Civil Engineering
Volume 168 Issue CE3

The long-term response of rivers to engineering works and climate change
de Vriend

ice | proceedings

Proceedings of the Institution of Civil Engineers
Civil Engineering 168 August 2015 Issue CE3
Pages 139–144 http://dx.doi.org/10.1680/cien.14.00068
Paper 1400068
Received 11/11/2014 Accepted 19/04/2015
Published online 17/06/2015
Keywords: floods & floodworks/hydraulics & hydrodynamics/river engineering

ice Institution of Civil Engineers
publishing

The long-term response of rivers to engineering works and climate change

Huib de Vriend MSc, PhD
Professor Emeritus River Engineering and Morphology, Delft University of Technology, Delft, the Netherlands

Rivers respond to changes in their geometry or their controls in various ways and at a wide range of space and time scales. The response consists of changes in properties such as cross-sectional shape and area, slope, planform pattern, bed roughness and bed sediment composition. Usually, attention for the morphological impact of engineering works focuses on short-term effects. The usually much slower, but also much more persistent large-scale response is often ignored, or countermeasures are ineffective. In many cases this has led to extra maintenance costs, in some even to hazardous situations or disaster. This paper refreshes and extends long-existing but seemingly forgotten knowledge on large-scale river behaviour. It gives examples of impacts of engineering works, climate change and sea level rise, discusses potential countermeasures and gives a number of general conclusions on the large-scale morphological behaviour of lowland rivers.

Notation

h_0	equilibrium water depth
i_b	bed slope
$p(Q)$	probability density function of the varying discharge
Q	river discharge
Q_0	river discharge at the upstream end of the river section considered
S_0	sediment input upstream
Δh	change in water depth
Δi_b	perturbation of the bed slope
ΔQ	discharge diverted from the river's main channel
ΔS	amount of sediment diverted from the river's main channel
ζ_0	water level at the downstream boundary

1. Introduction

When considering a river reach, its morphological behaviour is determined by a limited number of drivers and controls, such as

- the upstream discharge, which varies in time according to a certain discharge regime
- the input of sediment (transport rate, composition), which can either come from upstream, or – in the case of erosion – from the bed or the banks
- the downstream water level, which also varies according to a certain regime; depending on the situation, this is associated with the discharge regime (e.g. through a rating curve), or it concerns an independent lake or sea level variation
- geological constraints, such as valley width and slope, rock sills and subsoil composition
- vegetation, especially in the flood-conveying floodplains
- engineering works, such as dams, weirs, revetments, bed protections, flow distribution works or man-made channel profile changes
- other human activities, such as water abstraction or sand mining.

The river morphology will respond to these drivers and controls by way of 'dependent variables' such as the cross-sectional shape and area, the bed slope, the planform pattern, the bed sediment composition and the bed roughness.

Present-day numerical models (e.g. Brunner, 2010; DHI, 2009; Lesser *et al*., 2004; Villaret, 2010) are able to take most of these responses into account. If they are run with constant inputs in order to cover large space and time scales, however, their representativeness must be doubted, whereas their results will be dominated by short-term morphological responses if they are run with realistic time-varying inputs. The latter makes them difficult to interpret in terms of long-term effects.

One way to deal with the problem is to simplify things drastically and derive the long-term behaviour from the basic conservation laws of physics, generally flow continuity, flow momentum, sediment transport model and sediment balance. This gives insight into some of the basic long-term behaviour without having to filter out short-term variability.

This paper further elaborates the approach for lowland rivers, starting from long-existing knowledge and building it out to present-day problems. The paper is an elaboration and extension of an earlier report by the author (de Vriend, 2011).

2. Simplification

In a lowland river which flows in its own sediment and is not confined by geological constraints, the slope is small and the river discharges into a sea. At the upstream end, the river receives water and sediment from the catchment; at the downstream end the water level is given.

The timescale of the morphological processes is assumed to be much larger than that of the short-term water level variations at sea (tides, surges) and the river discharge in the downstream area is much larger than the tidal or surge discharge. Longer-term changes of the mean water level, such as mean sea level rise, can be taken into account.

The river can be simplified to a straight rectangular channel of constant width, with fixed banks and a mobile bed, constant bed roughness and sediment composition, and no lateral inflow. There are no floodplains, all the water remains in-bank. This means that the only remaining dependent variables are the bed slope and the water depth. In the first instance, it is also assumed inputs are constant, though subsequently this assumption can be relaxed to consider input regimes.

The reason for the very drastic simplification is that it allows for simple analytical solutions that give much insight into the relationship between responses and drivers and controls, while the results will be shown to agree qualitatively with reality in a number of cases.

3. Static equilibrium state

There are no time variations in a static equilibrium state. By implication, as spatial transport gradients lead to bed level changes, the sediment transport rate has to be constant along the river. Given the space and time scales considered, it makes sense to relate the transport rate to the local mean flow velocity.

If proportionality to some power of the velocity is assumed, the latter must also be constant. If the discharge and the width are also constant, the water depth must be constant as well. Finally, according to Chezy's law, the bed slope must be constant if the flow velocity, the water depth and the friction coefficient are constant. So static equilibrium means, in this case, uniform flow over a plane sloping bed.

For uniform flow and a sediment transport rate proportional to some power of the flow velocity, it can easily be shown that the remaining controls, that is the water depth and the bed slope, are simple functions of the water and sediment input (see also Jansen (1979: p. 119)).

Also, the product of the equilibrium water depth and bed slope is a function of the sediment input and the grain diameter alone, and the product of the slope and the grain diameter to a given power is proportional to the product of the discharge and the equilibrium bed slope. This is known as Lane's balance (Lane, 1955).

The relationships help to explain, at least in a qualitative sense, a variety of observed long-term effects of engineering works, human activities and sea level rise in lowland rivers. Section 4 considers some examples, including some in which the relationships seem to have been ignored by engineers and river managers.

4. Long-term responses

4.1 Slope reduction

The first example concerns the long-term effects of the training works in the Dutch Rhine branches, which took place in the late nineteenth and early twentieth centuries (Figure 1(a)). These works, boiling down to narrowing the main channel by building groynes, were primarily meant to improve navigability by increasing the depth, and to eliminate low-velocity zones where ice dams (until then an important cause of flooding) could form.

According to the Jansen (1979) relationships, narrowing the channel does lead to a depth increase, but also to a gradual reduction of the river slope. As the river will tilt around its downstream boundary, this means incision upstream. Figures 1(b) and (c) show that this is the case. Although channel narrowing is not the only factor contributing to this effect, it is clearly the most important (Visser *et al*., 1999). The fact that the river manager calls this phenomenon 'autonomous' illustrates that the underlying mechanism is not understood.

The incision has led to navigability problems on a non-erodible threshold near the Dutch–German border. This is why the Dutch have agreed with the Germans to take measures to keep the river from further incising. Other negative effects are destabilisation of banks and revetments, and groundwater drawdown in the riparian zone.

Also, the height of the groynes above the river bed keeps on increasing, so ever more water is discharged by way of the main channel, thus increasing the transport capacity. The river will respond to this by further reducing its slope, so there is a positive feedback and, hence, an unstable situation.

Driven by flood conveyance considerations, a substantial floodplain reconnection and groyne-lowering scheme is presently implemented and there are plans to replace part of the groynes by longitudinal dams (Rijkswaterstaat, 2014). Although not primarily meant to restore the slope, the combination of these measures is expected to compensate part of the upstream incision.

Based on regained insight into the aforementioned cause–effect relationship, the possibilities of river slope restoration by sediment nourishment are being considered.

4.2 Slope increase

Rivers convey water, which is scarce in many parts of the world. Hence it is tempting to use the river for water supply. If one does so, however, the capacity to transport sediment is reduced. If the upstream sediment supply is constant, the equilibrium slope according to the Jansen (1979) relationships will be inversely proportional to the discharge. So it increases as the discharge decreases, which in a long river can lead to a significant rise of the bed level upstream.

Figure 2 shows the case in the River Indus in Pakistan: the river bed upstream lies far above the surrounding area (a 'suspended river'). When in 2010 a high, but not very extreme flood occurred, one of the dykes failed and the river took a disastrous 500 km detour (Figure 2(b); see also Syvitski and Brakenridge (2013)), with many casualties and major societal disruption as a consequence. This is an example of poor river management by lack of awareness of the long-term consequences of water abstraction without corresponding sediment management.

Possible solutions here would be to concentrate the flow all along the river (like the Rhine normalisation) in such a way that the upstream sediment input can be discharged, or to take out exactly the amount of sediment that restores the original slope, as shown qualitatively in Figure 3. In other words: water and sediment should be managed at the same time and in the right proportion.

Note from Figure 3(a) that not only the river downstream of the abstraction is affected but also the part upstream. This is always the case if an intervention influences the bed slope, even if it is only over a limited reach. In general, if the slope is changed by Δi_b over a distance L, this leads to a bed level change $L\Delta i_b$ in the entire river upstream of the reach where the intervention takes place, up until the first dam, weir or rapid.

Also note from Figure 3 that the slope and the depth cannot both be restored (see also Section 5). Finally, note that if water is abstracted at a large number of locations along the river, the picture will be more complex (e.g. Li *et al*., 2014).

Another example is the Yellow River in China, which receives most of its sediment from erosion of the loess plateau, about halfway along its course. This plateau used to be a fertile and richly vegetated area, but overexploitation led, probably about a millennium ago, to desertification and susceptibility to water-induced erosion. Looking from a long-term perspective, this led to a dramatic increase of the sediment load of the river, with an increase of the bed slope as a long-term implication. This has materialised: some parts of the lower Yellow River have risen more than 15 m above the surrounding area.

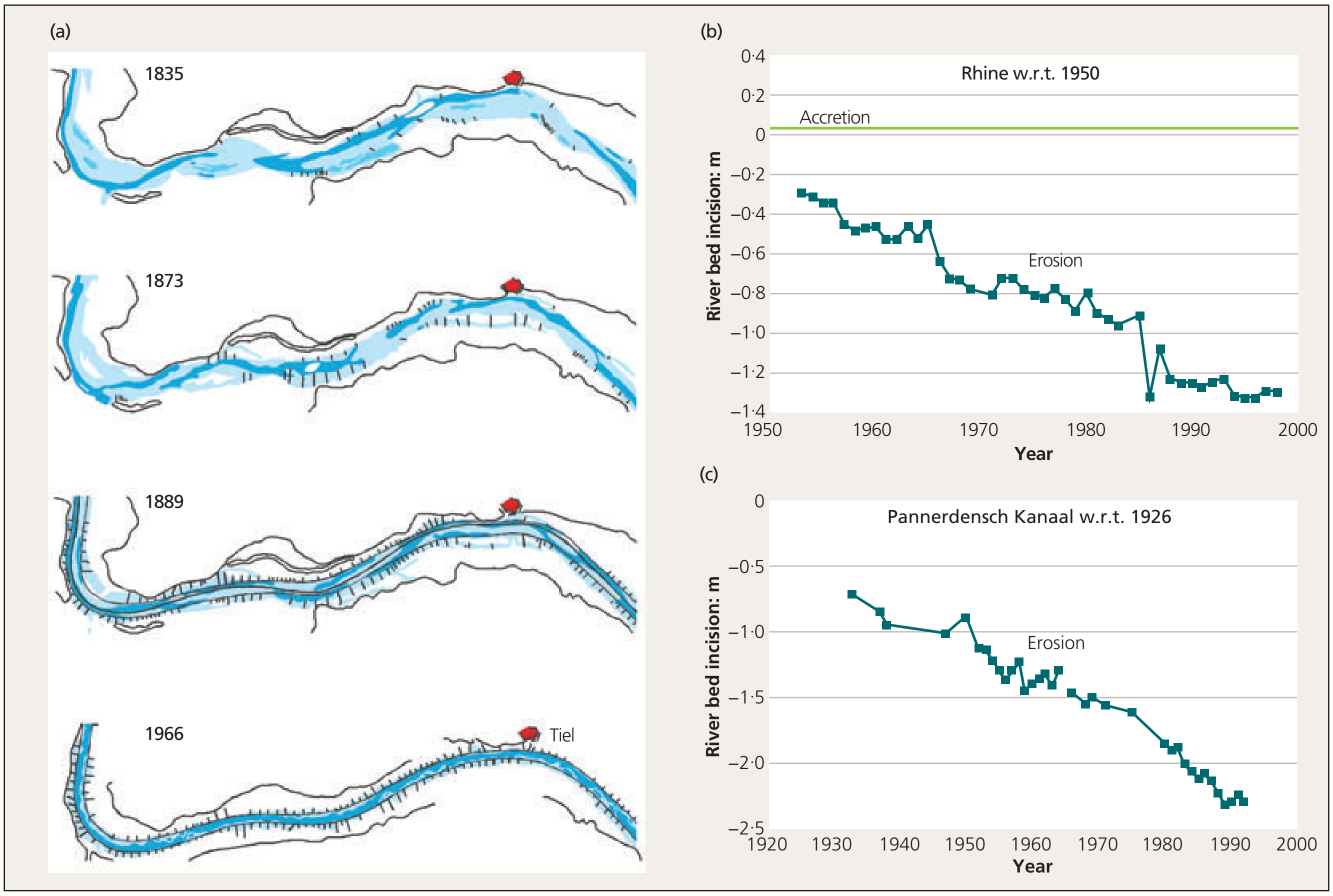

Figure 1. Successive training schemes of the River Waal in the Netherlands to confine the main channel (a); resulting river bed incision 120 km upstream (b) and after the first bifurcation some 110 km upstream (c)

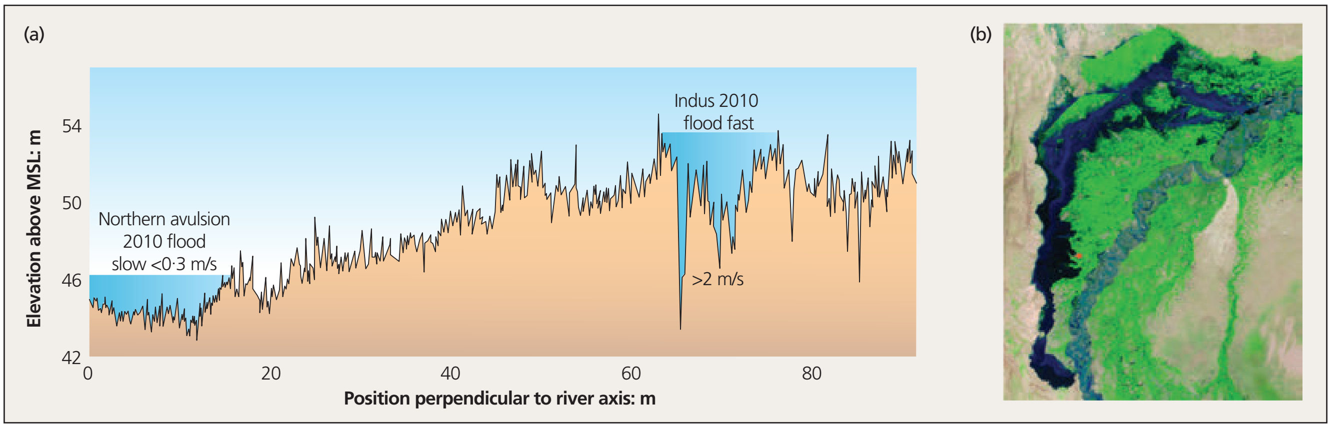

Figure 2. River Indus flood event in Pakistan in 2010: upstream cross-section shows how river is far above surrounding area (a) and aerial view of flooded area in 2010 (b) (courtesy J. Syvitski)

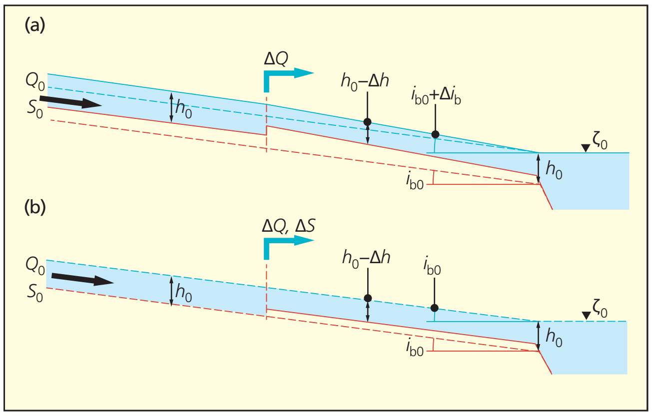

Figure 3. Effect of local water abstraction (dashed lines indicate undisturbed situation): with no countermeasures (a) and with water and sediment abstracted in such a proportion that the original slope is maintained (b)

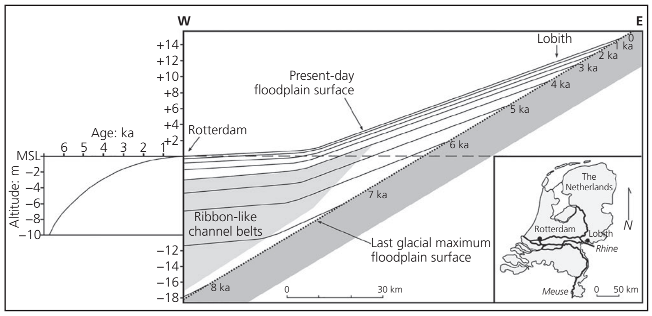

Figure 4. Time-evolution of groundwater table (as a proxy of river bed level) in the Rhine–Meuse system in north-west Europe during the past 8000 years, showing sea level rise curve (left) and reconstructions of groundwater table in thousands of years before present (Blum and Törnqvist (2000), reproduced by permission of John Wiley & Sons)

Apart from building ever-stronger flood defences, the remedy here is not obvious, due to the special nature of the sediment transport in the Yellow River, with its very high concentrations of very fine sediment. One way to try to keep the river bed from rising further is to manipulate the lowermost river dams in such a way that the released mixture of water and sediment scours the bed downstream over a long distance (e.g. Wang *et al*., 2015).

Here, too, the message is: start from how the river functions and manage water and sediment together.

4.3 Upstream effects of the downstream control

The third control to be considered is the downstream water level. If sea level rises, the river is bound to rise along with it, though with a time lag that increases with the distance to the sea. As sea level has risen over the past 10 000 years, this must be visible in the fluvial sediment deposits. Blum and Törnqvist (2000) analysed the quaternary stratigraphic record of the Rhine−Meuse system in north-west Europe and came to the reconstruction of the groundwater table (as a proxy of the river bed level) shown in Figure 4.

Note that the time lag in the morphological response is not visible in Figure 4, since the morphological timescale of the system is much smaller than the time intervals considered here. Also note that the kink at the upstream end is probably due to the fact that the bed sediment of the last glacial maximum floodplain surface is coarser than that of the accreted part.

The bed sediment of lowland rivers is often suitable as building material. Hence it is tempting to mine this material from the river bed. An example of the possible effect is the sand mining in the downstream part of the River Waal in the Netherlands. As indicated above, this river is tilting in response to its training works, but due to the effects of other engineering works the hinge point lies some 20 km upstream.

As the river was accreting in the downstream reach, sand mining was officially allowed, with the consequence that the entire river bed is now being drawn down (Figure 5), with many negative consequences. This is another example of lacking awareness of the long-term effects of an intervention, in this case sand mining.

An example inspired by an envisaged project in the River IJssel in the Netherlands concerns river bed lowering in the downstream part of the river, which discharges into a lake. The objective is to lower the flood level near a city some 20 km upstream, under the constraint that under normal conditions the water level there may hardly come down. The bed slope of this part of the river is rather mild, which means that the backwater curve extends significantly further than 20 km. In the lowered reach of a few kilometres the water level will come down due to the backwater effect (Figure 6(a)).

As the bed in this reach will be kept at the designated level, the lowering will lead to a permanent drawdown of the water level at the upstream end, and the backwater effect will extend this – in a gradually decreasing amount − beyond 20 km upstream. Yet, the drawdown at 20 km may initially remain within acceptable bounds.

The long-term morphological effect of the intervention, however, will be backward erosion, until ultimately the entire river bed has come down over a distance equal to the water level drawdown at the upstream edge of the lowered reach. Hence the water level constraint at 20 km can no longer be met. The suggested countermeasure is to restore the original river bed level whenever backward erosion occurs, but only over a small distance upstream of the lowered reach. This solution, however, will not be effective, because it is the downstream water level that controls backward erosion, not the downstream bed level.

As the reach over which the bed level is restored is much shorter than the backwater curve, the water level at its upstream end will still be drawn down and backward erosion will start from thereon (Figure 6(b)). To be effective, the bed level restoration should take place over the entire length of the backwater curve, which is practically more difficult to realise. Another option would be to set up the water level at the upstream end of the lower reach, but this will be an obstacle to navigation.

5. Statistical extension

5.1 Discharge regime

So far a constant discharge has been assumed, but the discharge of a river exhibits large random variations in time. When maintaining the assumptions of a constant sediment supply and a fixed downstream water level, and assuming the large-scale morphological processes to be much slower than the discharge variations, there will exist an almost-steady equilibrium state. Jansen (1979: p. 121) gives a version of the aforementioned relationships for the equilibrium water depth and bed slope in the case of random discharge variations.

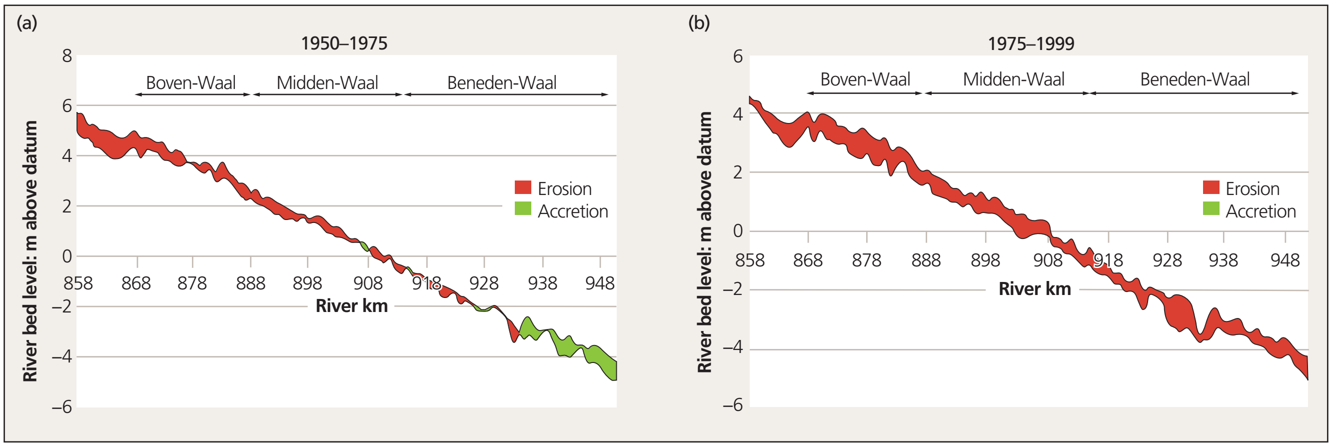

Figure 5. Tilting of the River Waal in the Netherlands before sand mining (a) and erosion after sand mining (b) (courtesy Rijkswaterstaat)

As the discharge varies, the water level will do so too, except at the downstream end, where it is fixed. Hence the equilibrium water depth is only defined at the downstream end. The equilibrium bed level elsewhere along the river has to be derived from this depth and the water surface and bed slopes.

An important conclusion to be drawn from the relationships for a randomly varying discharge is that the water depth and the bed slope each depend on a different statistical moment of the discharge (i.e. the statistical mean of the discharge raised to a different power). This means that there is not a single representative constant discharge that yields the same values of both the water depth and the bed slope as the randomly varying discharge.

Nonetheless, many river morphological studies work with such a representative discharge, often the one that yields the same net transport rate. According to the Jansen relationships, this produces the right water depth, but not the right bed slope.

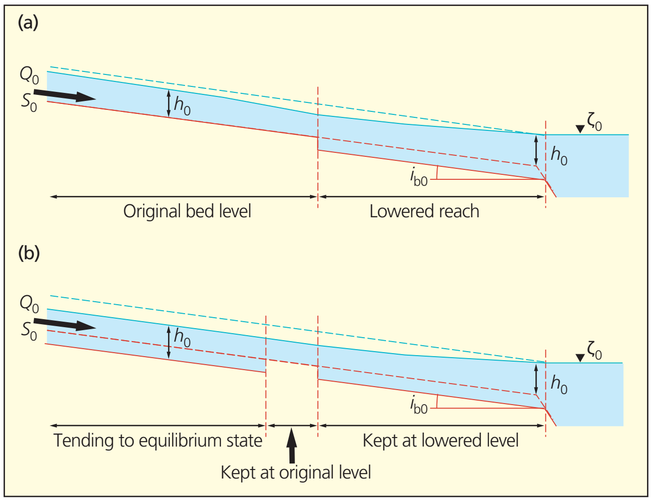

Figure 6. Effect of river bed lowering downstream (dashed lines indicate undisturbed state): initial effect (a) and equilibrium state if the bed level in the lowered reach and a short section upstream of it is maintained at the designated level (b)

5.2 Change of discharge regime

In north-west Europe, climate change is expected to lead to dryer summers and wetter winters (IPCC, 2013). This means that the probability density distribution of the discharge will change as qualitatively indicated in Figure 7(a). In the statistical moments of the Jansen relationships, this probability density distribution is multiplied by the discharge to a positive power. Hence the higher discharges will count the most in these moments.

As a consequence, the depth at the downstream boundary will increase and the bed slope decrease if the probability of occurrence of high discharges increases. This can be understood because the higher discharges provide more transport power, so the system needs less slope to transport the amount of sediment supplied upstream. A seldom-mentioned long-term effect of this particular aspect of climate change is therefore river incision.

An engineering measure affecting the discharge regime is dam building. Especially when a dam is built to store flood water, such as the Three Gorges Dam in China, the higher discharges are reduced in favour of the lower ones (Figure 7(b)). This means that if the sediment supply is constant, the depth downstream will decrease and the slope will increase. That the opposite is true for the lower reaches of most dammed rivers is due to the fact that the dam also reduces the sediment input.

Pick-up of sediment from the river bed restores the transport rate, at most up to the reduced capacity corresponding with the original river slope and the new discharge regime. This effect on the discharge regime, rather than the blockage of sediment transport, is – at least initially – the principal reason why dammed rivers supply less sediment to the estuary and the adjacent coast.

Once the effects of bed sediment coarsening (e.g. Yang *et al*. (2014) for the Yangtze River downstream of the last dam) and bed armouring have extended to the estuary, transport blockage by the dam will count more and the sediment supply problem will aggravate.

5.3 Change of sediment yield

Climate change is bound to influence not only the water supply from the catchment but also the sediment yield.

Assuming the changes in sediment yield to be very gradual as compared to the discharge variability, a simple variation of the Jansen (1979) relationships shows that an increase of the sediment yield (due to desertification, for instance) will lead to an increase

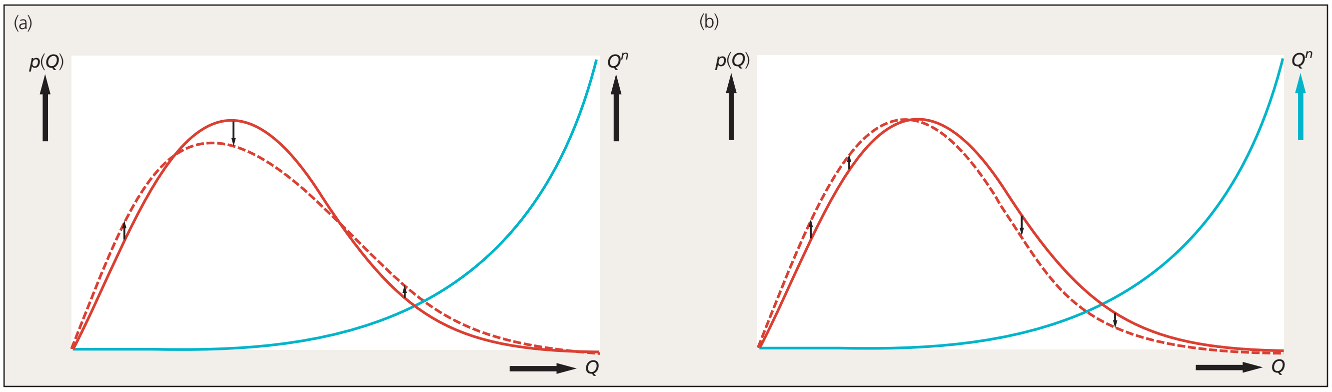

Figure 7. Effect on probability density function of discharge of climate change (a) and dam construction (b) – solid red line is before, dashed red is after, blue is discharge to the power n ($n > 1$)

of the bed slope and a decrease of the water depth downstream, with a suspended river as a consequence.

If vegetation increases, however, less sediment will be produced and the river will incise.

6. Conclusion

The principal conclusion to be drawn from the foregoing is that awareness of long-term river responses to human interventions or changes in environmental conditions, as well as insight into the underlying physical mechanisms, have long been available, but seem to be ignored by many river managers and their consultants.

A number of simple analytical relationships have been derived long ago for the morphological equilibrium state of a highly simplified river under steady and randomly varying conditions. Despite these simplifications, these relationships are applicable to identify qualitatively long-term responses in a wide range of real lowland rivers.

Important observations derived from these relationships are as follows.

- A single representative discharge does not give good estimates of both the bed slope and the water depth in the equilibrium situation.
- Engineering solutions that are initially feasible may fail in the longer term, due to slow large-scale responses.
- Every measure that affects the bed slope over a certain distance leads to erosion or accretion of the river bed upstream, ultimately extending all the way up to the first dam, weir or rapid.
- Affecting the flow regime means affecting a river's equilibrium state.
- Upstream erosion or accretion requires compensation measures restoring the downstream water level, or it has to cover over a distance of the order of the length scale of the backwater curve.

Acknowledgements

This paper makes grateful use of earlier findings by several of the author's predecessors, especially the late Prof. M. de Vries of Delft University of Technology and the authors who contributed to Jansen (1979). Probably because this material is difficult to find in the open literature, it may have been forgotten, although it is certainly not obsolete. This paper is meant to bring this material back to the attention of river researchers, engineers and managers.

References

Blum MD and Törnqvist T (2000) Fluvial responses to climate and sea-level change: a review and look forward. *Sedimentology* **47(Suppl. 1)**: 2–48.

Brunner GW (2010) *HEC-RAS River Analysis System 4.1 User's Manual*. US Army Corps of Engineers, Hydrologic Engineering Center, Davis, CA, USA. See http://www.oregon.gov/owrd/docs/SB839/HEC_RAS_4_1_Users_Manual.pdf (accessed 09/11/2014).

de Vriend HJ (2011) River science in the light of climate change. In *EurAqua Symposium: Impact of Climate Change on Water Resources – 200 Years Hydrology in Europe – A European Perspective in a Changing World*. German Federal Institute of Hydrology (BfG), Koblenz, Germany, pp. 25–33.

DHI (2009) *Mike 11 – A Modelling System for Rivers and Channels*. DHI, Hørsholm, Denmark, reference manual. See ftp://213.143.90.70/Uporabniki/UrosZ/MIKE/Manuals/MIKE_11/Mike_11_ref.pdf (accessed 09/11/2014).

IPCC (Intergovernmental Panel on Climate Change) (2013) *Climate Change 2013: the Physical Science Basis*. IPCC, Geneva, Switzerland.

Jansen PP (1979) *Principles of River Engineering: the Non-tidal Alluvial River*. Pitman, London, UK, facsimile edition published in 1994 by Delft University Press, Delft, the Netherlands.

Lane EW (1955) Design of stable channels. *Transactions of the American Society of Civil Engineers* **120**: 1234–1260.

Lesser GR, Roelvink JA, van Kester J and Stelling GS (2004) Development and validation of a three-dimensional morphological model. *Coastal Engineering* **51(8)**: 883–915.

Li W, Wang ZB, de Vriend HJ and van Maren DS (2014) Long-term impacts of water diversions on the longitudinal flow and bed profiles. *Journal of Hydraulic Engineering* **140(6)**: 04014021.

Rijkswaterstaat (2014) *Groin Lowering Along the River Waal*. Rijkswaterstaat, Amsterdam, the Netherlands. See http://www.rws.nl/water/plannen_en_projecten/vaarwegen/waal/kribverlaging_waal/ (accessed 10/11/2014).

Syvitski JPM and Brakenridge GR (2013) Causation and avoidance of catastrophic flooding along the Indus River, Pakistan. *GSA Today* **23(1)**: 4–10.

Villaret C (2010) *SISYPHE 6.0 User Manual*. EDF, Chatou, France, report HP-P73-2010-01219-FR. See also http://www.opentelemac.org/index.php/modules-list/164-sysiphe-sediment-transport-and-bed-evolution (accessed 09/11/2014).

Visser PJ, Havinga H and ten Brinke WBM (1999) How to keep the river navigable. *Land en Water* **29(9)**: 25–27 (in Dutch).

Wang ZY, Lee JHW and Melching CS (2015) *River Dynamics and Integrated River Management*. Springer, Heidelberg, Germany.

Yang SL, Milliman JD, Xu KH *et al.* (2014) Downstream sedimentary and geomorphic impacts of the Three Gorges Dam on the Yangtze River. *Earth-Science Reviews* **138**: 469–486.