The Regge River: from canalized to meandering

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ABSTRACT
The Water Board Regge and Dinkel and DLG would like the Regge, a canalized river, to be a naturally meandering river once again. Designing a natural river in the Netherlands, where a strong coherence between spatial planning and water systems exists, is a demanding process. Nature development receives high priority, but, for example, an increase of flooding of inhabited areas is unacceptable. Based on empirical formulas for meandering river characteristics, a design for the meandering Regge has been made. Hydraulic consequences of the design are calculated with a Sobek Rural 1D2D model. Consequences on groundwater levels are determined by means of a groundwater model in MODFLOW. The effects of the change in surface and groundwater levels in urbanized areas and on agriculture, nature and water retention are scored in a multi criteria analysis. There are two serious drawbacks associated with the natural river. Flood water levels in the meandering river increase significantly, which results in the flooding of inhabited areas. In dry periods, surface water levels decrease because present weirs are removed, causing groundwater levels to decrease and thereby reducing conditions for wetlands in the river valley. This paper provides suggestions on how to solve these drawbacks.

Keywords: Meandering, canalized, hydraulic modelling

1 INTRODUCTION

The Regge is a small river flowing through gently sloping terrain in the eastern part of the Netherlands (Figure 1). It flows alternately through relatively flat areas and incised valleys. The river has a length of 47 km and its width varies from 2 to 30 m. The Regge was canalized to make the area more suitable for habitation and agriculture, as has been the case for most Dutch rivers since 1900. The construction works were aimed at draining marshy areas and reducing flood risks. Small waterways were dug to drain the river valley and the flow width of the Regge was increased significantly. Weirs were installed to control the water levels. The weirs maintain relatively high water levels for agriculture during dry periods. The weirs lower to the canal bottom during floods to allow for unhindered passing of flood waves.

However, negative effects of canalization have become clear since the end of the 20th century, as more attention is being given to nature and natural hydrological systems. Effects such as reduced river dynamics, high peak discharges during floods and strong drainage are now seen as negative consequences of the canalization. Together

Figure 1 Location of the study area in The Netherlands, with the Regge River, the Vecht River and the Twenthe canal.

with the European Water Framework Directive (Directive 2000/60/EC, 2000), which requests the restoration of natural water systems, these are strong incentives for the Water Board Regge and Dinkel and the Dutch Government Service for Land and Water management (DLG) to restore the Regge River to a more natural, meandering river.

The Water Board and the DLG strive for a meandering Regge, without harming the habitation and agriculture outside the floodplain. The aim is a dynamic river, able to erode and deposit sediment freely, which will have a positive influence on the development of flora and fauna and the attractiveness of the landscape. Redimensioning of the riverbed could positively contribute to drought control and nature development in the river foreland. On several locations along the Regge, the Water Board and the DLG have started projects to restore a meandering Regge. The old course of the Regge River was excavated and, in one location, replaces the canalized river, which now functions as a flood channel. Figure 2 shows an example of the restoration. The width of the flow bed has been decreased and the river axis is meandering instead of straight.

In 2007, Water Board Regge and Dinkel, DLG and HKV CONSULTANTS investigated the possibilities of restoring the meandering Regge along its full length. Ideally, the starting point for the design should be the historical Regge as it was before canalization. However, conditions have changed, making it impossible to completely restore the old Regge. On the one hand, present land use makes historical flooding and high groundwater levels unacceptable. On the other hand, the catchment area and the discharge regime have changed. What used to be the upper part of the Regge is cut off by the Twenthe canal, which significantly reduces the catchment area. Improved drainage by means of ditches and an increase in built up area, with larger fast runoff components, have changed the discharge regime.

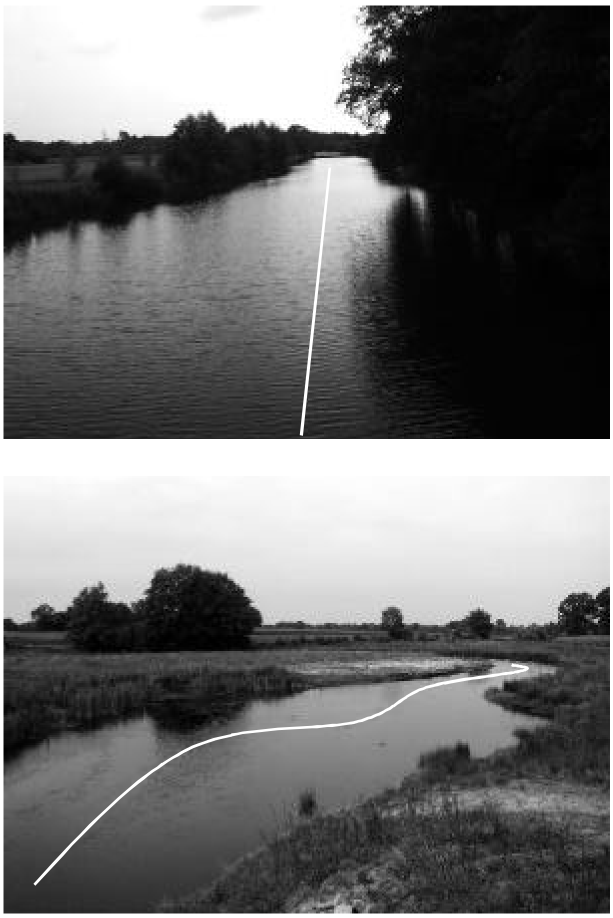


Figure 2 Restoration of the Regge, from canalized (at De Tatums, above) to meandering (at Velderberg, below).

2 DESIGN METHOD

The design process was iterative and took place in four steps within four loops. In the first step, a design of the meandering Regge is made. In the second step, the design is evaluated using surface water and groundwater models and the results are analysed in GIS. The third step consists of filling in a multi criteria analysis (MCA), which allows the Water Board and the DLG to evaluate the consequences of the design for a broad range of interests (Figure 3). In the fourth step, the MCA score on every aspect is discussed and aspects scoring unacceptably low are identified. These aspects have to be improved by changing the design, with which the process returns to step 1. After completion of four loops, the Water Board and DLG found the overall score on the MCA acceptable for a global design.

The surface water calculations are executed using a coupled 1D and 2D model (Sobek Rural, WL|Delft Hydraulics, 2006). The one-dimensional (1D) channel-flow model of the region is combined with a two-dimensional (2D) overland-flow model. The 1D flow model solves the continuity and momentum equations of Saint-Venant for the river. The two-dimensional flow is defined by three equations: the continuity equation and the momentum equation for the x-direction and the y-direction. The 2D-flow model uses a Digital Elevation Model (DEM) and a roughness grid for the routing of flow. The hydraulic roughness is related to land use like grass, cultivated area, forest, nature, water, main roads and built-up area. Figure 4 shows part of the schematisation. The Regge and its major tributaries are modelled 1D. The river valley is modelled 2D (cell size of 25 by 25 m). The groundwater calculations are executed with the Water Board's MODFLOW model (McDonald and Harbaugh, 1984).

To obtain a clear impression of the performance for a broad range in discharges, surface water calculations are executed with stationary discharges ranging from frequencies of 347 days per year up to one to two days in 50 to 100 years. The hydraulic regime is imported in the groundwater model, to calculate the groundwater regime. The model results (water levels, flow velocities and inundations) are processed in GIS and used in the MCA.

The flood dynamics of the final design are evaluated by the simulation of a flood wave with a frequency of 1/100 per year. An important aspect of the dynamics is the maximum discharge and the timing of the peak at the location where the Regge flows into the Vecht River (Figure 1). For flood control on the Vecht, it is important that the peaks of the flood wave in de Vecht and the flood wave in the Regge do not coincide.

Theme	Criteria	Variable to test	Reference situation	First design	Final design	Aim	Unit
Natural meandering Regge	River without obstructions	Percentage length without obstruction	0	94	94	100	%
	Meandering river	Percentage length meandering	0	94	86	100	%
	Free flowing and dynamic river	Upper width	61	91	91	100	%
		Flow velocity	72	35	68	100	%
	Inundations	Inundations at discharge exceeded 1 day/year	753	2931	2044	-	ha
		Inundations at discharge exceeded 1-2days/50-100 years	2774	5739	3987	-	ha
	Self-regulating river	Less self-regulating than first design?	-	no	yes	no	yes/no
Nature	Existing nature	Area with optimal groundwater conditions	79	77	77	100	%
	New nature	Average lowering compared to historical situation	35	58	77	0	cm
Built-up area	Groundwater	Area with average high levels > 80 cm below surface	84	82	84	100	%
	Surface water	Inundation built up area at discharge 2Q	+	+++	+	0	+/-
		Discharge locations influenced at discharge 1Q	15	88	17	0	%
Agriculture	Groundwater	Realization of optimal conditions	79.7	79.6	79.0	100	%
	Surface water	Inundation agricultural area at discharge 2Q	264	1747	853	0	ha
Historical values		Allow for historical values	-	100	100	100	%
Water retention	Groundwater	Realization storage change	0	-25	-171	>=100	%
	Surface water	Realization storage	127	392	193	>=100	%
Discharge to the Vecht	Discharge peak	Is the peak sufficiently attenuated?	-	-	yes	yes	yes/no
Other themes	Large scale structures	Are large scale structures applied?	-	no	no	no	yes/no
	Preservation of infrastructure	Is present infrastructure preserved?	yes	yes	yes	yes	yes/no

Figure 3 The table used for the multi criteria analyses, with results for the reference situation, the first and final design.

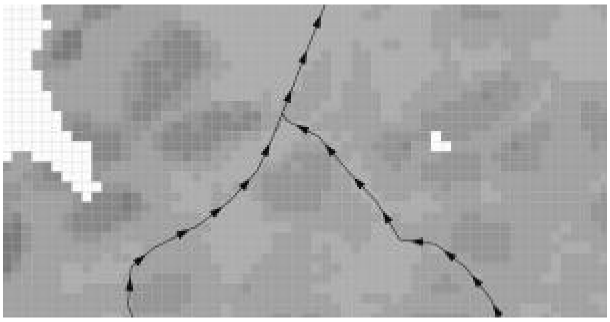


Figure 4 Part of the model schematisation in 1D (Regge and tributaries, black lines) and 2D (grey grid cells) (from Sobek Rural, WL|Delft Hydraulics, 2006).

3 FIRST DESIGN

3.1 *Designing a natural river*

The first design strives for a natural river (as far as man can design anything natural), without considering constraints on surface water levels, groundwater levels and morphodynamics by habitation, agriculture and nature. The characteristics of the meandering river are determined from historical and present characteristics of the river and from literature. In describing meanders, the standard characteristics are (Figure 5):

- meander wavelength l [m],
- meander amplitude a [m],
- flow width of the river B [m],
- meander radius R [m].

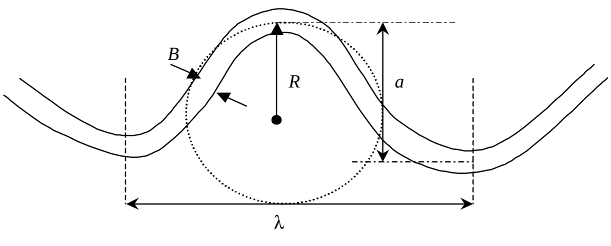


Figure 5 Definition of meander characteristics (Jansen et al., 1979).

By means of historical maps the characteristics of the Regge before canalization are studied. Based on the discharge, the Regge can be divided into three segments: the upper Regge, the middle Regge and the lower Regge. Especially the middle and lower Regge showed a high morphodynamic activity in the past; comparing maps from 1850 and 1900, meanders are shifting and being cut-off. Based on the historical activity, the Regge is expected to start meandering if the over-capacity of the main channel is reduced and no measures are taken to stabilize the banks. In the first design, the present channel is adapted to fit the characteristics of a dynamical meandering river. All weirs are removed to create a free flowing river.

The flow width (B) of the meandering river is calculated with a formula deriverd from CECW-EH-D (1994):

$$B = 3.83 \cdot Q^{0.5}$$

in which Q [m^3/s] is the bank full discharge. The formulations in CECW-EH-D (1994) are derived and subsequently used in areas with similar characteristics as those for the Regge.

The bank full discharge is chosen as the discharge that is exceeded 10 to 20 days per year, to accommodate the development of wetlands. By combining the formulations of CECW-EH-D (1994) with other empirical formulas derived from measurements on a range of meandering rivers (Zeller, 1967), meander characteristics l and a can be calculated. To fit the historical Regge (assuming that the soil structure is unchanged and historical vegetation types are aspired), the characteristics of the historical Regge are used to scale the formulas:

$$l = l_{hist} \left(Q / Q_{hist} \right)^{0.51} \text{ and } a = a_{hist} \left(Q / Q_{hist} \right)^{0.50}$$

in which l_{hist}, a_{hist} and Q_{hist} are the characteristics and the bank full discharge of the historical Regge. The l_{hist} and a_{hist} are measured on historical maps. The historical discharge is derived from cross sections from around 1900, which are available for five locations along the Regge. The length of the meandering channel follows from the relation between l and a and is 60 km (Zeller, 1967), equal to the historical length and 13 km longer than the present Regge. The bottom width and bottom level are determined with the Chézy equation (Ven Te Chow, 1959):

$$Q = C \cdot A\left(R \cdot i\right)^{1/2} \text{ with } C = k_m \cdot R^{1/6}$$

Characteristic		upper Regge	middle Regge	lower Regge
		0 – 13.5 km	13.5 – 34.5 km	34.5 – 47 km
bank full discharge	[m^3/s]	2.3	18.9	29.0
bottom width	[m]	2.2	8.8	12.5
bottom level	[MSL + m]	8.0	4.6	2.1
bank slope	[-]	1.2	2.0	2.0
meander wavelength (l)	[m]	120	432	557
meander amplitude (a)	[m]	33	117	150

Table 1 Characteristics of the first design of the natural meandering Regge. All values are averages; local variations are possible. The given distances are relative to the length of the present Regge.

in which C is the Chézy coefficient [$m^{1/2}$/s], A is the wet area [m^2], R is the hydraulic radius [m], i is the slope of the water level [-] and k_m is the Manning coefficient [$m^{1/3}$/s]. The slope of the water table is taken equal to the slope of the floodplain along the Regge. The k_m for a natural river with a relatively large hydraulic roughness (because of bed forms and vegetation in the river) is set at 30 $m^{1/3}$/s. A bank slope average of 1:2 for both riversides is assumed. This will be steeper in outer bends (e.g. 1:1) and less steep in inner bends (e.g. 1:3). The resulting design for the meandering Regge is summarized in Table 1.

According to the formulations of Leopold and Wolman (1957) and Struiksma (1988) this design is stable in horizontal direction. This does not mean that the meanders will not move, or that erosion and sedimentation will not occur. It only suggests that the characteristics of the river are in a dynamic equilibrium and will, on average, stay the same.

3.2 *MCA*

The MCA results differ significantly between the first design and the reference situation. Both differ from the objective (Figure 3). In general, the first design evaluates positively on aspects concerning natural meandering rivers. There are also serious drawbacks, however, of which the most important are discussed in the following sections.

3.3 *Drawbacks: floods*

During floods, water levels increase significantly. This leads to large inundation areas, increased flooding of built-up areas and hinder for the discharge of sewage water. Figure 6 shows water levels in a flood situation that occurs one to two days every 50 to 100 years on average. In built up areas, water levels should be at least 0.50 m below street levels. The figure shows the critical levels. In the reference situation, many of the street levels are only just high enough. Almost all critical levels are exceeded by the first design. The increase in water levels is due to:

- smaller dimensions of the meandering channel (flow area reduced to about 60%)
- higher hydraulic roughness of the meandering channel
- higher hydraulic roughness of the floodplain, due to nature development (roughness based on vegetation of marsh, grassland and shrubs instead of present land use)
- local absence of the floodplain, due to bridges and built-up area, where the river is forced to flow mainly trough the channel.

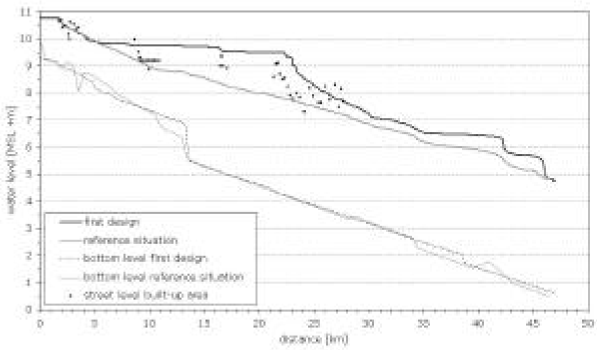


Figure 6 Surface water levels along the Regge for a situation occurring one to two days every 50 to 100 years.

3.4 *Drawbacks: dry situations*

Figure 7 shows the water levels in a dry situation. Weirs maintain relatively high water levels in the reference situation. The flow velocities are small and the Regge functions more or less as a range of reservoirs, with water flowing from one reservoir to the next. By removing the weirs, water levels drop significantly in the first design. As a consequence, the groundwater levels decrease, and this results in a reduction in groundwater conditions for wetlands in the river valley.

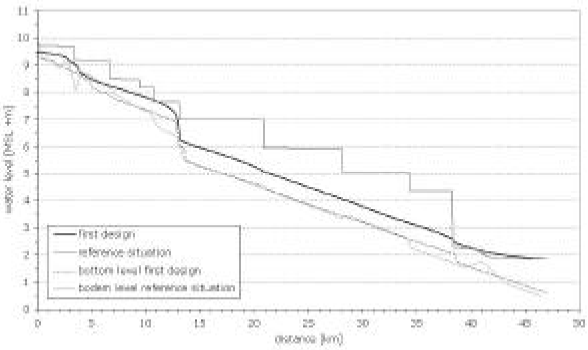


Figure 7 Surface water levels along the Regge for a dry situation.

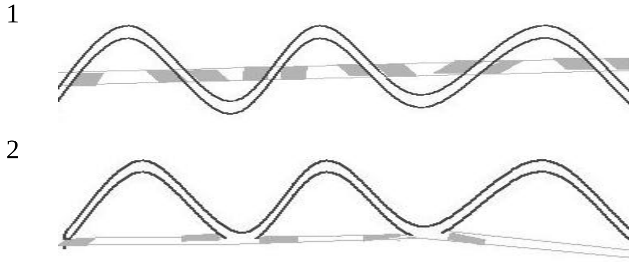
4 FINAL DESIGN

4.1 *Introduction*

The design process, from the first to the final design, is mainly aimed at reducing flood water levels and diminishing the drops in water level in dry situations after removing the weirs from the Regge. The following two sections describe the solutions that were incorporated in the final design to solve or diminish the drawbacks of the first design. The last section describes the distortion of the flood wave by the design and evaluates the consequences for flood control of the Vecht, the river in which the Regge discharges.

4.2 *Reducing flood levels*

During flood periods, the discharge capacity of the meandering Regge has to be equal to the present discharge capacity. To create extra capacity, while maintaining a relatively small meandering river, a flood channel parallel to the meandering river is introduced along the lower and middle Regge. Barriers just below the floodplain level separate the two channels. During average flow conditions, flow is routed only through the meander channel. During flood periods, flow is routed over the barriers and through the flood channel as well. Figure 8 shows two options for connecting the meander channel and the flood channel. The upper lay out (1) connects the channels every half meander wavelength. The bottom lay out (2) connects the channels every meander wavelength.



key — meander channel; flood channel with barrier

Figure 8 Schematization of connections between the meander channel and flood channel.

Along the lower Regge, the barriers overflow 10 to 20 days a year. Connections between the two channels are designed every half meander wavelength. Along the middle Regge, to obtain sufficient discharge capacity, the barriers overflow on average 80 days per year and connections between the channels are made every meander wavelength. Along the upper Regge the discharge capacity is increased by lowering the floodplain in a 50 m wide foreland around the river. The river is broadened to contain the design bank full discharge at a smaller water depth, so that the river still overflows 10-20 days per year. Figure 9 shows the resulting flood water levels of the final design.

4.3 *Raising levels in dry periods*

To increase groundwater levels in dry periods, the surface water levels have to be raised. The design is adapted by increasing the flow width by 20%, resulting in a higher bottom level (following from the Chézy equation), which leads to a reduced draining effect. The 20% increase in width lies within the range given by the empirical formulas used to calculate the river characteristics. Figure 10 shows the resulting water levels.

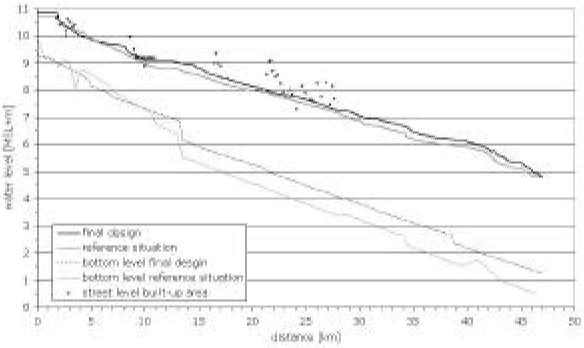


Figure 9 Surface water levels along the Regge for a situation occurring one to two days every 50 to 100 years.

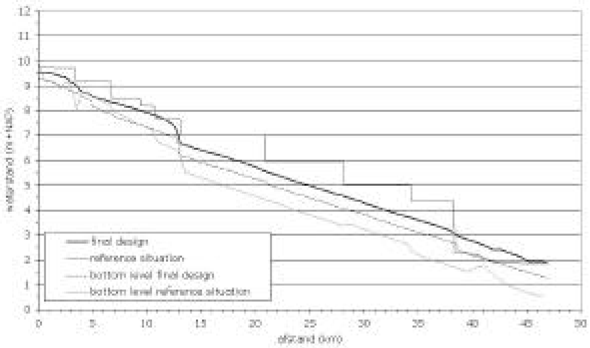


Figure 10 Surface water levels along the Regge for a dry situation.

4.4 *Flood control in the Vecht River*

Figure 11 shows a flood wave in the Regge for a 1/100 year precipitation event at the point where the river discharges into the Vecht River. The design reduces and delays the peak discharge. The peak reduces because the inundation area increases significantly from the reference situation to the final design. The delay is due to greater length of the Regge and the increased inundation area.

On average, flood waves in the Vecht reach their peak discharge a bit later than flood waves in the Regge, at the point where the Regge discharges in the Vecht. Delaying the peak discharge in the Regge can increase the peak discharge in the Vecht, which is not desired. Water boards in the catchment area of the Vecht have investigated flood waves in the

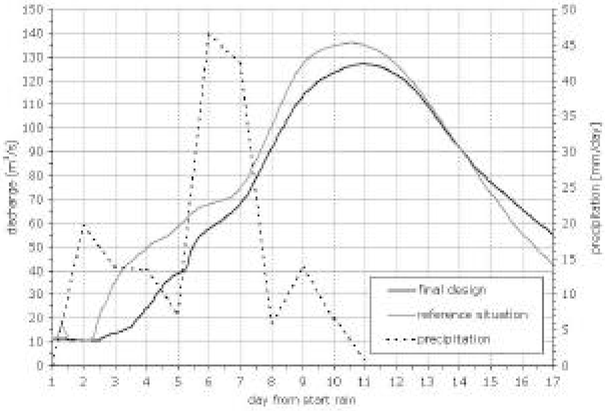


Figure 11 Discharge at the location where the Regge flows into the Vecht for T=100 year precipitation event.

Vecht and its tributaries (such as the Regge) and have agreed upon rules for distortion of flood waves on the tributaries. Flood waves on the tributaries may only delay if the peak discharge decreases sufficiently. The flood wave of the Regge delays 9 hours and the peak reduces with 6.5%. In accordance with the agreements, this is satisfactory.

Between the second day and the seventh day, the delay of the flood wave in the final design is relatively large. This is because, up to day seven, the capacity of the flood channel is not used efficiently. The barriers between the meandering river and the flood channel start overflowing from 14 m^3/s, but the depths and flows on the barriers are small. The flood channel contributes significantly to the total discharge capacity from a discharge of about 70 m^3/s. In between, the meandering Regge stores more water in the floodplains than the present Regge does.

5 DISCUSSION

5.1 *Natural water systems in densely populated areas*

In highly cultivated, relatively flat areas like the Netherlands, a strong coherence between spatial planning and water systems exists. Water systems are developed and adjusted to support several functions, such as agriculture, habitation and nature. In the past, the main aim was supporting agriculture and habitation. This had a negative impact on nature and natural water systems. Redesign of the Regge to a natural and dynamic river fits in with the tendency to give more priority to nature and natural water systems, which might decrease the conditions for agriculture and habitation. This certainly holds true for the first design, which represents the natural meandering Regge without measures to reduce negative impacts on agriculture and habitation. The first design significantly increases flooding in areas of habitation. Nature development has a high priority, but increased flooding of inhabited area is still unacceptable in the Netherlands.

5.2 *Monitoring and maintenance*

The solutions found to reduce flood water levels while maintaining a meandering channel with a relatively small discharge capacity, have serious drawbacks. The flood channel and the barriers at its connections with the meandering channel are located in the river floodplain. The meandering river may erode barriers and create unwanted connections with the flood channel. The flood channel can be sensitive to sedimentation, which will reduce its discharge capacity. Underneath bridges the channel may be prone to sedimentation as well. Raised bridge ramps restrict the flow width at bridges. The meandering channel and the flood channel connect and flow as a combined channel underneath the 34 bridges along the Regge. The present cross section dimensions will be maintained under these bridges to ensure sufficient discharge capacity. These local deviations in discharge capacity can be prone to sedimentation and erosion.

Monitoring the discharge capacity of the meandering Regge throughout the year, but at least prior to the flood season, is necessary to ensure flood protection. Important parameters such as channel location with respect to structures, channel width, channel depth and hydraulic roughness of the channel and the floodplain should be monitored. Maintenance must ensure that the discharge capacity is preserved and that the meander channel does not endanger structures.

5.3 *Drying of the river valley*

By removing weirs from the Regge, surface water levels and groundwater levels drop significantly in dry situations. Reduction of the flow area, increase of the hydraulic roughness and the increase in the length of the Regge compensate this slightly. The surface and groundwater conditions are less favourable for wetland development than they are in the reference situation, while the idea was that a more natural river would have positive effects on wetlands. For a natural river, this outcome should be accepted. One alternative to improve groundwater conditions is to keep weirs in the Regge, which can then be used to control water levels in the summer. Negative aspects of weirs are that they restrict movement of the meander channel at weir locations, they create stagnant water and hinder migration of fish.

5.4 *Future work*

If the Water Board decides to elaborate and implement the final design, construction of the meandering Regge and its flood channel will be a gradual process. Works that are feasible within the present situation can be carried out. Simultaneously, spatial planning might be adjusted to create more agreement between functions like agriculture, habitation and a natural water system. During this process, which will take many years, a natural and dynamic Regge might emerge in an area where nature, agriculture and habitation all have their place.

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