Morphology of secondary channels:

Design parameters and sediment control measures

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Abstract
Secondary channels in the floodplains of major Dutch rivers are usually not morphologically stable and may experience significant sedimentation. Such sedimentation has negative effects on flood water levels and the channels therefore require adequate maintenance. Effective measures might postpone the maintenance interval in such a way that it coincides with the cyclic rejuvenation interval (setting back vegetation), which takes place on a timescale of at least some decades or longer.
The recently constructed secondary channels in the Netherlands do not show strong sedimentation. This is mainly due to sediment traps at the entrance (in some cases) and above all, the moderate flow conditions in these channels. This situation, however, implies a non-dynamic or low-dynamic behaviour of these channels, while a more dynamic environment is desirable for e.g. environmental reasons.
The present research aims at improving the understanding of the morphology of secondary channels and the elaboration of effective measures, based on a desk study, one dimensional modelling and a survey of the effectiveness of sediment mitigation measures.
The results show that secondary channels might potentially be designed such that their geometry fits best with a dynamic equilibrium, while still allowing more dynamic conditions. The sediment influx to the channels, however, remains an uncertain parameter at present. Awaiting further data and research on this item, we envisage some measures that can be useful at present. Such measures should primarily focus on the reduction of sediment in the channel, e.g. by a sediment trap in the channel or by measures that reduce the sediment load before entering the channels. Curative measures other than dredging of the channels, have also been studied, but do not seem to be effective.

1. Introduction (background)

Within the framework of flood mitigation and river rehabilitation the number of restored or newly constructed secondary channels in the floodplains of major rivers in the Netherlands is increasing. Secondary channels are defined here as permanent water conveying channels that branch off from the major channel and flow back at several hundreds of meters up to some kilometres downstream, as shown in Figure 1. In the Netherlands they serve to reduce flood water levels (in the Room for the River program) as well as nature restoration (European Water Framework Directive). Despite the fact that they are usually constructed with an upstream flow regulating structure, secondary channels may still experience significant sedimentation. Sedimentation will reduce the flood water level lowering, which will make timely maintenance necessary. Some experts believe that secondary channels will be fully closed within a decade or so and hence intensive maintenance (i.e. dredging) might be necessary within that period. Cyclic rejuvenation (setting back vegetation) can also be considered as a form off maintenance, but requires an interval of many decades (Duel et al., 2001; Peters et al., 2006). Preferably, sedimentation should be controlled in such a way that these intervals may coincide.

Figure 1: Aerial photos of a secondary channel in the Gamerensche Waard of the River Waal (the major Rhine branch).

2. Objectives and setup

The aim of the research described in this paper is twofold. First the understanding of the morphology of secondary channels must be improved to determine in which circumstances sediment control is necessary. Second, for these situations it is investigated how to control undesirable sedimentation. Hereto a more sophisticated design for secondary channels is evaluated as well as additional sediment control measures, aiming at minimizing the sedimentation rate related to a longer maintenance intervention interval. The present research has been carried out within the framework of the M.Sc. thesis of the first author. First, a review of the Dutch experience with newly secondary channels is presented followed by fundamental processes that are relevant for the morphological development. Next a set of formulae will be introduced for sedimentation and erosion of secondary channels. With analytical analyses the morphological equilibrium state of a river bifurcation is studied for different sediment-discharge ratios. The stability of these equilibrium states is evaluated for abrupt water depth perturbations. After that a number of simulations with a morphological one-dimensional model are presented to elaborate on the sensitivity of governing parameters. Based on these findings, potential mitigation measures are presented. In addition guidelines will be given for designing secondary channels close to morphological equilibrium.

3. Monitoring of secondary channels

In the last two decades six secondary channels have been constructed in the floodplains of the River Rhine, partly in combination with restoring old meander bends: Opijnen (1993), Beneden Leeuwen (1997), Gamerensche Waard (1996 – 1999), Klompenwaard (1999 – 2000), Bakenhof (2002) and Vreugderijkerwaard (2002).

Up to now only the first three secondary channels have been monitored morphologically (Simons et al., 2000; Jans et al., 2000; Jans et al., 2002; Jans et al. 2004). From these observations it can be concluded that the first two secondary channels are more or less morphological inactive, which can be explained by sediment traps at the entrance and/or low design flow velocities. Only in the secondary channel at Gameren significant sedimentation has occurred, with an average sedimentation rate of 0.08 m/year (Jans, 2004). This sedimentation rate reflects a slowly aggrading channel and is in contrast to the prediction of some experts that the secondary channels can be (fully) closed off within a timescale of a decade (Mosselman, 2001). The period of monitoring is however to short to asses the validity of this prediction. Still, fully closure of the channel within a decade or so seems unlikely for the present channels.

4. Processes on morphological development of secondary channels

In order to describe the main processes that influence the morphological development of a secondary channel, a distinction has to be made between discharges that are lower or higher than the bankfull discharge of the river system (Baptist & Mosselman, 2002). During in-bank flow the secondary channel forms a bifurcation with the main channel. The sediment influx to the secondary channel, relative to the water influx, forms the major driver for the morphological

development. Sedimentation will automatically take place when the sediment influx exceeds the transport capacity. This sediment influx is however highly uncertain, because it depends on the detailed geometry of the intake and its environment. In association with spiral flow the location of the intake and the bifurcation angle plays a vital role (de Heer, 2003) as well as bed forms near the bifurcation point. In addition, the intake level of the secondary channel is usually higher than the bed level of the main channel. This creates a positive bed level gradient towards the secondary channel leading to a counter effect (gravity) on the sediment influx (Kleinhans, 2008). During over-bank flow the secondary channel is totally flooded and the bifurcation point acts as a non-bifurcated or semi-bifurcated system. During these situations the morphology of the secondary channel is mainly driven by the interaction between floodplain flow and channel orientation. During floods additional sediment flux to the secondary channel may occur. The influence of the orientation angle is important for the transport capacity of the channel (Baptist & Mosselman, 2002) and hence influences sedimentation.
Obviously the dynamics of secondary channels is highly complex. Rather than attempting to describe these processes in detail (for which we should need very complex models), we chose a nodal point relation to describe the sediment distribution at secondary channels.

5. Analytical equilibrium analysis

To obtain a better insight in the morphology of secondary channels, a morphological equilibrium analysis has been carried out for different sediment-discharge ratios. With this analysis the equilibrium state of a river bifurcation can be analyzed. This equilibrium state represents a stationary situation in which no bed level changes will occur for both branches. To enable such an analysis an analytical model of the river system has been set-up, which is described hereafter.

5.1 Analytical set up of the river system

The simplified river system is modelled by three straight channel sections with a uniform width B, flow resistance C and a rectangular cross-section with depth h. The discharge is denoted Q and the total sediment transport Q_s. The equilibrium bed slope angle is i_b. The upstream river section has suffix 0 (i = 0), the main channel suffix 1 (i = 1), and the secondary channel suffix 2 (i = 2), see also Figure 2. The values of the parameters of the upstream river section (h_0, B_0, C_0, i_0, Q_{s0}) and of the main channel (L_1, B_1, C_1) are directly derived from the numeric model that is used for the numerical simulations of the River Waal (the major Rhine branch). Only the geometry of the secondary channel (L_2 = 2500 m, C_2 = 46 $m^{1/2}$/s, B_2 = 30 m), parameter Y and Q_0 have been introduced into the model as new parameters for further analyses. Parameter Y is related to the nodal point relation for the sediment distribution and will be further discussed in section 5.2. Upstream a discharge of 2000 m^3/s has been taken as the bankfull discharge. This discharge can be considered as being representative for the morphodynamic development of the channels, from a practical point-of-view.

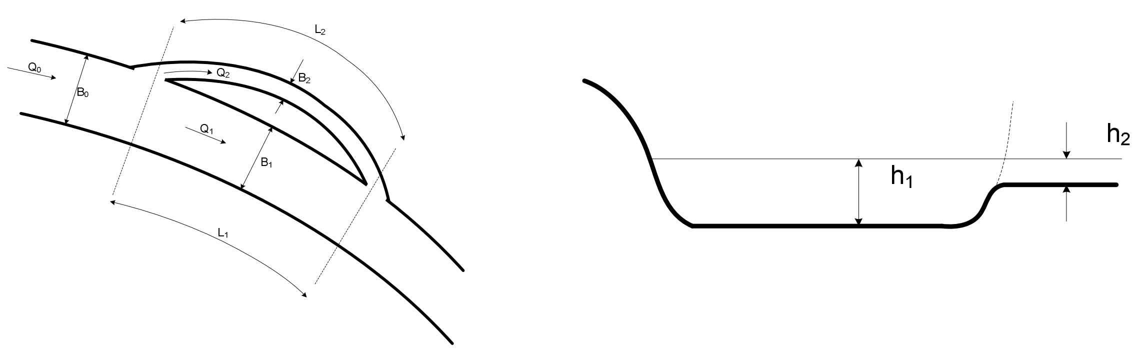

Figure 2: Visualization of river system for two highly unequal bifurcated branches (large main channel (i = 1) and a small secondary channel (i = 2).

Obviously the water level at the bifurcation and confluence for both branches is equal and there is no mass loss in the river system. With these boundary conditions the following momentum and a mass balance can be derived for the water – sediment motion, see also equations 3…7.

Water motion

$$\frac{Q_1}{Q_2} = \frac{C_1}{C_2} \cdot \left(\frac{h_1}{h_2}\right)^{\frac{3}{2}} \cdot \left(\frac{i_{b1}}{i_{b2}}\right)^{\frac{1}{2}} \cdot \frac{B_1}{B_2} \qquad (3)$$

$$Q_0 = Q_1 + Q_2 \qquad (4)$$

$$i_{b1} \cdot L_1 = i_{b2} \cdot L_2 \qquad (5)$$

Sediment motion

$$\frac{Q_{s1}}{Q_{s2}} = \left(\frac{Q_1}{Q_2}\right)^{n} \cdot \left(\frac{h_1}{h_2}\right)^{-n} \cdot \left(\frac{B_1}{B_2}\right)^{1-n} \qquad (6)$$

$$Q_{s0} = Q_{s1} + Q_{s2} \qquad (7)$$

The sediment transport in the river system is calculated with the power law formula that is given in equation (8). In this relation the transport of sediment is dependent of parameter n as an exponent of the flow velocity u.

$$Q_s = m \cdot u^n \cdot B \qquad (8)$$

It should be noted here that the parameters n and m are discharge-dependent when a wide range of conditions is considered. For this reason the power law formula (8) is fitted to the numerical sediment transport formulae (14 -15) for different flow velocities. For bankfull discharge the parameters n and m can be estimated at 3.33 (-) and 1.03E-04 (m^{2-n}/s^{1-n}) respectively. The fitting procedure guarantees that the total sediment transport is set up equally for both models for varying discharges, which enables comparison of both the analytical and numerical results at a later stage.

5.2 Nodal point relation

In reality the sediment division at a bifurcation point is not only determined by the flow distribution but also by three-dimensional (local) flow currents. These flow patterns are by definition excluded in a one-dimensional model. For this reason a nodal point relation is required, as presented in equation 9. In this equation the ratio between the sediment transport to both main and secondary channel is assumed proportional to a power of the discharge division (Wang et al, 1995).

$$\frac{Q_{s1}}{Q_{s2}} = \left(\frac{Q_1}{Q_2}\right)^{Y} \cdot \left(\frac{B_1}{B_2}\right)^{1-Y} = X \cdot \left(\frac{Q_1}{Q_2}\right)^{Y} \qquad (9)$$

In this equation a higher value of parameter Y implies a decrease of the sediment influx to the secondary channel. Parameter Y cannot be related in a direct physical sense to the sediment processes that are described in section 4 of this paper. Therefore caution is recommended in translating these generalized processes to specific situations. Generally it can be stated that the sediment influx into the secondary channel will increase as the intake is located in the inner bend or when the intake is located at a lower level. By choosing a nodal point approach, and introducing the parameter Y, we are able to study the basic mechanisms, while the analysis remains manageable.

5.3 Analytical solution

The morphological evolution of the initial situation can be evaluated with equilibrium analysis, expressed in a certain equilibrium depth (h_{ei}). Before the equilibrium depth in (10) can be calculated for the main and the secondary channel, first the discharge and the sediment ratios at the bifurcation point must be known. These ratios can be calculated with (11) and (12), equations that can be derived from equations (3…7) and (9). Next these ratios are substituted in (13) to calculate the discharge (Q_2) and the sediment transport (Q_{s2}) of the secondary channel. In combination with the mass balances (4 and 7) the influxes into the main channel can also be calculated. These equations are given to enable experts to make their own analyses for different sediment influxes and geometries of the secondary channel.

$$h_{ei} = m^{\frac{1}{n}} \cdot Q_i \cdot B_i^{\frac{1-n}{n}} \cdot Q_{si}^{\frac{-1}{n}} \qquad (10)$$

$$\frac{Q_1}{Q_2} = \left\{ \frac{1}{X^3} \cdot \left(\frac{C_1}{C_2}\right)^{2n} \cdot \left(\frac{L_2}{L_1}\right)^{n} \cdot \left(\frac{B_1}{B_2}\right)^{3-n} \right\}^{\frac{1}{3Y-n}} \qquad (11)$$

$$\frac{Q_{s1}}{Q_{s2}} = \left\{ \frac{1}{X^{\frac{n}{Y}}} \cdot \left(\frac{C_1}{C_2}\right)^{2n} \cdot \left(\frac{L_2}{L_1}\right)^{n} \cdot \left(\frac{B_1}{B_2}\right)^{3-n} \right\}^{\frac{Y}{3Y-n}} \qquad (12)$$

$$\frac{Q_2}{Q_0} = \left(1 + \frac{Q_1}{Q_2}\right)^{-1} \text{ and } \frac{Q_{s2}}{Q_{s0}} = \left(1 + \frac{Q_{s1}}{Q_{s2}}\right)^{-1} \qquad (13)$$

5.4 Analytical results

Corresponding to Wang et al (1995) two morphological regimes can be distinguished for different sediment influx ratios, with a transition for Y is equal to n/3 in the nodal point relation. Hereby the stability of the bifurcation is evaluated against abrupt water depth perturbations. Observe that these perturbations already originate in reality from small deviations in the sediment supply upstream the bifurcation. In this study the stability is evaluated for two highly unequal bifurcated branches, see Figure 2 (a small secondary channel and large main channel).

For a relatively high sediment influx (which implies $Y < n/3$) the secondary channel is in an unstable regime. Theoretically, in an unstable situation the equilibrium depth of the secondary channel is extremely large. In practice, however, the initial water depth of the secondary channel will be much smaller than that of the main channel. Due to this relative low water depth the high equilibrium depth will never be reached, and hence this 'water depth perturbation' will always lead to fully closure of the secondary channel. As the deviation of the equilibrium depth is extremely large, unstable situations (i.e. a closure of the secondary channel) could only be prevented with sediment reduction measures.

For a relatively low sediment influx (which implies $Y > n/3$) the secondary channel is in a stable regime in which the bed level converges to a certain (dynamic) equilibrium. In this stable regime sedimentation could be expected as now the equilibrium depth of the secondary channel is relatively low. In contrast, erosion could also occur if the sediment influx to the secondary is too low (implies a high value of Y). The actual morphological development is thus dependent of the initial bed level of the secondary channel. These tendencies are also obtained with numerical computations for a secondary channel in the River Waal as visualized in Figure 5.

Within the constraints of the chosen nodal point relation, especially the uncertainty of Y, the above principles are valid in every river system. Only the value of the equilibrium depth could be different. Hence, the analysis can be used for designing a more sophisticated secondary channel with dimensions that are close to a (dynamic) equilibrium (see also section 6.3).

6. Numerical analyses

Numerical simulations are needed to gain insight in the morphological development in time and to assess characteristic timescales. In the present study a one-dimensional SOBEK-RE model (In Dutch: Rijntakken model) has been used to this purpose. This model has been set-up by the Dutch Ministry of Transport, Public Works and Water Management, to evaluate the morphological effects of flood mitigation measures in the branches of the River Rhine.

6.1 Set up river system (numerical)

In the numerical model a secondary channel has been schematized for the present research, as a characteristic secondary channel of the River Waal (major branch of the Rhine). At this location the bed level of the River Waal is situated at NAP-4.9 m, and with the intake level at NAP+0.4 m. The length of the secondary channel is 2500 meter which equals the length of the channel in the analytical study. The flow resistance (with k_s = 0.18 m) is now discharge dependent. With the defined geometry the secondary channel conveys 3 percent of the total discharge or less during a bankfull discharge situation, with a typical flow velocity of about 0.3 -0.4 m/s. These moderate hydraulic conditions satisfy the present design principles for secondary channels to control the sedimentation in the main channel within acceptable limits (Mosselman, 2001). During the numerical computations, a stationary bankfull discharge of 2000 m^3/s is applied as well as a realistic discharge hydrograph over a period of 80 years, consisting of repeated historical discharge series of 15 years. With the stationary discharge of 2000 m^3/s the results of the analytical analysis can be evaluated for similarities and differences. With the hydrograph a more realistic morphological development of the river bifurcation is obtained. In the hydrograph the discharges vary in between 500 m^3/s and 6000 m^3/s for the Waal. The sediment transport is being calculated in the numeric model with equations (14) and (15) while the sediment division is described with the nodal point relation (9).

$$Q_{si} = B_{si} \cdot \sqrt{g \cdot \Delta \cdot D_{50}^3} \cdot \phi \qquad (14)$$

$$\phi = \frac{A \cdot \beta_u}{1-\varepsilon} \cdot \left(\mu \cdot \theta_s - \theta_c\right)^{\alpha_u} \qquad (15)$$

6.2 Numerical results

Similar to the stability analysis, the simulations show that the secondary channel will be fully closed off within a decade during unstable situations (Y < n/3), see Figure 3 [left]. At present the secondary channels in the Netherlands are not closed off by far, so this indicates that the bifurcations in the Dutch river system seem to be in the stable regime. However, it should be remarked here that Kleinhans et al. (2008) elaborated from a three-dimensional model that parameter Y in the nodal point relation should be variable during high discharges. Hence, transient transitions between stable and unstable situations are still possible theoretically. In our simulations parameter Y is always fixed and independent of the discharge.

Typical for the morphological development is the occurrence of a sediment-front, which originates upstream and gradually extends to the downstream. Such a sediment-front is depicted in Figure 3 [right] for bankfull discharge of 2000 m^3/s. Even in the long term at the downstream end of the channel morphological changes will not occur. For the ‘real situation’ with the discharge hydrograph, the same tendency with a more extended morphologic development can be observed as a result of higher discharges, see Figure 4 [left].

From the simulations it can be concluded that the morphological activity decreases in time. This is in accordance with a decrease of discharge and sediment influx as the upstream bed level of the secondary channel rises. Thus, the strong sedimentation in the upstream reaches tend to gradually cut off secondary channels from the main river, up to the moment that the sediment influx has been decreased so much (which implies a higher value of parameter Y), that a (dynamic) equilibrium situation may be reached, see Figure 4 [right].

Then, the sediment transport is equal to the transport capacity leading to ‘neutral’ morphological activity. For maintenance of secondary channels this is a preferable situation as the sedimentation rate is sufficiently small or even absent.

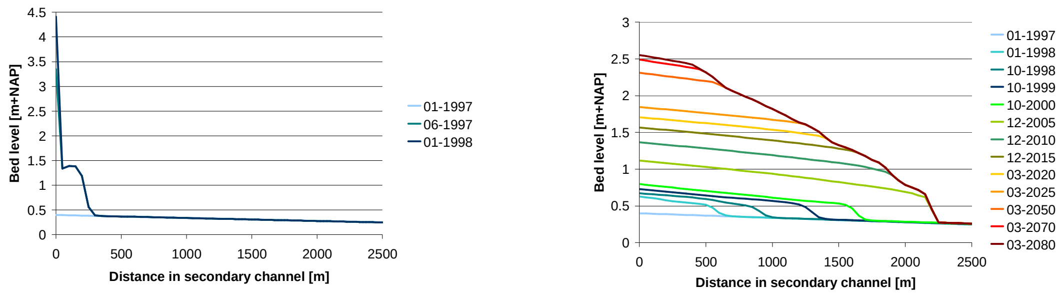

Figure 3: [Left] Morphological development of the secondary channel in 1 year with hydrograph and Y = 0.5 (< n/3) [Right] Morphological development of the secondary channel in 83 years with a stationary discharge and Y = 1.4 (> n/3).

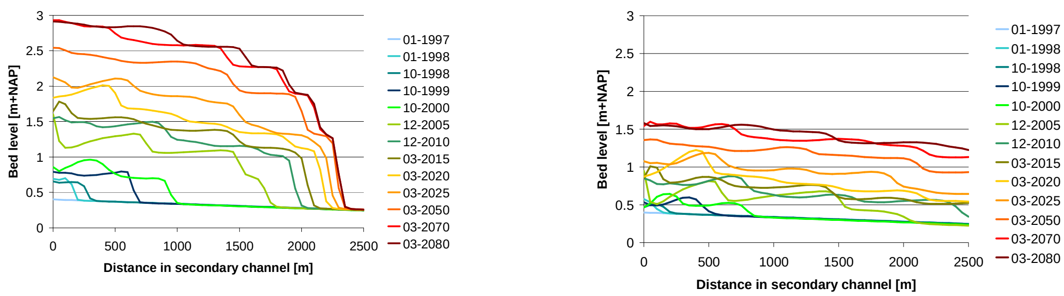

Figure 4: [left] Morphological development of the secondary channel in 83 years with hydrograph and y = 1.4 (Y > n/3) [right] Morphological development of the secondary channel in 83 years with hydrograph and Y = 1.8 (> n/3)

6.3 Equilibrium design

From Figure 5 the equilibrium upstream bed level of the channel can be assessed for different sediment distribution ratios over the bifurcation. Unfortunately this equilibrium level may not satisfy the level of intake that is required from flood mitigation and environmental aspects. In general a relative low intake level is desired to reduce water levels sufficiently during high discharges and to guarantee permanent water conveyance through the channel.

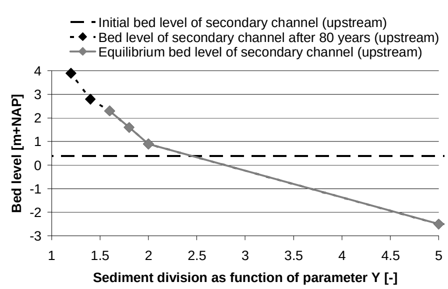

Figure 5: Upstream bed level of the secondary channel in relation to sediment distribution parameter Y (large Y means relatively low transport to secondary channel).

In order to solve this conflict of interest sensitivity analyses have been carried out on the equilibrium depth, as function of the basic geometry of the secondary channel discerned in a certain length (L2), width (B2) and roughness (C2). A straightforward analysis shows that the results are not unambiguous and are dependent on the sediment influx to the secondary channel.

For stable regimes (n/3 < Y < n) the equilibrium depth can only be increased with a length reduction (L_2), a lower flow resistance (C_2) or a narrower channel (B_2), as visualized in Figure 6. In this figure, the changes are indicated with respect to the reference situation as described in section 5.1.

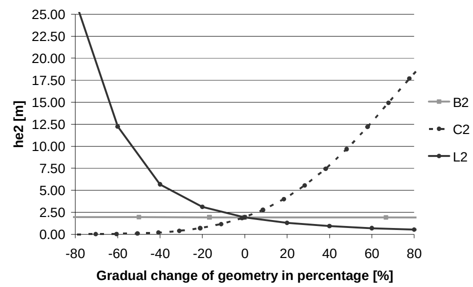

Figure 6: Influence of changes in channel parameters (length, width, roughness) on the equilibrium channel depth (sensitivity analyses).

It can be concluded that the channel length is the most important parameter as the width of the channel has minor influence and the flow resistance may practically be rather difficult to control. With the above design principles a more sophisticated equilibrium design can be achieved in which the maintenance can be simply reduced or even prevented. A prerequisite is that shortening of the secondary channel is possible or that the flow resistance can be increased. Moreover higher stream velocities can be allowed leading to more horizontal morphological dynamics in advantage of environmental aspects. At present this equilibrium design can only be achieved by redesigning the secondary channel after a certain trial/monitoring period, as the sediment division is still not well known for specific locations. For this reason intensified monitoring of secondary channels in the future is strongly recommended. Alternatively, 3-D modelling can be used to gain more insight in how the sediment influx to the secondary channel is affected by detailed geometry of the intake and its environment.

7. Sediment control measures

Depending on the sediment distribution at the bifurcation and the deviation of the actual geometry of the channel from the (dynamic) equilibrium design, in practice sedimentation can be expected in the secondary channels. This may occur for stable, as well as for unstable situations. Additional to the intervention for cyclic rejuvenation, (mitigation) measures may have to be applied to control undesirable sedimentation.
The sand trap is a well-known solution, but is not taken into account here, as we are exploring alternative measures. Based on the balance between sediment influx and the transport capacity Ghimire (2003) has discerned the following three types of sediment controlling measures: 1) cross-sectional control measures, 2) flow control measures and 3) sediment reducing measures.

7.1 Cross-sectional control measures

Cross-sectional control (mitigation) measures deal with temporary reduction of the cross-section as to increase the transport capacity locally, e.g. by gabions or by screens (bandalls). By transferring the local measures from the upstream to the downstream edge, the excessive sediment can be forced to leave the channel. Numerical simulations show that there is a practical contradictory problem. Instead of an undisturbed water influx, the influx will be reduced in reality. This can be explained by an increase of the flow resistance by the local reduction of the flow profile. Hence sedimentation will be increased outside the restricted flow-profile and will exceed the local erosion. For this reason cross-sectional control (mitigation) measures will not form a solution to control the morphology of secondary channels adequately.

7.2 Flow control measures

Flow control measures aim at increasing the flushing capacity. In this study two possible measures are further investigated that leave shipping conditions in the main river unaltered. The first solution is to pump extra water through the channel by pumping water into the channel at the upstream side. At the pump location the secondary channel has to be artificially closed off to prevent recirculation with the main channel. The effect of pumping has been simulated in the numerical model using 10, 30 and 60 m^3/s pump capacity for a typical secondary channel. Even with the huge capacities of 30 and 60 m^3/s, the removal of additional sediment may take years and hence, does not seem to be feasible.
Another solution may be found by applying a separate ‘feeder channel’ that increases the water level at the intake of the secondary channel. This implies that the actual offtake of the secondary channel is further upstream. Such a feeder channel should have sufficient length (e.g. some kilometres), a large conveyance and low flow velocities in the channel as to have a smaller water level gradient than in the main channel. In the Netherlands such a feeder channel can be created by a longitudinal flow separation dam in stead of groynes (or by partly removing groynes). A feeder channel may also be attractive from a river restoration point-of-view and may reduce the sediment influx. To obtain small flow velocities in the feeder channel, the connecting secondary channel, however, should have a relatively small flow capacity. Computation of the whole system will require three-dimensional modelling and can not be verified properly with a one-dimensional model.

7.3 Sediment reducing measures

These measures aim at reducing the sediment feed to the channel by e.g. weirs or sediment deflecting structures upstream of the channel entrance (Ankum & Brouwer, 1993). More voluminous measures deal with flow approach alteration in such a way that secondary currents are generated that deflect the sand transport away from the channel entrance. These measures can be simulated indirectly in the 1D- model with a supposed sediment influx reduction, which implies a higher value of parameter Y. The first approach is to utilize these measures after a certain period of sedimentation. From the simulations it can be concluded that this (mitigation) approach is not effective, as increasing sediment transport is becoming more and more difficult after some time. The reason is that while the upstream bed level rises in time, the water influx to the channel will decrease. Hence the transport capacity of the flow will be reduced. Moreover the maximum flow width also increases as the bed level rises, related to the gentle bank slopes. Thus erosion will only be achieved as the sediment influx reduction is extremely large, which does not seem to be feasible. In contrast, to make such measures more effective, they will have to be implemented upon completion of the secondary channel. For the modelled secondary channel it is illustrated in Figure 7 that in the stable regime the morphological development can be delayed from 5 to 70 years. Hereto the sediment influx to the channel has to be reduced from 3 to 1 percent of the total sediment transport of the main river.

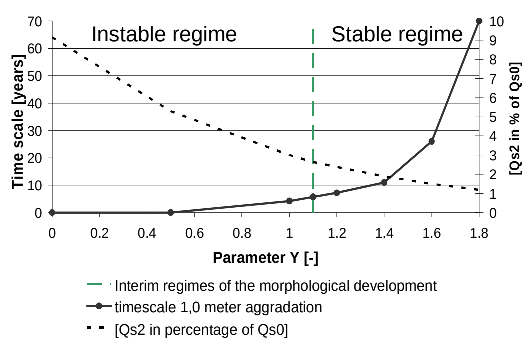

Figure 7: Timescale of channel aggradation (full line) and sediment transport in the channel (relative to sediment transport in the river; dashed line) with respect to the sediment distribution parameter Y.

In this study it can not be verified whether these reductions in the sediment flux are attainable with the sediment reduction measures mentioned before. This must be further investigated with advanced modelling. The expectation is, however, that it is not easy to reduce the sediment influx significantly. The reason is that the sediment influx to the secondary channel is already relatively low in comparison with the total sediment transport of the main river. Hence, for the time being, a sediment trap may still be considered as the most successful measure because the other measures do possibly lack effectiveness or may need a long operational time. This emphasizes the importance of applying a channel geometry that is close to its equilibrium.

8. Conclusions and recommendations

Secondary channels that branch off from a main river system may develop according to a stable or an unstable regime. In both situations sedimentation may occur, which may require frequent maintenance to maintain the flood water level reduction. The maintenance interval is dependent on the sediment distribution at the bifurcation point. To postpone this interval in order to coincide with the interval of cyclic rejuvenation (setting back vegetation) two solutions are given below.

The excess sedimentation during unstable situations can only be solved with sediment reduction measures upstream of the channel entrance. However, the occurrence of this situation in Dutch rivers system seems to be unlikely.

For stable situations it is strongly recommended to design the channel close to equilibrium by designing the best combination of initial depth, length, width and roughness of the channel. Given the sediment distribution at the bifurcation, this optimal geometry can be derived for each river system with the equilibrium formulae given in this paper. However, as the sediment influx usually is not known well, intensified monitoring of existing and future secondary channels is indispensable. This may lead to some ‘smart’ channel adaptations.

In addition, advanced modelling can be used to gain more insight in the sediment influx to the secondary channel in relation to detailed geometry of the intake and its environment.

Other simulations and case studies showed that temporary sediment control measures, such as discharge control or sediment flushing measures will not be generally feasible. Only sediment reducing measures may be effective, when they are implemented upon completion of the secondary channel. With the knowledge we have at present, a sediment trap may still be a good measure. The best solution, however, would be to strive for a more balanced channel design that will avoid strong sedimentation.

9. Acknowledgements

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10. Notation

B_i	width of channel [m]
C_i	Chezy roughness coefficient [$m^{1/2}/s$]
D_{50}	median grain size [m]
g	gravitational acceleration [9.8 m/s^2]
h_i	waterdepht [m]
h_{ei}	equilibrium depth [m]
i	brach number index [-]
i_{bi}	bed slope [-]
k_s	Nikuradse roughness height [m]
L_i	length of channel [m]
m	coefficient in power law formulae [m^{2-n}/s^{1-n}]
n	effective power in power law formulae [-]
Q_i	flow discharge [m^3/s]
Q_{si}	sediment transport in channel [m^3/s]

u_i flow velocity [m/s]
X constant in nodal point relation [-]
Y power on discharge ratio in nodal point relation [-]
μ ripple factor [-]
α_u coefficient in User-Defined transport formulae [-]
ε porosity of sediment [-]
β_u coefficient in User-Defined transport formulae [-]
θ_s Shields parameter [-]
θ_c critical shields parameter [-]
Δ relative density of sediment [-]
Φ transport parameter [-]
NAP Normal Amsterdam Water level [m+NAP]

11. References

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