River science in the light of climate change

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1 Introduction

Climate change and a river's response to it are likely to be slow processes as compared to the responses to direct human interventions such as engineering works. Therefore, we have to look at timescales of centuries. Such timescales are difficult to be covered by numerical models and, moreover, uncertainties are so large that the degree of detail offered by numerical model simulations hardly pays off in terms of extra information. Therefore, we fall back on simple basic models providing first-order insight into a river's long-term behaviour. Starting from the basic drivers and controls of large-scale river morphology, we describe long-term changes as can be expected from climate change and long-lasting human interventions.

2 Drivers and controls

In order not to end up in the smallest upland streams, we confine ourselves to the more downstream parts of a river, where the slope is small and the bed is entirely alluvial. The principal drivers of a river defined this way are the amounts of water and sediment coming out of the drainage basin. The function of a river is to discharge these amounts. The water will end in a sea or a lake, in a groundwater reservoir, or evaporate, the sediment may be deposited underway, in the river bed or the riparian zone, or at the downstream end.

Important controls of a river are the valley slope and the downstream water level. Generally speaking, the river establishes its own bed slope, but the valley slope is an important control to the alignment (e. g. meandering). Depending on the timescale of the river bed response, short-term variations of the downstream water level, such as the semi-diurnal tide, may be of little influence, whereas longer-term variations, such as the 18.6-yearly nodal cycle and mean sea level rise, may have a much larger effect.

3 Equilibrium state model

For further analysis, we reduce the river to a straight channel of constant width, $\boldsymbol{B}$, with an alluvial bed at level, $z_b(x)$, in which x is the spatial co-ordinate along the channel. The remaining drivers and controls are the water discharge, $\boldsymbol{Q}$, the sediment input, $\boldsymbol{S}$, and the downstream water level (called erosion base), ζ_0 , which are all taken constant here.

We consider the equilibrium state of this simplified 'river'. In several instances, this approach, despite its strong simplification of reality, has been shown to give good insight into the long-term response of lowland rivers to changes in its drivers and controls. In Section 4 we will give some examples.

This simplified 'river' has two variables to adjust its equilibrium state to such changes: the water depth, $\boldsymbol{h}$, and the bed slope, $\boldsymbol{i_b}$. The formulae describing these variables in terms of $\boldsymbol{Q}$ and $\boldsymbol{S}$ (the downstream water level only determines the absolute height of the bed) follow straightforwardly from the basic flow equations, as shown below (also see JANSEN 1979, p. 119).

mass balance water:	$Q = BhU$	
mom. balance water:	$Q = BCh\sqrt{hi_b}$	
sed. transport formula:	$S = aBU^b$	
sediment balance:	$\dfrac{\partial S}{\partial x} = 0 \Rightarrow \dfrac{\partial U}{\partial x} = 0$	

$$\left.\begin{array}{l} Q = BhU \\ Q = BCh\sqrt{hi_b} \\ S = aBU^b \\ \dfrac{\partial S}{\partial x} = 0 \Rightarrow \dfrac{\partial U}{\partial x} = 0 \end{array}\right\} \quad h = \left(\frac{S}{aB}\right)^{-1/b} \frac{Q}{B}, \qquad i_b = \left(\frac{S}{aB}\right)^{3/b} \frac{B}{C^2 Q} \tag{1}$$

in which $\boldsymbol{U}$ denotes the cross-sectional mean velocity, $\boldsymbol{C}$ Chezy's friction coefficient, $\boldsymbol{a}$ a coefficient of proportionality which is inversely proportional to some power of the grain size and $\boldsymbol{b}$ a constant exponent, usually somewhere between 3 and 5.

These formulae help explaining many observed large-scale responses of lowland rivers. Not that for $\boldsymbol{b = 3}$ the second one is equivalent to what is called Lane's balance (LANE 1955), stating that the product of the water discharge and the bed slope is proportional to the product of the transport rate and the grain size.

4 Effects of human activities

4.1 Normalisation of the main channel

River training often involves normalisation of the main channel, i. e. establishing a constant channel width, usually narrower than before in order to improve navigability. In the Netherlands, extensive normalisation works have been executed in the Rhine branches in the 19th and 20th century (see Figure 1a for the River Waal).

In order to improve navigability, the main channel was narrowed. According to Eqs. (1), this led – as intended – to a deeper channel, but also to a smaller slope, hence to an incision further upstream (Figure 1b; also see VISSER et al. 1999). This causes problems with structures such as bridge piers, bank protections and man-made or natural poorly erodible layers. One example is a coarse sill near Emmerich, near the Dutch-German border, over which navigation becomes increasingly difficult as the downstream bed level decreases. Therefore, Germany and the Netherlands have agreed that the incision of the Rhine branches needs to be stopped and the Dutch are investigating measures to achieve this (e. g. sediment nourishments).

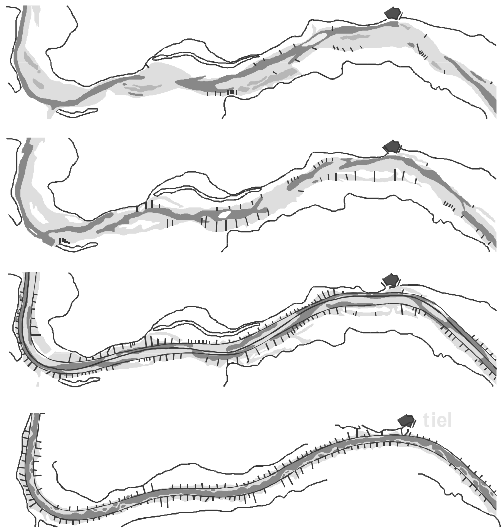

Fig. 1a: Successive normalisations of the Waal

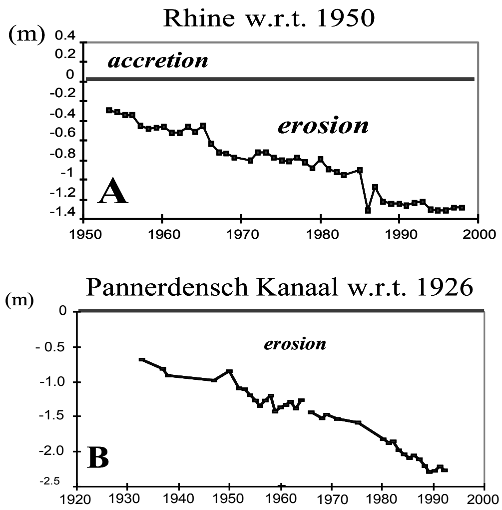

Figure 1b: Upstream response: incision

4.2 Sand mining

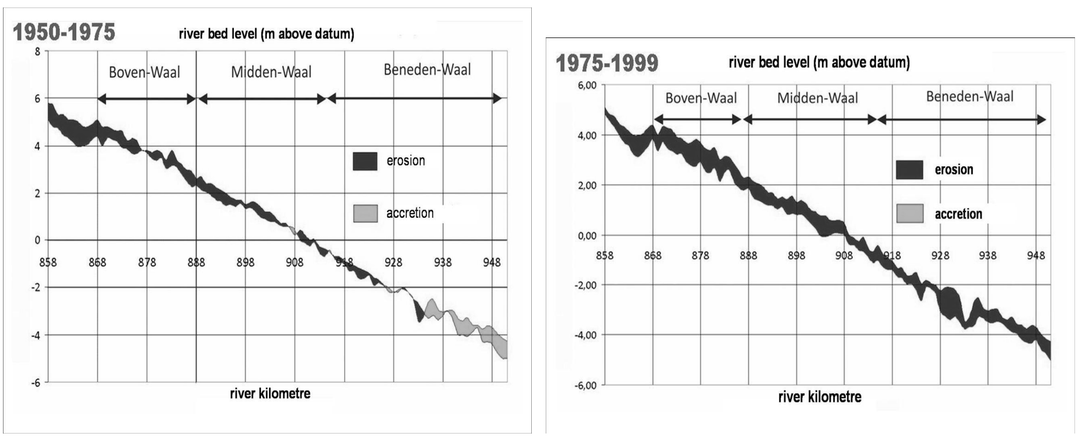

Figure 2: Profile evolution of the River Waal, before and after downstream sand mining

The tilting of the River Waal caused by the normalisations used to take place around a hinge point near Zaltbommel (Figure 2, left panel), because at the same time sea level rose and the downstream boundary shifted seawards, due to the closure of the Haringvliet estuary as part of the Deltaworks. The sand deposited downstream of Zaltbommel was allowed to be mined for commercial purposes. As a consequence, the erosion base came down to its original level and the entire river is bound to follow (Figure 2, right panel).

4.3 Water offtake

Many rivers around the world serve as a source of fresh water, used for various purposes, such as human consumption, irrigation, industrial use and to combat salt intrusion. If part of the river's discharge is taken out while the same amount of sediment has to be transported, however, the river will tend towards another equilibrium state. According to Eqs. (1), the depth will decrease and the slope will increase. Assuming the downstream boundary to re-main the same, this means that the river bed further upstream will tend to rise above the surrounding land, yielding a so-called ‘suspended river’. Also, the depth reduction will lead to a reduction of the river’s flood conveyance capacity. Examples of rivers behaving this way are the Lower Yellow River (see, for instance: SUO 2004) and the Indus (see http://www.bbc.co.uk/worldservice/news/2010/08/100818_indus_wt_sl.shtml).

4.4 Sediment trapping

Dams and weirs are found in the upstream parts of many rivers. Not only do they trap sediment, they also influence the discharge regime, hence the river’s transport capacity. In the highly simplified constant-discharge model described by Eqs. (1), the depth increases as the sediment supply decreases, but the slope decreases more (power $3/b$ instead of $-1/b$). The obvious and well-known consequence is river incision, starting from the sediment trapping obstacle and gradually extending downstream.

4.5 Model validity

The above examples make clear that the equilibrium relationships, despite the highly simplified model used, qualitatively explain a number of observed responses to human interventions. Hence one may assume that the same holds true for the response to climate change. As climate change is expected to affect discharge statistics, however, we can no longer stick to the assumption of constant discharge. Therefore, we will first extend the model to situations with a variable discharge.

5 Equilibrium state with variable discharge

The discharge in a river is by no means constant, it usually exhibits large variations. Therefore, and because climate change is expected to influence discharge statistics, it is important to work out the equilibrium state in case of a variable discharge, say with a probability density distribution $p(\underline{Q})$. If the upstream sediment supply remains constant, and we may assume the morphological evolution to be slow compared to the discharge variation, there exists an almost steady equilibrium state. This state can be derived in the same way as Eqs. (1), to yield:

$$h_m = \left(\frac{S}{aB}\right)^{-1/b} \frac{\left[\int_0^\infty Q^b p(Q)dQ\right]^{1/b}}{B} \quad ; \quad i_b = \left(\frac{S_0}{aB}\right)^{3/b} \frac{B}{C^2\left[\int_0^\infty Q^{b/3} p(Q)dQ\right]^{3/b}} \qquad (2)$$

Note that for constant Q these formulae reduce to Eqs. (1), since $\int_0^\infty p(q)dQ = 1$ by definition. Also note that in case of a variable discharge, the water level will vary with the discharge, except at the mouth, where a constant level is imposed. Therefore, the equilibrium water depth can only be defined in the mouth and the equilibrium bed level has to be construed from the level in the mouth ($\zeta_0 - h_m$) and the bed slope.

6 Effects of climate change

6.1 Discharge effects

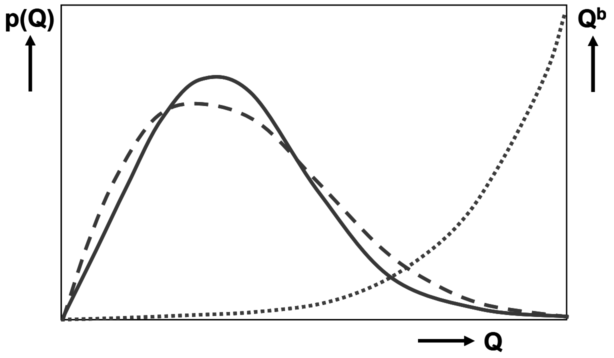

Figure 3: Climate change effect on discharge probability density function (drawn: present; dashed: future; dash-dotted: exponential discharge function)

Climate predictions indicate dryer summers and wetter winters, meaning a relative increase of low and high discharges at the expense of the average ones. This means that the probability density function for the discharge will change as qualitatively indicated in Figure 3.

According to Eqs. (2), the equilibrium state is determined by the product of the probability density function and an exponential function of the discharge which is different for the depth in the mouth and the bed slope. Especially the increase of the higher discharges will be of influence. Generally, the predicted climate change effects will lead to an increased depth in the mouth and a reduced bed slope, and the depth will exhibit the strongest response to these changes in the discharge-pdf. Both effects lead to bed erosion and incision of the river.

6.2 Sediment yield effects

Climate change will not only affect precipitation and river discharges, but also land use and land cover. Also, rock weathering may be influenced. This means that climate change will also affect the basin’s sediment yield and the sediment input into the river. Sign and magnitude of this change are difficult to predict and will depend on the region considered.

Both Eqs. (1) and Eqs. (2) indicate that an increase of the sediment supply will yield a smaller depth in the mouth and a steeper bed slope. This means: less navigable depth under low discharge conditions and a tendency towards a suspended river. A decrease of the sediment supply, on the other hand, will lead to a larger depth in the mouth and a smaller bed slope, so better navigability, but incision of the river.

6.3 Effects via the erosion basis

A third type of effect of climate change is an accelerated sea level rise. This affects the erosion base, hence the absolute level of the river in equilibrium, but it leaves the water depth in the mouth and bed slope unaltered. Note that this refers to the equilibrium state and that time is an important factor in the actual response of a river to sea level rise. In order to know more about this, we have to look into the time evolution of river morphology.

7 Morphological evolution with time

7.1 Basic time-behaviour

In a simplified model like the one considered here, the time-evolution of the bed level is a mixture of two basic types of behaviour, viz. propagation and spreading (also see RIBBERINK & VAN DER SANDE 1985). The corresponding equations read:

propagation: $$\frac{\partial z_b}{\partial t} + c_b(z_b)\frac{\partial z_b}{\partial x} = 0 \quad with \quad c_b = \frac{b}{1-\varepsilon}\frac{S}{Bh} \qquad (3)$$

spreading: $$\frac{\partial z_b}{\partial t} - K(z_b)\frac{\partial^2 z_b}{\partial x^2} = 0 \quad with \quad K = \frac{b}{1-\varepsilon}\frac{S}{3Bi_b} \qquad (4)$$

in which ε is the porosity of the bed. Generally speaking, propagation processes proceed rather fast, and – under low Froude number conditions – in downstream direction ($c_b > 0$). Spreading proceeds generally much slower and both in upstream and downstream direction. An example clearly illustrating this is that of a 5 km long constriction (fixed banks) in the schematised 'river' with a constant discharge (Figure 4). If we assume this constriction to be built in no time, the short term morphological response is erosion of the bed in the constricted reach and deposition of the erosion products downstream of it. These erosion products form a rapidly expanding bed wave moving downstream. Once this has left the model domain, a much slower upstream and downstream redistribution process takes over and ultimately produces the static equilibrium state.

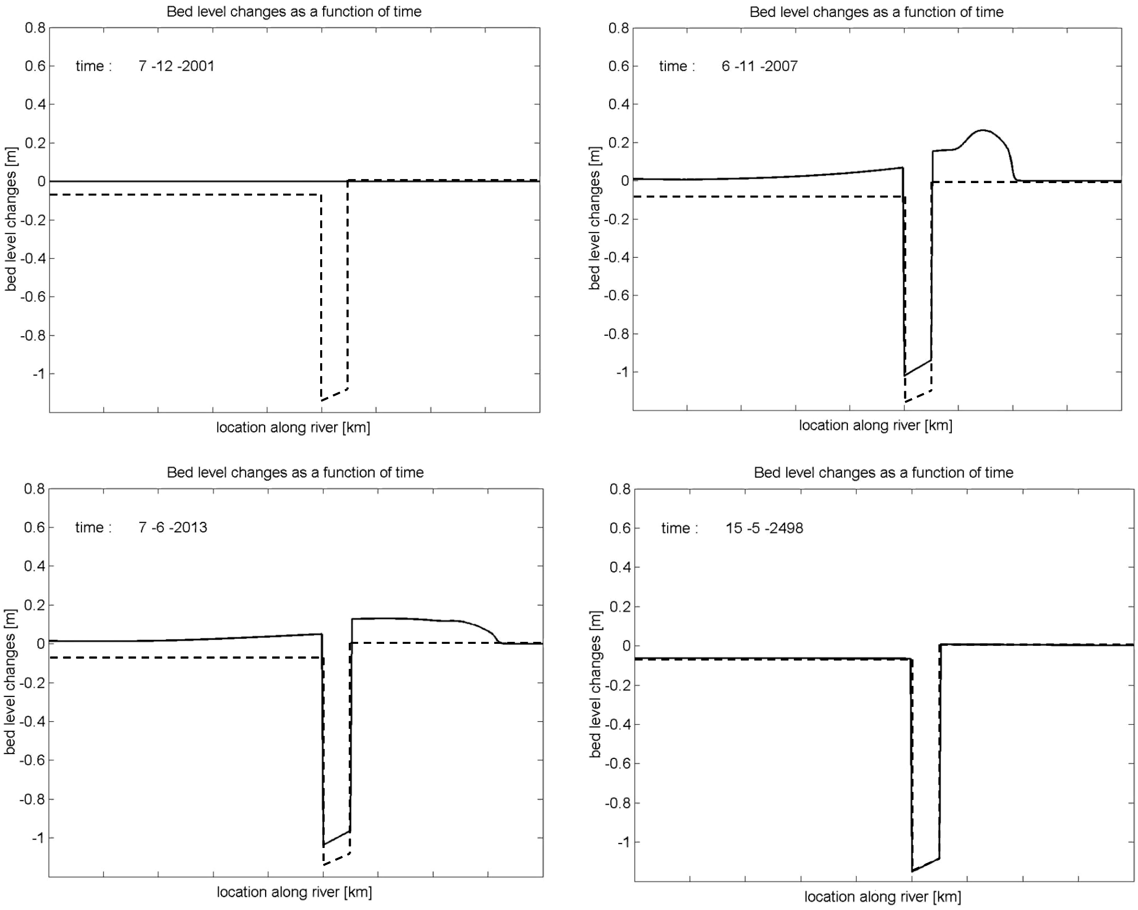

Figure 4: Numerical model simulation for a long constriction (drawn line) at different points in time, compared with the theoretical equilibrium state (dotted line). Also see VAN VUREN (2006).

7.2 Backward accretion

By nature, the propagation behaviour dominates in the first period after an intervention and the spreading behaviour manifests itself at a longer timescale. Climate change, however, is a slow process, which means that the response it causes will mainly exhibit a spreading behaviour. If sea level slowly rises, for instance, and the upstream conditions remain the same, upstream spreading will be the dominant mechanism. This leads to a gradual backward accretion of the river bed. If the sea level rise is a step function and $\boldsymbol{K}$ is taken constant, Eqs. (4) has an analytical solution which can be expressed in terms of error functions (Figure 5).

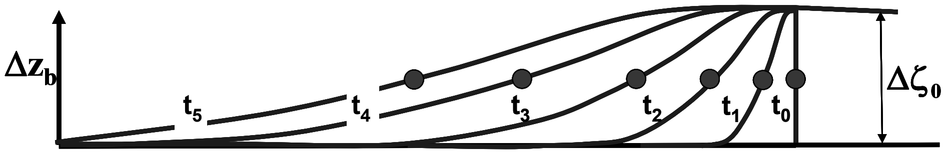

Figure 5: Solution of Eq. (4) in case of a stepwise sea level rise (flow from left to right, mouth right)

7.3. Morphological time scale

One may attribute a time scale to this solution by following the displacement of one point of the bed profile, for instance the point where half of the ultimate accretion has been reached. The time – expressed in years – needed for this point to travel over a distance $\boldsymbol{L}$ is given by (see JANSEN 1979, p. 123):

$$T = \frac{L^2}{Y} \quad with \quad Y = \frac{b}{1-\varepsilon} \frac{1}{3Bi_b} \int_0^{1\,year} S\,dt \qquad (5)$$

One can use this time scale definition to compare rivers by the speed of their response to changes in environmental conditions. When doing so, it turns out that the River Waal, with its relatively coarse sediment and its mild slope, is a slowly responding river (JANSEN 1979, p. 124). This is in line with the observed slow response to the normalisation works of the nineteenth and early twentieth century: The incision is still going on.

This means that this river is probably unable to follow the rising sea level over its entire length, so that it will be out of equilibrium as long as sea level rises. It also means that, if the sea level stops rising, or some engineering measure disconnects the river from the effect of sea level rise, there will be a long aftermath in the river's morphological response.

8 Conclusions

The tendency of a lowland river's long-term response to human interventions or changes in environmental conditions can be derived qualitatively from highly simplified, elementary and long-known models, such as Eqs. (1) for the static equilibrium state at constant discharge, or Eqs. (2) for the equilibrium state at variable discharge. In this way, a qualitative estimate of a river's response to climate change can be given without complex model simulations.

Climate change affects a number of important drivers and controls of a river, such as water discharge (via precipitation and snowmelt), sediment input (via land use, land cover and rock weathering) and the downstream water level (via sea level rise). The above models make it possible to predict the effects of each of them. As these models are basically non-linear, however, these effects cannot simply be superimposed. Combinations of effects and quantitative predictions therefore require numerical simulation models.

In long-term river morphology, time becomes an important factor if the timescale of the morphological response is similar to the timescale of change of the environmental conditions. A slowly responding river like the Rhine may therefore never reach equilibrium as long as it experiences the effects of climate change and sea level rise. This needs to be taken into account when designing climate adaptation measures.

Despite the possibility to use simple and well-known models to estimate the trend of a lowland river's response to climate change, knowledge needed for more accurate and quantitative assessments is still exhibiting important gaps. The research agenda for long-term river morphology includes items such as adequate model schematisation (pays off for long-term simulations and scenario studies), dealing with graded sediments (e. g. downstream fining and the effects of nourishments), bifurcations (including the long-term evolution of their flood conveyance capacity), sediment management (pathways, sediment as a resource) and biogeomorphology (the interaction of vegetation and morphology).

Summary

Simple, well-known models are proposed to estimate the long-term effects of climate change on lowland rivers. They concern the static and quasi-static equilibrium states of highly simplified straight fixed-bank channels with an alluvial bed, as well as the long-term limit of their evolution with time. These models are validated qualitatively against observed responses to a number of human interventions in such rivers and, subsequently, applied to qualitatively predict the effects of climate change on a number of important drivers and controls.

This leads to the conclusion that, for a slowly responding river like the Rhine, trends in the response to climate change can be identified from the equilibrium models, but that the river will probably never actually reach such an equilibrium state as long as climate changes and sea level rises.

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Specialisms
River flow and morphodynamics
Coastal morphodynamics
Shelf sea morphodynamics
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Building with Nature