Pfister, L., J. Kwadijk, A. Musy, A. Bronstert, and L. Hoffmann. 2004. Climate change, land use change and runoff prediction in the Rhine-Meuse basins. *River Research and Applications* 20: 229–241.

Project Organisation Room for the River. 2007. *Spatial planning key decision—Room for the River approved decision 19 December 2006*. The Hague: Project Organisation Room for the River, 42 pp.

Stone, B.M., and H.T. Shen. 2002. Hydraulic resistance of flow in channels with cylindrical roughness. *Journal of Hydraulic Engineering* 128: 500–506.

Van Velzen, E.H., P. Jesse, P. Cornelissen, and H. Coops. 2003a. *Flow resistance in embanked floodplains, part 1, handbook version 1–2003*. RIZA, report 2003.028, Arnhem, The Netherlands, 134 pp (in Dutch).

Van Velzen, E.H., P. Jesse, P. Cornelissen, and H. Coops. 2003b. *Flow resistance in embanked floodplains, part 2, background document version 1–2003*. RIZA, report 2003.029, Arnhem, The Netherlands, 124 pp (in Dutch).

Vollebregt, E.A.H., M.R.T. Roest, and J.W.M. Lander. 2003. Large scale computing at Rijkswaterstaat. *Parallel Computing* 29: 1–20.

Wolfert, H.P. 2001. *Geomorphological change and river rehabilitation*. Alterra, Scientific Contributions 6, Wageningen, The Netherlands, 200 pp.

Wu, F.-C., H.W. Shen, and Y.-J. Chou. 1999. Variation of roughness coefficients for unsubmerged and submerged vegetation. *Journal of Hydraulic Engineering* 125: 934–941.

AUTHOR BIOGRAPHIES

Bart Makaske (✉) is a geomorphologist, specialized in river and floodplain morphodynamics. He is currently involved in projects on floodplain ecology, river restoration, and river management. In addition to fluvial geomorphology, his research interests also comprise sea-level change and paleogeography of deltas.

Address: Alterra, Wageningen University and Research Centre, P.O. Box 47, 6700 AA Wageningen, The Netherlands.
e-mail: bart.makaske@wur.nl

Gilbert J. Maas is a landscape ecologist and has been involved in a series of ecological mapping projects in the embanked river floodplains in the Netherlands.

Address: Alterra, Wageningen University and Research Centre, P.O. Box 47, 6700 AA Wageningen, The Netherlands.

Claus van den Brink is a free-lance consultant in hydraulic engineering. He has worked for many years at the Directorate-General for Public Works and Water Management of the Netherlands.

Address: Duurzame Rivierkunde, Hoenloseweg 3, 8121 DS Olst, The Netherlands.

Henk P. Wolfert is a physical geographer, specialized in river restoration. He is currently executive secretary of the Environmental Sciences Group of Wageningen University and Research Centre.

Address: Alterra, Wageningen University and Research Centre, P.O. Box 47, 6700 AA Wageningen, The Netherlands.