Morphological development of side channels

Erik Mosselman

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Appendices

1 Introduction

1.1 Background

Cyclic floodplain rejuvenation (CFR) is a new strategy for flood risk management and nature restoration. The CFR project has been set up to assess the sustainability of this strategy for the floodplains of the river Rhine in Germany and the Netherlands. Secondary channels or side channels through floodplains have been identified as “rejuvenation components” that fit in the CFR strategy, because they can mitigate flooding risks and enhance fluvial habitat diversity. As sedimentation in a side channel leads to a gradual reduction of these effects, periodic excavation to clear the side channel will be required. The required frequency of this periodic rejuvenation depends on the morphological development of the side channel. This implies that information on the morphological development of side channels is needed for proper planning of CFR measures. The present CFR project report deals with this topic. It has been prepared in the framework of the IRMA-SPONGE programme and the Delft Cluster programme “Biogeomorphological Development of Floodplains”.

1.2 Definition

Side channels are defined as floodplain channels which convey water during at least 180 days per year.

1.3 Objectives

The objectives of this report are:

- *to review the present state-of-the-art regarding the modelling and prediction of the morphological development of side channels*;
- *to derive simplified expert rules for the morphological development of side channels*.

1.4 Main results

In theory, the morphological development of side channels can be computed with two- or three-dimensional morphological models, but the required data and computational effort are still too demanding for an evaluation of CFR strategies. Moreover, there is even a lack of good submodels for some of the key processes, because application of two- and three-dimensional models to floodplain morphodynamics is only a recent development. Applications in the past were traditionally limited to river engineering problems in the main channel. The following relevant processes are still poorly known: exchange processes between main channel and floodplains, interactions between vegetation and sediment, and the transport of sediment over obstacles and upward slopes (e.g. into a shallower side channel or over a weir at the entrance of a side channel).

The simpler approach of using a one-dimensional model requires an empirical *"nodal point relation"*. This relation expresses the ratio of the sediment transports into main channel and side channel as a function of other parameters. Usually its details are poorly known. That is a serious problem, because time scale and end state of the morphological development depend sensitively on this relation. As a consequence, one-dimensional computations of the morphological development of side channels are inherently inaccurate.

Given these shortcomings of three-, two- and one-dimensional modelling, simplified and more robust expert rules are derived, based on the key parameters from more sophisticated modelling approaches. In their present form, these rules are mainly based on mere expert judgement, because no adequate field data are available to test them. This underscores the need of long-term monitoring programmes for the morphological development of side channels.

1.5 Structure of report

Chapter 2 presents the current design rules for side channels. These rules are still relatively conservative. Chapter 3 reviews the present state-of-the-art regarding the modelling and prediction of the morphological development of side channels. Here conditions of overbank flow and in-bank flow are treated separately. The review underlies the derivation of the simplified expert rules in Chapter 4.

A one-dimensional non-linear analysis in Appendix A provides theoretical explanations for the essential behaviour of river bifurcations as well as for the influences of various parameters on this behaviour. It reveals the crucial role of the empirical nodal point relation for sediment distribution in one-dimensional models. Appendix B gives an overview of the CFR expert rules for the morphological development of floodplains, for which the rules derived in Chapter 4 are only a part. An overview of all CFR project reports is given in Appendix C.

1.6 Acknowledgements

This report has been prepared within the framework of the IRMA-SPONGE programme and the Delft Cluster programme "Biogeomorphological Development of Floodplains". Thanks are due to Max Schropp of Rijkswaterstaat RIZA for his explanations regarding monitoring data. Nathalie Asselman and Martin Baptist of WL | Delft Hydraulics have contributed to the derivation of simplified expert rules.

2 Present design rules

Design rules for side channels along the Rhine branches in the Netherlands have been developed from the work by De Haas (1991) and Barneveld, Nieuwkamer & Klaassen (1994). The current practice is that side channels are designed with a tendency to exhibit sedimentation. The design is thus kept on the safe side, because:

- Eroding side channels produce sedimentation in the main channel. This deteriorates the navigability and hence leads to more maintenance (dredging);
- It is feared that eroding side channels might grow uncontrollably under flood conditions.

Side channels are given a sedimentation tendency by applying the following rules of thumb:

- The side channel should make a larger angle with the approach flow direction than the main channel;
- The side channel should not be shorter than the main channel between offtake and confluence.

Usually a weir is constructed at the entrance of the side channel. This reduces the flow velocities in the side channel under normal conditions and prevents part of the sediment from entering the side channel.

Furthermore, the design is also kept on the safe side by applying the following rules of thumb:

- The side channel should not convey more than 3% of the total discharge during average discharge conditions. Then sedimentation in the main channel is thought to remain within acceptable limits;
- The flow velocity in the side channel should be about 0.3 m/s during average conditions. The morphological activity is then thought to remain within acceptable limits;
- No side channels should be excavated within a distance of 100 m from the river dikes, to avoid geomechanical instability of the dikes. A limit of 50 m from the river dikes is applied when the floodplain contains a sufficiently thick layer of stiff clay.

If side channels do not convey more than 3% of the total discharge during average discharge conditions, they convey definitely less than 3% of the total discharge during representative floods, *unless the side-channel discharge during average conditions is kept low by a weir at the entrance.* This means that, in the absence of entrance weirs, side channels according to present-day design principles can provide only minor reductions of flood water levels.

The dimensions of the side channels are designed using Chézy's formula for steady uniform flow at bankfull discharge, with a Chézy coefficient of 30 to 40 $m^{1/2}/s$. Detailed design should also address specific topics such as the resulting sedimentation of the main channel, cross-currents hindrance for navigation, bank erosion (cf. Barneveld & Mosselman, 1993) and the effect on ice jam formation (cf. Wijbenga, 1993).

3 Morphological development

3.1 Introduction

Two conditions require separate treatment when assessing the morphological development of side channels:

- Overbank flow, when side channels form a local depression of a submerged floodplain topography;
- In-bank flow, when side channels appear as separate branches around islands excised from the floodplain.

These two conditions are discussed in Sections 3.2 and 3.3 respectively.

The RIZA-funded project *"Morfologie en herinrichting"* (Mosselman, Barneveld & De Vriend, 2001) results in the conclusion that the following morphological effects of side channels along the Rhine branches require more research:

- Effect of a side channel on the morphology of the main channel during a flood (on a time scale of days);
- Effect of large-scale application of side channels on the large-scale development of the Rhine branches (on a time scale of years to decades).

However, morphological effects on the main channel are not a topic of research under the present CFR project. Only the morphological development (or "succession") of side channels is considered, in relation to vegetation succession and strategies of cyclic floodplain rejuvenation.

3.2 Overbank flow conditions

Side channels are only a part of a submerged bed topography when water flows over the floodplains. In theory, the morphological development can then be computed with a two-dimensional morphological model such as Delft2D-Rivers, a subset of the Delft3D modelling system specifically dedicated to river engineering applications. In practice, however, this is still difficult because application of Delft2D-Rivers to floodplain morphodynamics is only a recent development. Applications in the past were traditionally limited to river engineering problems in the main channel. Under CFR, a pilot application of Delft2D-Rivers to a floodplain with side channels has been set up for the Gamerensche Waard (Baptist, 2001).

The difficulties in the modelling of floodplain morphodynamics can be ascribed to the lack of good submodels for the following poorly-known processes:

- *Exchange processes between main channel and floodplains:* Convective and diffusive exchanges of water and sediment affect the sediment budget of floodplains. General information can be derived from Asselman's (2001) studies on floodplain sedimentation, but detailed modelling is still in its infancy. Specific problems include (1) the role and proper representation of the groyne belt between main channel and floodplain, (2) the role of large horizontal eddies (Large Eddy Simulation), (3) three-dimensionality near steep bed level gradients (Havinga, 1999), (4) vertical grain sorting in concentration profiles of suspended sediment, and (5) methods to avoid strong deformation of computational layers at steep transitions between main channel and floodplain (multiblock method for location-dependent number of layers in Delft3D).

- *Interactions between vegetation and the erosion, transport and deposition of sediment:* Some effects of vegetation on sediment transport may be known qualitatively, but there are hardly any quantitative data from field measurements or laboratory experiments. As a consequence, it is difficult to develop or to test submodels for these effects. One of the problems emerging from Baptist's (2001) pilot study is that the equivalent Nikuradse roughness, k, which is currently being applied for ecotopes along the Dutch rivers, can be much larger than the water depth, h. As a result, the Chézy coefficient becomes extremely small (even negative when applying White-Colebrook's 18 log(12h/k)). This Chézy coefficient is used in customary sediment transport formulae, in such a way that low Chézy values imply a very high sediment transport capacity. Hence, unrealistically, vegetated zones become zones of slow currents with very intense sediment transport. New approaches to the hydraulic roughness of vegetation are being considered: (1) a linear (u) instead of quadratic (u^2) resistance term in Delft3D (flow through vegetation obeying Darcy's law in analogy to groundwater flow), and (2) a theoretical study of the effect of flexible vegetation on vertical velocity profiles and flow resistance. The interactions between vegetation and sediment will have to be studied in laboratories and the field.

- *Sediment transport over obstacles:* Relevant obstacles in the context of floodplain morphodynamics are (1) weirs at side-channel entrances, (2) low levees on floodplains and (3) groynes in the transition area between the main channel and the floodplains (groyne belt). Lauchlan's (2001) experiments and Busnelli's (2001) numerical simulations have shown that our capacity to model flow and sediment transport over steep slopes and weirs is still very limited. Existing slope corrects are inadequate.

Given the present stage of development, the morphological development of side channels under overbank flow conditions can be assessed using expert judgement, preferably on the basis of results from two-dimensional hydrodynamic computations. Two basic situations are distinguished, based on the orientation of the channel with respect to the flow (see Figure 3.1):

1. *Side-channel aligned across the flow:* Conservation of mass is the dominating principle which governs the flow field. This causes a deceleration of the flow at the side channel. As a consequence, the side channel works as a sediment trap. Rates of sedimentation are similar to those derived for floodplain sedimentation by Asselman (2001);
2. *Side-channel aligned along the flow:* Conservation of momentum is the dominating principle which governs the flow field. The side channel works as a zone of lower

hydraulic resistance, accelerating the flow. As a consequence, the side channel attracts flow and may grow through erosion. The possible occurrence of this phenomenon can be identified qualitatively, but no simple rules of thumb are available for a quantitative prediction.

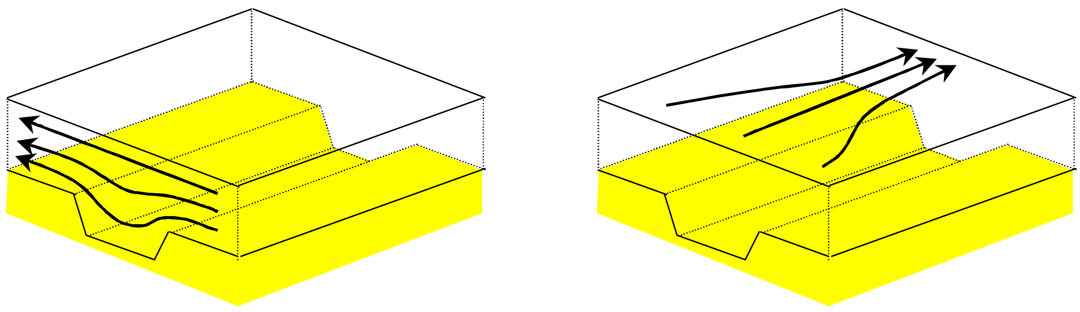

Figure 3.1: Distinction between flow field dominated by conservation of mass and flow field dominated by conservation of momentum.

The simplified expert rules in Chapter 4 account for this distinction by using an "orientation angle", defined as the average angle between the side channel and floodplain flow lines during a flood.

3.3 In-bank flow conditions

3.3.1 Introduction

Side channels appear as separate river branches during in-bank flow conditions (occurring at discharges equal to or lower than the bankfull discharge). Insight in the combined morphological behaviour of main channel and side channel can be derived from studies on various analogous systems:

- *Side channels proper:* monitoring data by Sorber et al (1999), Jans et al (1999, 2000, 2001), Simons, Bakker & Sorber (2000) and Schropp et al (2000, 2001);
- *River bend cut-offs:* empirical relations from India (Joglekar, 1956; Varma, Saxena & Rao, 1989), one-dimensional analyses by Klaassen & Van Zanten (1989) and Biglari (1989), two-dimensional numerical modelling by Jagers (1999);
- *Channel creation and channel abandonment in braided rivers:* derivation of empirical relations from data of the Brahmaputra-Jamuna River by Klaassen & Masselink (1992), Klaassen, Mosselman & Brühl (1993) and Mosselman et al (1995);
- *River avulsions:* studies by Fisk (1952), McCarthy, Ellery & Stanistreet (1992), Richards, Chandra & Friend (1993), Makaske (1998) and Stouthamer (2001);
- *Intakes of water from rivers:* handbooks by Avery (1989), Bouvard (1992) and Raudkivi (1993), literature review by Meijer (1993), experiences in South-Asia by Elsdon (1916)

and Ahmad, Ali & Khaliq (1960), physical modelling by Klaassen & Boogaard (1982), numerical modelling by El-Sayed (1995) and Wilson (2000);

- *River bifurcations in deltas:* Rhine bifurcation Pannerdense Kop (history by Van der Ven, 1979; physical modelling by Booij et al, 1953-55, and Van der Zwaard, 1981; mathematical modelling by Struiksma, 1998, and Mosselman & Sloff, 1998), Rhine-IJssel bifurcation IJsselkop at Westervoort (physical modelling by Breusers, 1959, and De Vries, 1969-70), Kattenkop bifurcation at the IJssel River mouth (physical modelling by Schijf, 1942; dredging data by Van Til, 1954, Havinga, 1984, and Mosselman, Lambeek & Meijer, 1993), Merwede bifurcation at Dordrecht (hydraulic physical modelling by Olthoff, Aarents & Beenhakker, 1961), Ganges-Gorai bifurcation (numerical modelling by Delft Hydraulics & Danish Hydraulics Institute, 1996; recent field measurements and physical and mathematical modelling in the framework of the Gorai River Restoration Project);

Figure 3.2: Rhine bifurcation Pannerdense Kop.

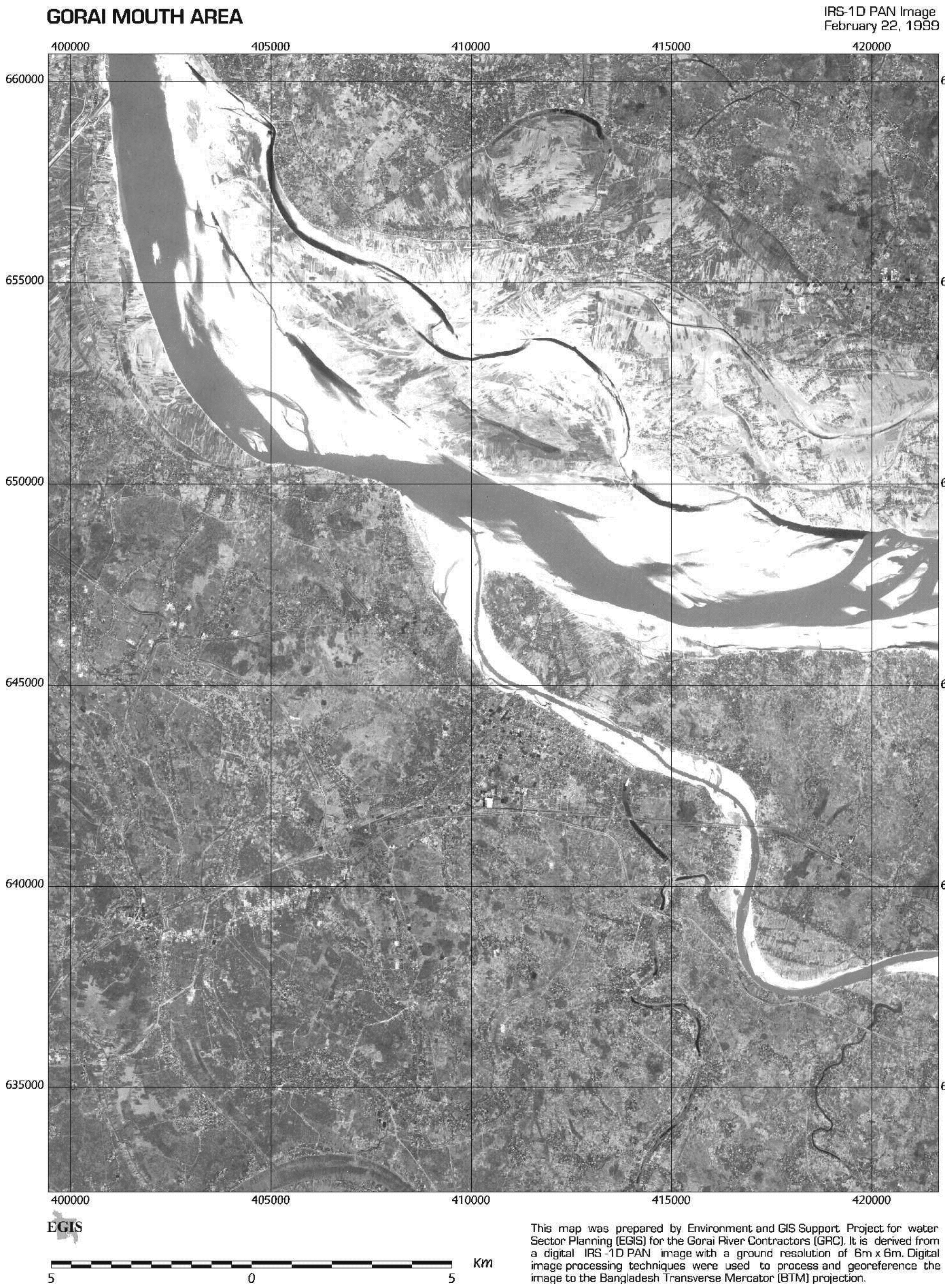

Figure 3.3: Ganges-Gorai bifurcation, Bangladesh.

- *Channel bifurcations in laboratory experiments:* Technical University of Karlsruhe (Bulle, 1926), WL | Delft Hydraulics (Riad, 1961) and Bangladesh University of Engineering and Technology, with assistance from Delft University of Technology (Den Dekker & Van Voorthuizen, 1994; Roosjen & Zwanenburg, 1995).

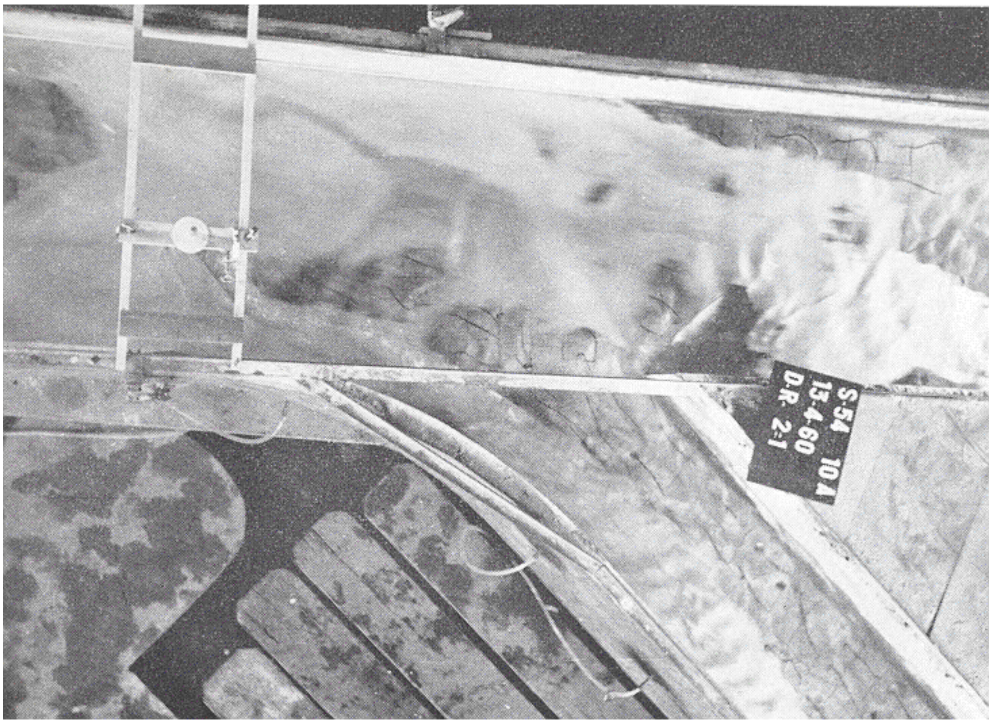

Figure 3.4: Experiments by Riad (1961).

Figure 3.5: Experimental facility at Bangladesh University of Engineering and Technology.

Information can also be found in the literature reviews by Struiksma & Barneveld (1990) and Akkerman (1993). The present report does not give a complete review of all information available, but focuses on the following aspects:

- empirical relations (Subsection 3.3.2);
- monitoring data from side channels (Subsection 3.3.3);
- one-dimensional analyses (Subsection 3.3.4);
- two- and three-dimensional numerical models (Subsection 3.3.5).

3.3.2 Empirical relations

The design rules of Chapter 2 indicate that the following parameters are important:
- ratio between the lengths of the two branches ("length ratio");
- bifurcation angles between the branches and the upstream flow direction.

The effect of differences in branch length can be understood from the corresponding differences in water level slope and, hence, flow velocity. Flow velocites are higher in shorter and steeper branches but lower in longer and flatter branches. Thus shorter branches can be expected to erode whereas longer branches can be expected to experience sedimentation.

The effect of the bifurcation angle can be understood from flow inertia and the Bulle effect (Bulle, 1926). The latter results from the spiral water motion which is generated in curved flows (see Figure 3.6).
This spiral motion deflects the water near the surface towards the outer part of the curve and deflects the water near the bed towards the inner part. As most sediment is transported on or close to the bed, a disproportionate part of the sediment transport is directed into the offtaking channel with the largest bifurcation angle. The resulting sedimentation forms initially a spit or sand arrow, and hence increases the angle between the offtaking channel and the approach flow. This enhances the flow curvature and the Bulle effect. Further development may cause bank erosion at the nose of the floodplain wedge between the side channel and the main channel.

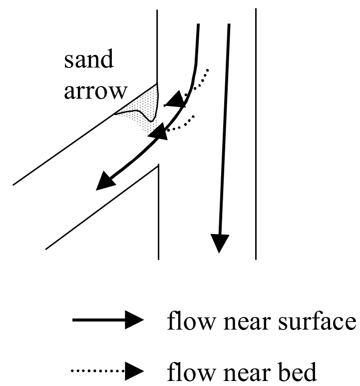

Figure 3.6: Spiral water motion in offtaking channel.

The transport of the sediment close to the bed into the offtaking channel with the largest bifurcation angle implies also that the sediment in this offtaking channel is coarser than the sediment in the channel with the smallest bifurcation angle. The Bulle effect explains also the design rule that water intakes should be located in the outer bend of a river, as channels offtaking from the inner bend tend to experience sedimentation.

For natural bend cut-offs, Joglekar (1971) introduces a "cut-off ratio" as a critical value for the ratio between the lengths of a deep river bend and a shallow shortcut channel. The bend is cut off by erosion of the shallow channel when the length ratio exceeds the cut-off ratio. Cut-off ratios vary from river to river.

For artificial bend cut-offs, Varma, Saxena & Rao (1989) do not consider cut-off ratios. They recommend a different type of relation, which, nonetheless, contains an effect of the length ratio. Their guidelines consider the bifurcation angle as well. Artificial cut-offs consist of an excavated "pilot channel" or "cunette", designed in such a way that it becomes the new course of the river at the expense of the bend which is being cut off. Artificial cut-offs may be combined with a diversion bund to improve their functioning. The following guidelines apply to the design of pilot channels:

- If the soil is resistant against erosion, the pilot channel should be excavated initially to the main river section. Otherwise it is sufficient to excavate the pilot channel so far that its R/L^2 is greater than for the main course (R = hydraulic radius, L = distance along channel from entrance to outlet). Further excavation will be realized by fluvial erosion;
- The entrance of the pilot channel should be made bellmouth;
- The pilot channel should be aligned in such a way that the flow into the pilot channel is less curved than the flow into the original river bend. This promotes the formation of sand arrows at the entrance of the original river bend and avoids the formation of sand arrows at the entrance of the pilot channel. Sand arrows (or: spits) eventually close a channel (cf. Figure 3.6).

Empirical relations for the probability of channel abandonment as a function of cut-off ratio and bifurcation angles have been derived for channels in the braided Brahmaputra-Jamuna River in Bangladesh (Klaassen & Masselink, 1992; Klaassen, Mosselman & Brühl, 1993; Mosselman et al, 1995). The length ratio was not a distinctive parameter in this low-sinuosity river. The main parameter was found to be the bifurcation angle. Some results are shown in Figure 3.7, but those results cannot be extrapolated to other rivers without further data analysis.

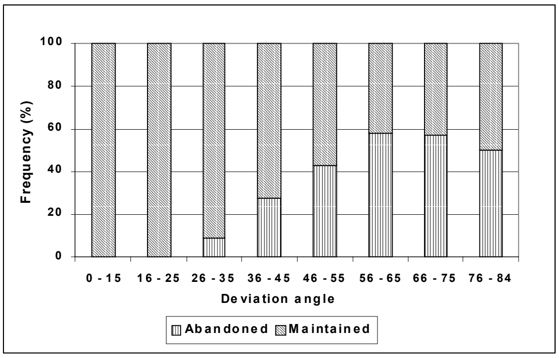

Figure 3.7: Frequency of channel abandonment occurrence in braided Brahmaputra-Jamuna River as a function of bifurcation angle.

The length ratio and the offtake angle are used in the simplified expert rules derived in Chapter 4.

3.3.3 Monitoring data from side channels

Vanhemelrijk & Paalvast (1997) present an inventory of nature development projects along rivers in various countries. Many of these projects include side channels through floodplains. In most projects, however, the monitoring focuses on biological developments and remains inadequate for morphological processes. The side channels in the Gamerensche Waard along the Waal River in the Netherlands appear to be a positive exception. The reports on the monitoring of these channels contain aerial photographs and synoptic bed topography measurements at different points of time (Sorber et al, 1999; Jans et al, 1999, 2000, 2001; Simons, Bakker & Sorber, 2000; Schropp et al, 2000, 2001). One of the interesting morphological developments thus visualized is the propogation of a sand front over a clayey subsoil in the Eastern side channel. The data are also used for Baptist's (2001) numerical study under CFR .

Despite the good quality of the monitoring of side channels in the Gamerensche Waard, the resulting data are insufficient for an assessment of correlations between morphological developments and key parameters such as length ratio and offtake angle. At this moment it is only possible to say that the following expert opinions have emerged from the monitoring of those side channels:

- side channels remain open during about 15 years (*"life-time"*);
- ship passages contribute substantially to the morphological development of side channels as they counteract sedimentation, an effect unknown until recently.

The apparent importance of ship-generated water motion implies that side channels now behave differently from side channels in the period before the large-scale training ("normalization") of the river Rhine. Studies of historical maps are hence of limited use.

Relevant field experience has also been obtained by Consulting Consortium FAP21/22[1] in the Flood Action Plan in Bangladesh. Figures 3.8 to 3.13 show the testing of various recurrent measures to close a minor side channel, over 200 m wide, in the braided Brahmaputra-Jamuna River.

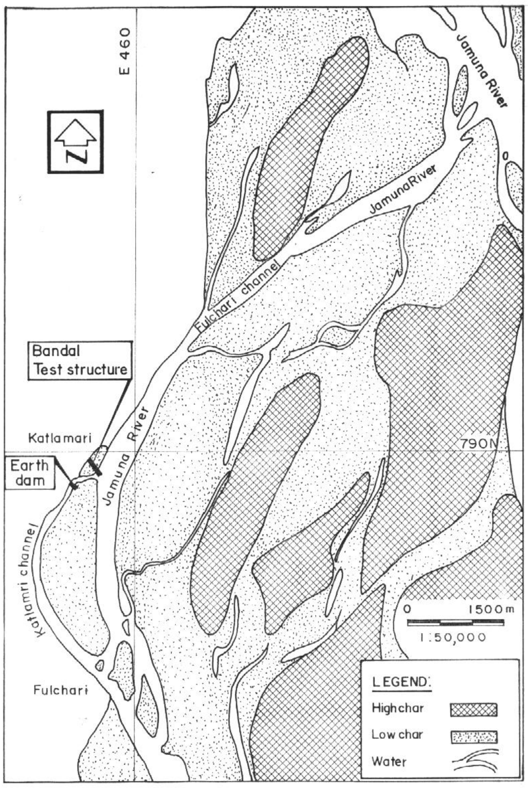

Figure 3.8: Layout of recurrent measures to close Katlamara side channel of Brahmaputra-Jamuna River.

[1] Rhein-Ruhr Ingenieur-Gesellschaft mbH, Compagnie Nationale du Rhône, Prof. Dr. Lackner & Partners and WL / Delft Hydraulics.

Figure 3.9: Construction of improved bandals at entrance of Katlamari channel, March 1997.

Figure 3.10: Construction of earth dam in Katlamari channel, March 1997.

Figure 3.11: Surface screens mounted between country boats to influence the motion of water and sediment near Katlamari channel, July 1997.

Figure 3.12: Improved bandals at entrance of Katlamari channel during flood, July 1997.

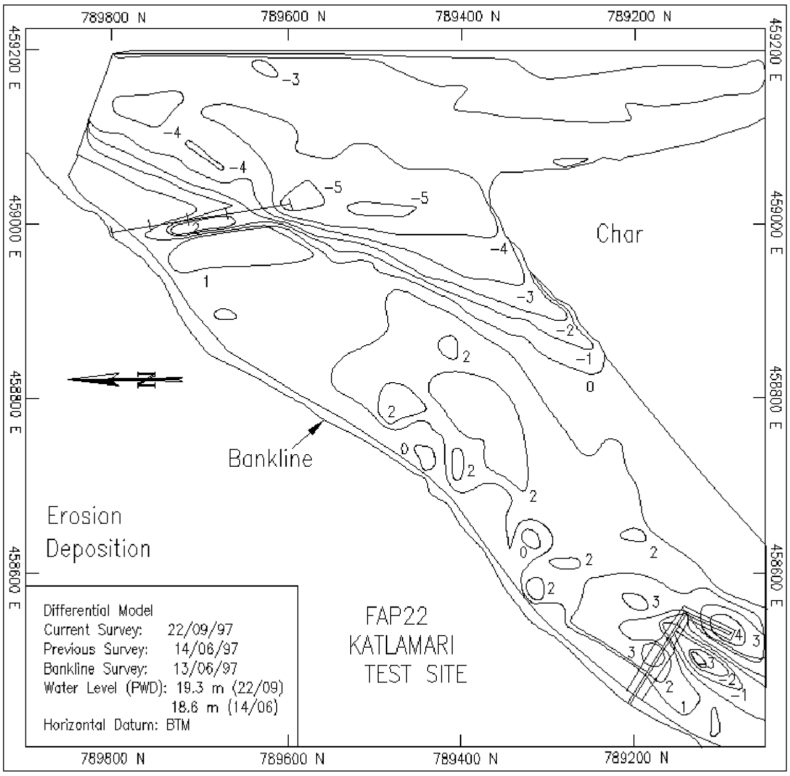

Figure 3.13: Erosion and sedimentation in entrance area of Katlamari channel, monsoon 1997.

3.3.4 One-dimensional analyses

Key parameters in one-dimensional models of river bifurcations are the distributions of water and sediment over the bifurcated branches. These distributions determine the morphological evolution of both downstream branches. The distribution of water is calculated straightforwardly by one-dimensional models such as SOBEK. The distribution of sediment, however, requires additional input in one-dimensional models. This additional input regards the parameters of a *"nodal point relation"* which expresses the ratio of the sediment transports into the two branches as a function of other system parameters, including the ratio of the discharges through the two branches.

Appendix A presents a nonlinear phase-plane analysis, based on the work of Flokstra (1985), Fokkink & Wang (1993), Wang, Fokkink & Karssen (1993), Wang & Van der Kaaij (1994) and Wang et al (1995). The analysis demonstrates that the system behaviour of main channel and side channel depends sensitively on the parameters of the nodal point relation. Certain parameter ranges produce a behaviour in which either the main channel or the side channel is closed inevitably by sedimentation, whereas other parameter ranges produce a behaviour which tends to a stable equilibrium in which both channels remain open.

Appendix A includes a sensitivity analysis, based on the work by Klaassen & Van Zanten (1989).

The morphological development of a side channel can be computed well with a one-dimensional morphological model such as SOBEK-Rivers if the nodal point relation is known and the banklines are fixed. Side channels overloaded with sediment experience sedimentation whereas side channels underloaded with sediment experience erosion. The resulting time-dependent development has been studied by Ribberink & Van der Sande (1984, 1985), Van der Knaap (1994) and Sieben (1995, 1999). Qualitatively, the time-dependent development is such that

- deep side channels are closed by deposition of a sand plug (sand arrow, spit) at the entrance;
- shallow side channels are closed by deposition over a long reach.

However, the nodal point relation is usually poorly known, which leads to the conclusion that a two-dimensional or three-dimensional approach is mandatory for proper assessment of the morphological development of side channels, even during in-bank flow conditions. In two- and three-dimensional computations, the nodal point relation is not an input but an implicit outcome.

3.3.5 Two- and three-dimensional numerical models

The morphological behaviour of river bifurcations has also been studied numerically with various two- and three-dimensional models. These models do not require any specification of an empirical nodal point relation, because the distribution of sediment transport is computed from the same morphological equations as the development of the bed. Nonetheless, also two- and three-dimensional modelling of river bifurcations is not without problems. Specific problems include:

- the relative contributions of bedload and suspended load (both requiring different modelling approaches);
- the representation of sediment transport over upward slopes (into a shallower side channel or over a weir at the entrance of the side channel) (Lauchlan, 2001).

Some results from selected modelling studies are discussed below.

Bolla Pittaluga, Repetto & Tubino (2001) apply a locally two-dimensional description at the bifurcation in an otherwise one-dimensional model, in order to arrive at a more physically-based nodal point condition.

Meijer & Ksiazek (1994) carried out three-dimensional flow computations for several geometries of channel bifurcations. They used a k-ε turbulence model and simulated sediment transport by particle trajectories. The interesting feature of their study is that they investigated how the coefficients in an empirical nodal point relation depend on the offtake angle. For particles with a diameter of 0.01 mm, transported as suspended load, the nodal point relation is found to approach $S_{1,in}/S_{2,in} = Q_1/Q_2$, where S denotes sediment transport, Q denotes discharge and subscripts 1 and 2 refer to a main channel and an offtaking channel respectively. The additional subscript “in” expresses that S denotes an actual sediment supply into the channel instead of the sediment transport capacity. For particles with a diameter of 0.15 mm, transported as bedload, two different nodal point relations have been fitted to the data:

$$\frac{S_{1,in}}{S_{2,in}} = \alpha\left(\frac{Q_1}{Q_2}\right) + \beta \tag{3-1}$$

$$\frac{S_{1,in}}{S_{2,in}} = \left(\frac{Q_1}{Q_2}\right)^p \left(\frac{B_1}{B_2}\right)^q \tag{3-2}$$

where B denotes channel width. It is found that α and p reach maximum values (α = 2.63, p = 1.15) if the offtake angle equals 90°. Smaller as well as larger offtake angles lead to lower values of α and p. Similarly, β and q are found to reach minimum values (β = -0.10, q = -0.71) if the offtake angle equals 90°.

Application of a two-dimensional morphological model in the 1980s to the Rhine bifurcation at Pannerden has long been one of the success stories of morphological modelling, because the bed topography computed by the model agreed better with prototype measurements than the bed topography obtained in a mobile-bed physical model (Figure 3.14). Those computations had been carried out using spatially constant sediment properties and a spatially constant Chézy coefficient for hydraulic resistance. Samples of river bed material indicate, however, that sediment granulometry varies spatially due to grain sorting. The computations were therefore repeated in the late 1990s using spatially varying grain sizes. Surprisingly, it appeared no longer possible to correctly reproduce transverse bed profiles and the locations between consecutive bends (Struiksma, 1998). A linear analysis reveals that spatial grain size variations can have this effect and that spatial variations in hydraulic roughness can counterbalance this effect (Mosselman & Sloff, 1998; Mosselman & al, 1999). The success of model applications using constant grain size and Chézy coefficient suggests that in the Dutch Rhine branches such couterbalancing does occur. However, detailed investigation of bed material samples and bedforms does not provide sufficient information on spatial variations to test this against field measurements. This is a topic of ongoing further research (Kazi Iqbal Hassan, 2000; Smale, 2000).

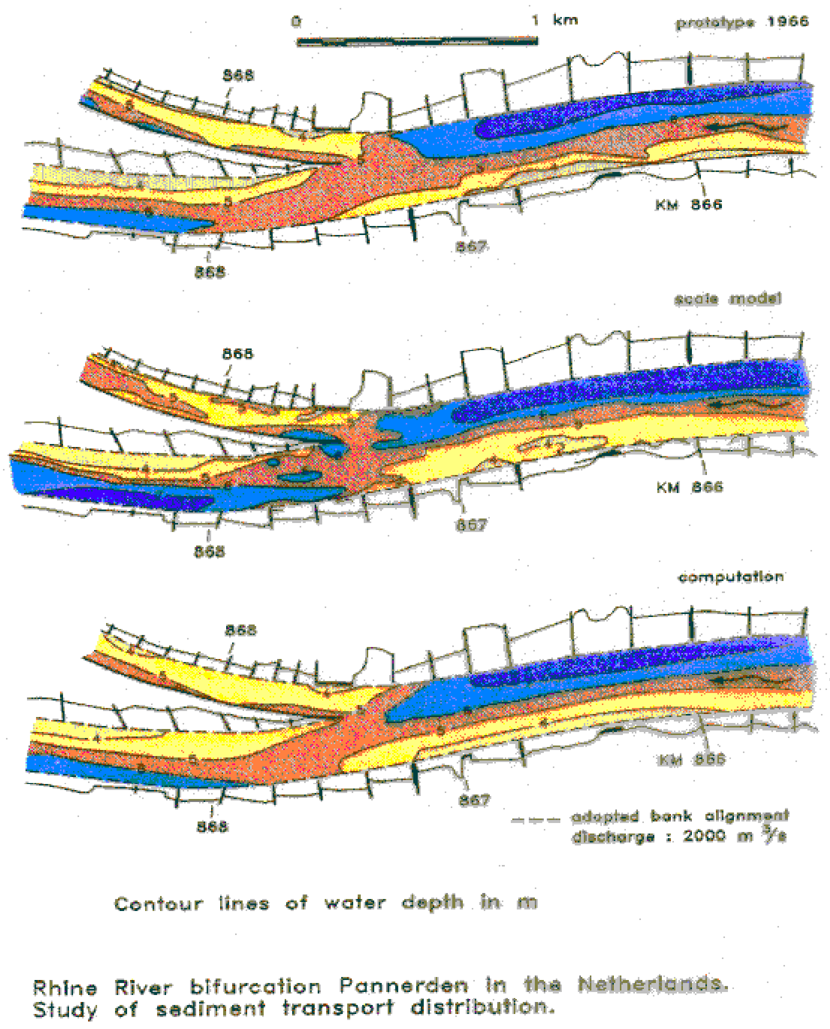

Figure 3.14: Prototype and model bed topographies of Rhine bifurcation at Pannerden.

4 Derivation of simplified expert rules

Chapter 3 demonstrates that the knowledge and tools for quantitative predictions of the morphological development of side channels is still limited. Predictions under CFR are therefore based on simple expert rules, which are inevitably inaccurate. These expert rules are derived from the following information in Chapter 3:

- Deep side channels are closed by deposition of sand at the entrance (Subsection 3.3.4);
- Key parameters for the morphological development of side channels are length ratio, offtake angle and orientation angle (Section 3.2 and Subsection 3.3.2);
- Most side channels are believed to remain open up to at least 15 years (Subsection 3.3.3).

The side channels are divided into the following morphological units with distinct morphological behaviour:

- *Entrance sections:* areas at the entrance of side channels with a length equal to about twice the side channel width. Channels are classified as side channels when they convey flow during at least 180 days per year. The entrance sections are subdivided into slowly, moderately and fast aggrading ones, depending on geometrical conditions which are explained further below. The aggradation results from deposition of sand;
- *Other sections:* downstream sections of channels which convey flow during at least 180 days per year. Sedimentation in these sections consists of silt and clay.

The distinction between slowly, moderately and fast aggrading side channels is based on the following three parameters:

- *Length ratio*, defined as the ratio of side-channel length to main-channel length between the offtake and the confluence (from Subsection 3.3.2). In the calculation, the length of a side-channel reach through a deep sand mining pit should be subtracted from the total side-channel length in order to account for the low hydraulic resistance of the pit. This effect of sand mining pits is studied in more detail by Baptist (2001);
- *Offtake angle*, defined as the angle between the side channel and the main channel at the offtake (from Subsection 3.3.2);
- *Orientation angle*, defined as the average angle between the side channel and floodplain flow lines during a flood (from Section 3.2).

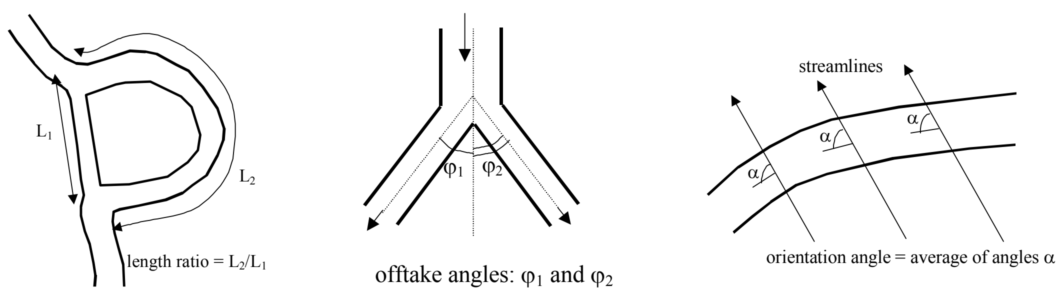

Figure 4.1: Definition sketches of length ratio, offtake angle and orientation angle.

Most side channels are assumed to be *moderately aggrading*. They are expected to be closed after about 15 years of sedimentation. Computations show that this corresponds to a sedimentation rate of 1 mm per day of inundation. As a typical example, a side channel entrance bed at 3 m below floodplain level rises with this sedimentation rate 0,3 m in the first year, 0.25 m in the second year and 0.2 m in the third year. *Fast aggrading* side channels are channels with such an unfavourable geometry that they act as a sand trap. Those are expected to be closed after 5 years of sedimentation. This is found to correspond to a sedimentation rate of 2 mm per day of inundation. As a first guideline, the geometry of a side channel is considered unfavourable if two or three of the following conditions are met:

- The length ratio is larger than 1.5;
- The offtake angle is 90º or larger;
- The orientation angle is 45º or larger;
- The side channel takes off from an inner bend of the main channel.

Slowly aggrading side channels are characterized by length ratios below 1 and offtake angles below 10º. They are assumed to remain open and, actually, they present a risk of erosion. Higher offtake angles may still correspond to slowly aggrading channels if the length ratio is considerably lower than 1, i.e. if the side channel is considerably shorter than the main channel.

Table 4.1 summarizes the aggradation rates for each morphological unit. The expression in millimetres per day of inundation implies that the rates of aggradation decrease as bed elevation increases.

Table 4.1: Aggradation of morphological floodplain units.

Morphological unit	**Deposit composition**	**Aggradation rate (mm per day of inundation)**
Entrance section of slowly aggrading side channel	-	0
Entrance section of moderately aggrading side channel	sand	1
Entrance section of fast aggrading side channel	sand	2
Other sections of side channel	silt, clay	0.13

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A One-dimensional analysis of river bifurcations

A.1 Introduction

Morphological changes in bifurcated river channels depend on the distributions of discharge and sediment transport at the bifurcation. The discharge distribution can be computed with an iterative procedure. The distribution of sediment transport, however, is very difficult to assess. It is determined by the local three-dimensional flow structure, which depends heavily on the geometry of the bifurcation and affects the transport mode (bedload versus suspended load). Information about geometry and three-dimensional flow structure vanishes in one-dimensional models for river morphology such as SOBEK. In those models the distribution of sediment transport is usually described with empirical *nodal point relations*.

This appendix presents nonlinear analyses of a simplified one-dimensional model. It contains a sensitivity analysis, based on the work of Klaassen & Van Zanten (1989), and a phase-plane stability analysis, based on the work of Flokstra (1985), Fokkink & Wang (1993), Wang, Fokkink & Karssen (1993), Wang & Van der Kaaij (1994) and Wang et al (1995). The latter analysis demonstrates that the system behaviour of river bifurcations depends sensitively on the parameters of the nodal point relation. Certain parameter ranges produce a behaviour in which one of the channels is closed inevitably by sedimentation, whereas other parameter ranges produce a behaviour which tends to a stable equilibrium in which both channels remain open.

A.2 Assumptions

The present analysis is based on the following simplifying assumptions:

1. The discharge and sediment supply from upstream are constant, i.e. they do not change in time;
2. Both bifurcated channels have the same water level at the downstream boundary (e.g. because they join downstream);
3. The water level at the downstream boundary remains constant;
4. The water level at the bifurcation remains constant;
5. The distribution of discharges over the two bifurcated channels is equal to the distribution which would occur for uniform flow;
6. Each channel has a constant and uniform width;
7. Each channel has a constant and uniform Chézy coefficient for hydraulic roughness;
8. The sediment is uniform, so that no grain sorting occurs and all channels have the same sediment transport formula;
9. The sediment transport formula can be approached by a power-law dependence on flow velocity;

10. Changes in water depth can be ascribed entirely to changes in bed level as a result of erosion and sedimentation (rigid-lid approximation);
11. The distances between the bifurcation and the downstream boundary are short, so that rates of erosion and sedimentation can be assumed to be uniform within each channel;
12. Morphological changes in the upstream channel can be neglected.

A.3 Set of equations

The equations for steady uniform flow in each channel read

$$Q_0 = B_0 h_0 u_0 \tag{A-1}$$

$$Q_1 = B_1 C_1 h_1^{3/2} i_1^{1/2} = B_1 C_1 h_1^{3/2} \left(\frac{\Delta z_w}{L_1} \right)^{1/2} \tag{A-2}$$

$$Q_2 = B_2 C_2 h_2^{3/2} i_2^{1/2} = B_2 C_2 h_2^{3/2} \left(\frac{\Delta z_w}{L_2} \right)^{1/2} \tag{A-3}$$

$$Q_0 = Q_1 + Q_2 \tag{A-4}$$

where Q is the discharge, B is the channel width, h is the water depth, i is the channel slope, u is the flow velocity, C is the Chézy coefficient for hydraulic roughness, Δz_w is the water level difference between the bifurcation and the downstream boundary and L is the length of the channel between the bifurcation and the downstream boundary. Subscript 0 refers to the upsteam channel whereas subscripts 1 and 2 refer to the two bifurcated channels.

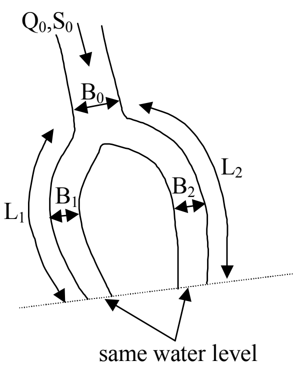


Figure A.1: Definition sketch.

Elimination of Δz_w and application of Eq. (A-4) reduces the set of flow equations to

$$Q_0 = B_0 h_0 u_0 \tag{A-5}$$

$$Q_1 = \frac{B_1 C_1 h_1^{3/2} L_1^{-1/2}}{B_1 C_1 h_1^{3/2} L_1^{-1/2} + B_2 C_2 h_2^{3/2} L_2^{-1/2}} Q_0 \tag{A-6}$$

$$Q_2 = \frac{B_2 C_2 h_2^{3/2} L_2^{-1/2}}{B_1 C_1 h_1^{3/2} L_1^{-1/2} + B_2 C_2 h_2^{3/2} L_2^{-1/2}} Q_0 \tag{A-7}$$

The assumption that the sediment transport formula can be approached by a power-law dependence on flow velocity leads to the following expressions for the sediment transport capacities:

$$S_{0,e} = S_0 = B_0 m u_0^b = B_0^{1-b} m Q_0^b h_0^{-b} \tag{A-8}$$

$$S_{1,e} = B_1^{1-b} m Q_1^b h_1^{-b} \tag{A-9}$$

$$S_{2,e} = B_2^{1-b} m Q_2^b h_2^{-b} \tag{A-10}$$

where m and b are the coefficient and the exponent of the sediment transport formula respectively. The distribution of sediment transport at the bifurcation is described by an empirical nodal point relation, F:

$$\frac{S_{1,in}}{S_{2,in}} = F \tag{A-11}$$

Hence

$$S_{1,in} = \frac{F}{1+F} S_0 \tag{A-12}$$

$$S_{2,in} = \frac{1}{1+F} S_0 \tag{A-13}$$

Erosion or sedimentation of the bifurcated channels results from differences between the incoming amounts of sediment ($S_{1,in}$, $S_{2,in}$) and the sediment transport capacities ($S_{1,e}$, $S_{2,e}$). The bifurcated channels are assumed to be so short that erosion and sedimentation occur uniformly over their lengths. Furthermore assuming that the channel widths remain constant[2], the sediment balance for each channnel can be written as

$$L_1 B_1 \frac{dz_{b1}}{dt} = S_{1,in} - S_{1,e} \tag{A-14}$$

$$L_2 B_2 \frac{dz_{b2}}{dt} = S_{2,in} - S_{2,e} \tag{A-15}$$

Assuming a rigid-lid (i.e. a constant water level, so that bed degradation is equal to the resulting channel deepening, and bed aggradation equal to the resulting shallowing) and substituting Eqs. (A-8) to (A-13), one obtains

[2] *Mosselman, Lambeek & Meijer (1993) briefly discuss the relation for channels narrowing or widening when erosion and sedimentation produce bank retreat and advance in addition to bed degradation and aggradation.*

$$L_1 B_1 \frac{dh_1}{dt} = S_{1,e} - S_{1,in} = B_1^{1-b} m Q_1^b h_1^{-b} - \frac{F}{1+F} B_0^{1-b} m Q_0^b h_0^{-b} \tag{A-16}$$

$$L_2 B_2 \frac{dh_2}{dt} = S_{2,e} - S_{2,in} = B_2^{1-b} m Q_2^b h_2^{-b} - \frac{1}{1+F} B_0^{1-b} m Q_0^b h_0^{-b} \tag{A-17}$$

Substitution of Eqs. (A-6) and (A-7) and application of Eqs. (A-5) and (A-8) yield

$$\frac{dh_1}{dt} = \frac{S_0}{L_1 B_1} \left(\left(\frac{B_0}{B_1} \right)^{b-1} \left(\frac{h_0^{3/2} B_1 C_1 i_1^{1/2}}{Q_0} \right)^b \left(\frac{h_1}{h_0} \right)^{b/2} - \frac{F}{1+F} \right) \tag{A-18}$$

$$\frac{dh_2}{dt} = \frac{S_0}{L_2 B_2} \left(\left(\frac{B_0}{B_2} \right)^{b-1} \left(\frac{h_0^{3/2} B_2 C_2 i_2^{1/2}}{Q_0} \right)^b \left(\frac{h_2}{h_0} \right)^{b/2} - \frac{1}{1+F} \right) \tag{A-19}$$

This is a system of two nonlinear differential equations which describes the combined behaviour of h_1 and h_2. Note that F may depend on h_1 and h_2 as well. This system forms the basis for the analyses in the following sections.

A.4 Time scale of channel closure

Equations (A-16) and (A-18) show that the time scale for the development of the first bifurcated channel is given by

$$T_1 = \frac{L_1 B_1 \Delta h_1}{S_{1,e} - S_{1,in}} = \frac{L_1 B_1 \Delta h_1}{S_0 \left(\left(\frac{B_0}{B_1} \right)^{b-1} \left(\frac{h_0^{3/2} B_1 C_1 i_1^{1/2}}{Q_0} \right)^b \left(\frac{h_1}{h_0} \right)^{b/2} - \frac{F}{1+F} \right)} \tag{A-20}$$

where Δh_1 denotes a representative change in water depth due to erosion or sedimentation, $L_1 B_1 \Delta h_1$ representing the corresponding volume of scour or fill. The selection of Δh_1 depends on the problem under consideration. Klaassen & Van Zanten (1989) define $\Delta h_1 = h_2 - h_1$ in their time scale for cutoff development, as they study situations in which the water depth, h_1, of a shallow cutoff channel develops into the water depth, h_2, of a main channel.

Shields & Abt (1989) also define $\Delta h_1 = h_2 - h_1$ in their empirical time scale for the sedimentation of cutoff bends. As they do not derive their time scale theoretically from fundamental laws of physics, they arrive at a relation which differs from Eq. (A-20):

$$T_1 = \frac{1}{K_d} = \frac{\left(\frac{\Delta h_1}{h_2} + 2 \right)^{1.4}}{0.13 \cdot 10^{-5} \ C_s^{0.78}} \tag{A-21}$$

where C_s denotes the mean concentration of suspended bed material upstream of the bifurcation.

Equation (A-20) shows that the time scale depends strongly on the empirical nodal point relation, F.

A.5 Nodal point relations

Equations (A-18) and (A-19) show that equilibria are always unstable if a nodal point relation, F, does not depend on h_1 and h_2. If the water depth in one of the channels is only slightly smaller than the equilibrium value for which dh/dt = 0, it will decrease further (dh/dt < 0). This positive feedback in the neighbourhood of equilibria holds for all positive values of b. An example is the relation $F = (B_1/B_2)^q$ with positive q. It is also readily seen that such nodal point relations are not very realistic, as they imply that sediment continues to be pumped into a dying channel even when this channel has been closed almost completely.

Usually, nodal point relations depend implicitly on h_1 and h_2 because F is expressed as a function of Q_1/Q_2. Meijer & Ksiazek (1994) study the following two relations:

$$F = \alpha\left(\frac{Q_1}{Q_2}\right) + \beta \tag{A-22}$$

$$F = \left(\frac{Q_1}{Q_2}\right)^p \left(\frac{B_1}{B_2}\right)^q \tag{A-23}$$

where α, β, p and q are empirical coefficients. For q = 1-p , relation (A-23) reduces to a relation between sediment transports per unit width and specific discharges.

Klaassen & Van Zanten (1989) use relation (A-22) with $\alpha = 1/\sigma$ and $\beta = 0$. Their analysis is presented in Section A.7. The nonlinear phase-plane analysis in Section A.6 is based on relation (A-23) with q = 0.

A.6 Phase-plane stability analysis

The stability of the system is studied through a nonlinear phase-plane analysis. For convenience we take $B_1 = B_2 = B_0/2 = B$, $C_1 = C_2 = C$ and $L_1 = L_2 = L$. These simplifications do not affect the character of the system. The nodal point relation is $F = (Q_1/Q_2)^p$, which corresponds to relation (A-23) with q = 0. Applying the simplifications, this reduces to

$$F = \left(\frac{h_1}{h_2}\right)^{3p/2} \tag{A-24}$$

Substitution of the simplifications, the nodal point relation (A-24) and the Equations (A-2) to (A-4) for Q_0 into Equations (A-18) and (A-19) yields

$$\frac{dh_1}{dt} = \frac{S_0}{BL}\left(\frac{2^{b-1} h_0^b h_1^{b/2}}{\left(h_1^{3/2} + h_2^{3/2}\right)^b} - \frac{h_1^{3p/2}}{h_1^{3p/2} + h_2^{3p/2}} \right) \tag{A-25}$$

$$\frac{dh_2}{dt} = \frac{S_0}{BL}\left(\frac{2^{b-1} h_0^b h_2^{b/2}}{\left(h_1^{3/2} + h_2^{3/2}\right)^b} - \frac{h_2^{3p/2}}{h_1^{3p/2} + h_2^{3p/2}} \right) \tag{A-26}$$

This set of equations is still too complicated to be solved analytically, but it can be analyzed qualitatively in a phase plane (h_1 , h_2). The equilibria are represented by critical points for which $dh_1/dt = 0$ and $dh_2/dt = 0$. The solution for $dh_1/dt = 0$ reads

$$h_1 = 0 \quad \vee \quad 2^{b-1} h_0^b h_1^{(b-3p)/2}\left(h_1^{3p/2} + h_2^{3p/2}\right) = \left(h_1^{3/2} + h_2^{3/2}\right)^b \tag{A-27}$$

The solution for $dh_2/dt = 0$ reads

$$h_2 = 0 \quad \vee \quad 2^{b-1} h_0^b h_2^{(b-3p)/2}\left(h_1^{3p/2} + h_2^{3p/2}\right) = \left(h_1^{3/2} + h_2^{3/2}\right)^b \tag{A-28}$$

Apparently $h_1 = h_2$ if both h_1 and h_2 are nonzero. Thus the critical points are found to be $(0 , 2^{(b-1)/b}h_0)$, $(2^{(b-1)/b}h_0 , 0)$ and (h_0 , h_0).

The critical points can be asymptotically stable, unstable or an unstable saddle point. The nature of a critical point can be determined by linearizing the system around the critical point and by subsequently considering the eigenvalues of the linear system. If both eigenvalues are negative, perturbations of the equilibrium are always damped so that the critical point is asymptotically stable. Perturbations of the equilibrium grow exponentially if both eigenvalues are positive, which corresponds to an unstable critical point. The critical point is an unstable saddle point if the two eigenvalues have opposite signs.

Linearization of the system around a critical point yields:

$$\left.\frac{dh_1}{dt}\right|_{h_{1c},h_{2c}} = 0 + \frac{\partial}{\partial h_1}\left(\frac{dh_1}{dt}\right)\Bigg|_{h_{1c},h_{2c}}\left(h_1 - h_{1c}\right) + \frac{\partial}{\partial h_2}\left(\frac{dh_1}{dt}\right)\Bigg|_{h_{1c},h_{2c}}\left(h_2 - h_{2c}\right) \tag{A-29}$$

$$\left.\frac{dh_2}{dt}\right|_{h_{1c},h_{2c}} = 0 + \frac{\partial}{\partial h_1}\left(\frac{dh_2}{dt}\right)\Bigg|_{h_{1c},h_{2c}}\left(h_1 - h_{1c}\right) + \frac{\partial}{\partial h_2}\left(\frac{dh_2}{dt}\right)\Bigg|_{h_{1c},h_{2c}}\left(h_2 - h_{2c}\right) \tag{A-30}$$

which can be written in matrix notation as

$$\begin{pmatrix} dh_1 / dt \\ dh_2 / dt \end{pmatrix} = \frac{S_0}{BLh_0} A_{h_{1c},h_{2c}} \begin{pmatrix} h_1 - h_{1c} \\ h_2 - h_{2c} \end{pmatrix} \tag{A-31}$$

where $A_{h1c,h2c}$ is a 2×2 matrix. For the critical point (h_0 , h_0) this matrix becomes

$$A_{h_0,h_0} = \frac{1}{8} \begin{pmatrix} -(b+3p) & -3(b-p) \\ -3(b-p) & -(b+3p) \end{pmatrix} \tag{A-32}$$

Remark: the equivalence with the relation given by Wang, Fokkink & Karssen (1993) can be demonstrated easily by substituting b = 5 and p = 1 while using

$$\frac{S_0}{BLh_0} = \frac{mQ_0^b}{2^{b-1} h_0^{b+1} B^b L} \tag{A-33}$$

The eigenvectors of the system are vectors that are transformed by $A_{h0,h0}$ into multiples of themselves: $A_{h0,h0}\ \underline{x} = \lambda \underline{x}$. This has nontrivial solutions if λ is chosen such that the determinant of $A_{h0,h0}-\lambda I$ equals zero. The values for λ which satisfy this condition are the eigenvalues of the matrix $A_{h0,h0}$. The corresponding equation reads

$$\lambda^2 + \frac{b+3p}{4}\lambda - \frac{b}{8}(b-3p) = 0 \tag{A-34}$$

This second-degree polynomial has two solutions for λ, at least one of them being negative and hence an attracting eigenvalue. The second eigenvalue is also negative if p > b/3. The critical point is then asymptotically stable. If p < b/3, then one eigenvalue is attracting and one eigenvalue is repelling. The critical point is then an unstable saddle point. Hence p < b/3 produces a behaviour in which one of the channels is closed inevitably by sedimentation, whereas p > b/3 produces a behaviour which tends to a stable bifurcation.

For the critical point (0 , $2^{(b-1)/b}h_0$), the matrix becomes

$$A_{0,2^{(b-1)/b}h_0} = \frac{1}{2^{(b-1)/b}} \begin{pmatrix} 0 & 0 \\ 0 & -b \end{pmatrix} \tag{A-35}$$

The eigenvalues are the roots of the characteristic equation $\lambda(\lambda+b/2^{(b-1)/b}) = 0$. This leads to $\lambda = 0$ or $\lambda = -b/2^{(b-1)/b}$. The eigenvalue 0 causes difficulties, because it is not immediately clear whether the corresponding critical point is stable or not. For further analysis we take b = 5 and p = 1. Hence

$$A_{h_0,h_0} = \frac{1}{2} \begin{pmatrix} -2 & -3 \\ -3 & -2 \end{pmatrix} \tag{A-36}$$

with eigenvalues -5/2 and +1/2. Elaboration of $A_{h0,h0}\ \underline{x} = \lambda\underline{x}$ shows that the attracting eigenvalue of -5/2 is associated with eigenvectors (1,1) and that the repelling eigenvalue of 1/2 is associated with eigenvectors (1,-1). Furthermore

$$A_{0,2^{4/5}h_0} = \frac{1}{2^{4/5}}\begin{pmatrix} 0 & 0 \\ 0 & -5 \end{pmatrix} \tag{A-37}$$

with eigenvalues $-5/2^{4/5}$ and 0, and

$$A_{2^{4/5}h_0,0} = \frac{1}{2^{4/5}}\begin{pmatrix} -5 & 0 \\ 0 & 0 \end{pmatrix} \tag{A-37}$$

with the same eigenvalues. The critical points are intersection points of curves for which $dh_1/dt = 0$ with curves for which $dh_2/dt = 0$. These curves are described by Equations (A-27) and (A-28), which read for b = 5 and p = 1:

$$h_1 = 0 \quad \vee \quad h_2^{3/2} = 2h_0^{5/4}h_1^{1/4} - h_1^{3/2} \tag{A-38}$$

$$h_2 = 0 \quad \vee \quad h_1^{3/2} = 2h_0^{5/4}h_2^{1/4} - h_2^{3/2} \tag{A-39}$$

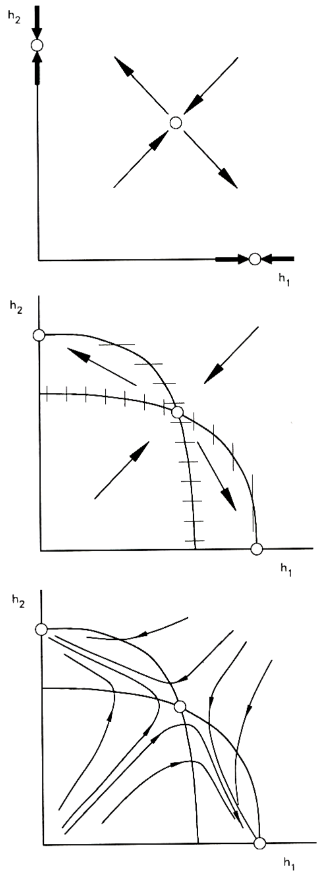
These curves divide the phase plane into four regions: one for which dh_1/dt and dh_2/dt are positive, one for which both derivatives are negative, and two regions for which dh_1/dt and dh_2/dt have opposite signs. The character of the regions in the neighbourhoods of the critical points with eigenvalues $-5/2^{4/5}$ and 0 implies that these equilibria are asymptotically stable. Trajectories from an arbitrary point in the phase plane can be sketched easily when these curves and the critical points and their character are known. The construction of trajectories is illustrated in Figure A.2.

A.7 Sensitivity analysis

Klaassen & Van Zanten (1989) present a sensitivity analysis of the set of equations with nodal point relation $F = (1/\sigma)Q_1/Q_2$. They focus on one channel only, i.e. they analyze whether the cutoff channel of a bend (channel 1) grows or decays without considering the question whether the main channel (channel 2) remains open or silts up in the case of a growing cutoff channel. Their results are given in Figures A.3 and A.4 as functions of depth ratio, h_1/h_2 , and length ratio, L_2/L_1.

Figure A.3 shows the influence of $\sigma\cdot\gamma$, where σ is the coefficient in the nodal point relation and γ is the ratio between the Chézy coefficients of the two channels: $\gamma = C_1/C_2$. This figure holds for b = 5 and $B_1/B_2 << 1$.

Figure A.4 shows the influence of the width ratio, β, defined as $\beta = B_1/B_2$. This figure holds for b = 5, $\sigma = 1$ and $C_1 = C_2$.



Step 1:
Critical points with attraction and repelling along main directions.

Step 2:
Curves for $dh_1/dt = 0$ and $dh_2/dt = 0$, and regions in which dh_1/dt and dh_2/dt do not change sign.

Step 3:
Trajectories for time-dependent development of h_1 and h_2.

Figure A.2: Construction of trajectories in phase plane for behaviour of river bifurcations.

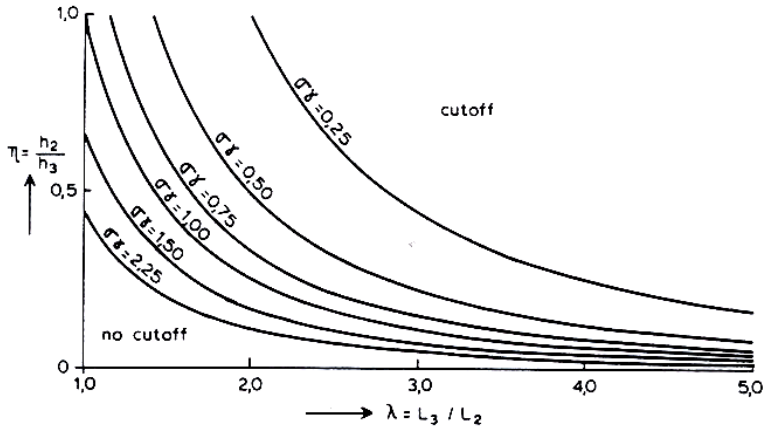


Figure A.3: Influence of coefficient, σ, in linear nodal point relation and ratio of Chézy coefficients, γ, on development of cutoff channel (b = 5, β << 1).

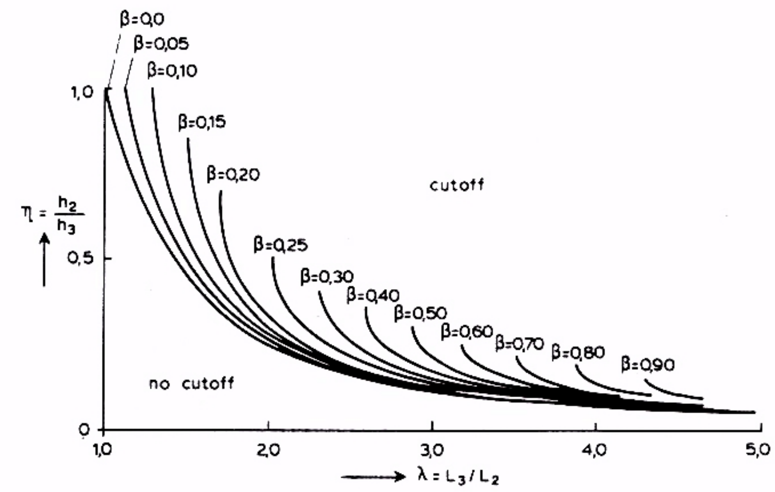


Figure A.4: Influence of width ratio, β, on development of cutoff channel (b = 5, σ = 1, γ = 1).

B Simplified expert rules for morphological development of floodplains

The morphological development of the floodplains is assessed through simple expert rules in the evaluation of CFR strategies. These rules are presented here. The rules for side channels are based on the present report. The backgrounds on the rules for other parts of the floodplains are explained by Asselman (2001). Rejuvenation measures are assumed to be designed safely in the sense that they will not lead to erosion in the floodplains. Floodplain erosion would enhance the sedimentation in the main channel and thus deteriorate the navigability, necessitating an increase in maintenance costs. Moreover, it is feared that eroding floodplain areas, in particular eroding side channels, might erode uncontrollably under flood conditions. Accordingly, all morphological developments are assumed to be a form of sedimentation.

The floodplains are divided into the following morphological units with distinct morphological behaviour:

- *Inflow areas:* areas where water enters the floodplains during floods. These areas exhibit deposition of sand in accordance with the formation of natural levees;
- *Extensions of point bars:* areas adjacent to the downstream parts of point bars in the main channel. These areas exhibit deposition of sand during floods as an extension of the sand deposits on the adjacent point bars in the main channel;
- *River dunes:* areas where sand accumulates due to fluvial-aeolian interactions. The accumulations occur in areas that satisfy a set of specific conditions, which are explained further below;
- *Entrance sections of side channels:* areas at the entrance of channels with a length equal to about twice the side channel width. Channels are classified as side channels when they convey flow during at least 180 days per year. The entrance sections are subdivided into slowly, moderately and fast aggrading ones, depending on geometrical conditions which are explained further below. The aggradation results from deposition of sand;
- *Other sections of side channels:* downstream sections of channels which convey flow during at least 180 days per year. Sedimentation in these sections consists of silt and clay;
- *Rest of floodplains:* areas which are not classified as inflow areas, point-bar extensions, river dunes or side channels. Sedimentation in these areas consists of silt and clay.

These morphological units have been delineated in a GIS, allowing automation of the expert rules for morphological development.

Fluvial-aeolian interactions produce river dunes on areas which meet the following conditions:

- Large amounts of fine sand are available in the beaches between groynes, which can be eroded and transported by the wind when the water levels are low;
- Gravel is absent;
- The vegetation cover is too poor to protect the sand from the eroding force of the wind;
- Wind velocities exceed the critical velocity for initiation of motion;

- The prevailing wind direction is more or less parallel to the river bank, i.e. the edge between floodplain and main channel;
- Several beaches between the groynes are interconnected.

The distinction between slowly, moderately and fast aggrading side channels is based on the following three parameters:

- *Length ratio*, defined as the ratio of side-channel length to main-channel length between the offtake and the confluence. In the calculation, the length of a side-channel reach through a deep sand mining pit should be subtracted from the total side-channel length in order to account for the low hydraulic resistance of the pit. This effect of sand mining pits is studied in more detail by Baptist (2001);
- *Offtake angle*, defined as the angle between the side channel and the main channel at the offtake;
- *Orientation angle*, defined as the average angle between the side channel and floodplain flow lines during a flood.

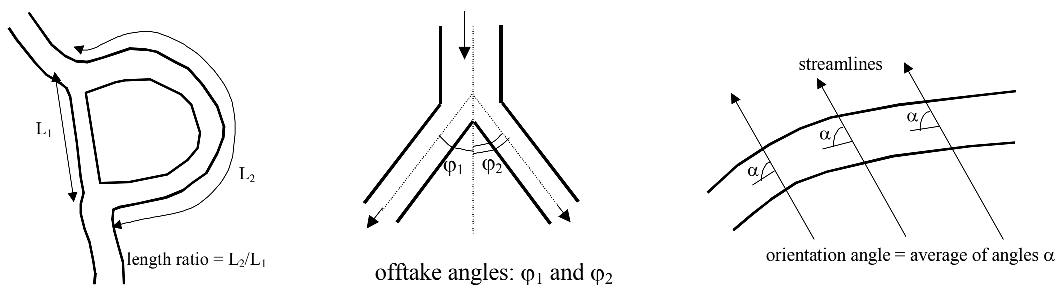


Figure B.1: Definition sketches of length ratio, offtake angle and orientation angle.

Most side channels are assumed to be *moderately aggrading*. They are expected to be closed after about 15 years of sedimentation. *Fast aggrading* side channels are channels with such an unfavourable geometry that they act as a sand trap. Those are expected to be closed after 5 years of sedimentation. As a first guideline, the geometry of a side channel is considered unfavourable if two or three of the following conditions are met:

- The length ratio is larger than 1.5;
- The offtake angle is 90º or larger;
- The orientation angle is 45º or larger;
- The side channel takes off from an inner bend of the main channel.

Slowly aggrading side channels are characterized by length ratios below 1 and offtake angles below 10º. They are assumed to remain open and, actually, they present a risk of erosion. Higher offtake angles may still correspond to slowly aggrading channels if the length ratio is considerably lower than 1, i.e. if the side channel is considerably shorter than the main channel.

Table B.1 shows the aggradation rates for each morphological unit. The aggradation rates expressed in millimetres per day of inundation imply that the rates of aggradation decrease as bed elevation increases. The values for inflow areas, point-bar extensions, river dunes and the rest of the floodplain have been based on field measurements and sedimentation modelling for the Rhine branches in the Netherlands (Asselman, 2001). The values for side channels have been taken from Chapter 4.

Table B.1: Aggradation of morphological floodplain units.

Morphological unit	**Deposit composition**	**Aggradation rate**	
		(mm per day of inundation)	**(m/year)**
Inflow area	sand	1	-
Point bar extension	sand	1	-
River dune	sand	-	0.15
Entrance section of slowly aggrading side channel	-	0	-
Entrance section of moderately aggrading side channel	sand	1	-
Entrance section of fast aggrading side channel	sand	2	-
Other sections of side channel	silt, clay	0.13	-
Rest of floodplain	silt, clay	0.13	-

Cyclic rejuvenation of floodplains also affects the morphological development of the main channel, with implications for navigation and overall river development. The effects of various CFR strategies on the main channel are not assessed in the present project, but rough estimates of the effects can be made with formulae derived from Jansen et al (1979). This is illustrated here for a floodplain lowering which causes 3% of the river discharge to be deviated from the main channel to a course through the floodplain. It is assumed that this occurs during a discharge which is more or less representative for the morphological development. In the Rhine branches in the Netherlands, this discharge could be the one which is exceeded during about 125 days per year (Q_{35}). The corresponding water depth is assumed to be 5 m. Local execution of this floodplain lowering results in main-channel sedimentation which amounts to 3% of 5 m water depth, i.e. 0.15 m of sedimentation on average.

If the same floodplain lowering is not limited to a single location but executed along a 100 km long river reach, much more sedimentation will occur because the main channel will assume a steeper slope. The eventual steepening, reached after an adaptation period on the order of a century, will amount to 3% of the existing slope. Assuming a river slope of 100 mm/km, the slope increases with 3 mm/km. This implies 100 km × 3 mm/km = 0,3 m of sedimentation at the upstream part of the reach in addition to the 0.15 m due to local floodplain lowering. Given the ungoing degradation of the Rhine branches in the Netherlands, it may be that this sedimentation slows down degradation rates rather than that it produces aggradation.

C Overview of CFR project reports

The present CFR project report is part of a series of reports, prepared in the framework of the IRMA-SPONGE programme and the Delft Cluster programme "Biogeomorphological Development of Floodplains". The complete list of CFR project reports is given below.

Duel, H., M.J. Baptist & W.E. Penning (2001), Cyclic floodplain rejuvenation: a new strategy based on floodplain measures for both flood risk management and enhancement of the biodiversity of the river Rhine. **CFR project main report**, NCR report 14-2001, Delft.

Duel, H., M.J. Baptist & W.E. Penning (2001), Cyclic floodplain rejuvenation: a new strategy based on floodplain measures for both flood risk management and enhancement of the biodiversity of the river Rhine. **CFR project executive summary**, NCR, Delft.

Baptist, M.J. (2001), Review on biogeomorphology in rivers: processes and scales. **CFR project report 3** , Delft University of Technology.

Glasbergen, M.J. (2001), Fish habitat requirements in the Dutch part of the river Rhine. **CFR project report 4**, WL | Delft Hydraulics & Hogeschool Zeeland.

Nijhof, B.S.J. (2001), Vegetation succession in floodplain flats; Inventarisation and modelling of measured data and expert judgement. **CFR project report 5**, Alterra, Wageningen.

Geerling, G.W., B. Peters & A.J.M. Smits (2001), Development of floodplain ecotopes in the Netherlands (Rhine tributaries). **CFR project report 6**, University of Nijmegen.

Lee G.E.M. van der, H. Duel, W.E. Penning & B. Peters (2001), Modelling of vegetation succession in floodplains. **CFR project report 7**, WL | Delft Hydraulics & University of Nijmegen.

Asselman, N.E.M. (2001), Sediment processess in floodplains. **CFR project report 8**, WL | Delft Hydraulics.

Mosselman, E. (2001), Morphological development of side channels. **CFR project report 9**, WL | Delft Hydraulics.

Stone, K. & M.J. Baptist (2001), Effects of hydraulic measures and nature development in the Gelderse Poort. **CFR project report 10**, WL | Delft Hydraulics.

Baptist, M.J. (2001), Numerical modelling of the biogeomorphological developments of secondary channels in the Waal river. **CFR project report 11**, Delft University of Technology.

Glasbergen, M.J. (2001), Fish habitat modelling in the Gamerensche Waard. **CFR project report 12**, WL | Delft Hydraulics & Hogeschool Zeeland.

Kerle, F., F. Zöllner, B. Kappus, W. Marx & J. Giesecke (2001), Fish habitat and vegetation modelling in floodplains with Casimir. **CFR project report 13**, IWS, University of Stuttgart.

Peters, B., A. Dittrich, T. Stoesser, A.J.M. Smits & G.W. Geerling (2001), The Restrhine: future chances for nature rehabilitation and flood prevention. **CFR project report 14**, University of Nijmegen & University of Karlsruhe.

Lee, G. van der, M.J. Baptist, M. Ververs & G.W. Geerling (2001), Application of the cyclic floodplain rejuvenation strategy to the Waal river. **CFR project report 15**, WL | Delft Hydraulics, Delft University of Technology & University of Nijmegen.