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The impact of changes in climate, upstream land use and flood plain topography on overbank deposition

IVO THONON, HANS MIDDELKOOP & MARCEL VAN DER PERK

Centre for Geo-ecological Research (ICG), Department of Physical Geography, Universiteit Utrecht, PO Box 80115, 3508 TC Utrecht, The Netherlands

h.middelkoop@geo.uu.nl

Abstract Changes in climate, upstream land use, and flood plain topography may drastically affect the functioning of flood plains as sinks for sediments and associated contaminants. We estimated the impacts of such changes on overbank deposition rates and conveyance losses for two reaches of the lower River Rhine by a scenario study for the year 2050. In the climate change scenario, deposition rates increase by 13% compared to current deposition rates, but combined with land-use changes, the deposition rates decrease by 12%. Topographical changes considered in the flood plain rehabilitation scenario cause an increase of 6% in the deposition rates. Conveyance losses, currently 5–7%, increase by a considerable 18% under the scenario with all changes combined. Flood plains are therefore expected to increase in importance as sediment and contaminant sinks under future changes.

Key words climate change; flood plains; heavy metals; land-use change; modelling; overbank deposition; river rehabilitation; River Rhine; sedimentation

INTRODUCTION

Flood plains serve many vital functions in the riverine landscape. One of their widely acknowledged functions is the sequestration of sediment and associated heavy metals (e.g. Walling *et al*., 1998; Middelkoop, 2000). Losses of contaminated sediments due to sequestration in flood plains can be considerable. For instance, Walling *et al.* (2003) reported conveyance losses of nearly 50% for Pb to the flood plains of the River Swale in northwest England. Several factors influence this flood plain sequestration function. In general, larger upstream inputs of sediments (Asselman *et al*., 2003) and heavy metals (Foster & Charlesworth, 1996), higher inundation frequencies (Hren *et al*., 2001), lower flow velocities (Asselman, 1999; Thonon *et al*., 2005) and longer inundation durations (Lecce & Pavlowsky, 2001) lead to more deposition of sediments and associated heavy metals. Upstream land use and emissions mainly govern the input of sediments and heavy metals, while climate and flood plain topography mainly determine inundation frequencies and duration. Flood plain topography also controls flow patterns over the flood plain during inundation. Yet, climate and land-use change and flood plain rehabilitation may change the above factors and hence influence the sequestration function of flood plains.

We aimed to quantify the individual and combined impact of changes in climate, land use and flood plain topography on the deposition of sediment and associated Zn, Pb, Cu and Cd on lower River Rhine flood plains. Firstly, we defined scenarios for climate, upstream land-use changes, and changes in flood plain topography for the year 2050. Secondly, we calculated sediment and heavy-metal deposition for two river reaches along the lower River Rhine for the current situation and all scenarios using a two-dimensional (2-D) flood plain deposition model. In these two river reaches the Dutch national government will implement various flood plain rehabilitation measures (RIZA, 2003). Finally, we compared the calculated deposition rates and conveyance losses for the different scenarios for the entire river branch.

STUDY AREA

The lower River Rhine has a mean discharge of 2250 $m^3 s^{-1}$ at the Dutch–German border. Besides water, the lower River Rhine discharges on average 2.9 10^9 kg of suspended sediment per year. Attached to the suspended sediment, the river carries approximately 1.2 10^6 kg Zn, 2.3 10^5 kg Pb, 1.9 10^5 kg Cu and 4 10^3 kg Cd per year. In The Netherlands, the river's main distributary is the Waal River, which discharges two-thirds of all the water, sediment and heavy metals. Figure 1 depicts the two river reaches studied: the Upper Waal River reach (UWR reach) and the Middle Waal River reach (MWR reach). Both reaches are located between major embankments and encompass flood plains of 1 to 2 km in extent (Figs 2(a) and 3(a)). Currently, all flood plains are also bordered by minor embankments, which protect the flood plains against inundations by low-magnitude floods (Figs 2(a) and 3(a)). With these characteristics the two river reaches are representative for the total Waal River branch. Rehabilitation programmes (RIZA, 2003), however, envisage the removal of the minor embankments in the Afferdensche & Deestsche Waarden (ADW) and Millingerwaard (MW) flood plain sections in the two river reaches (Figs 2 and 3). Other rehabilitation plans include the construction of a flood-plain lake in the Bemmelsche Waard (BW) flood plain and a secondary channel (ADW flood plain), the lowering of the flood plain surface (MW flood plain) and the reallocation of a major embankment (Figs 2(b) and 3(b)).

MATERIALS AND METHODS

We calculated the impact of the following scenarios for the reference year 2050 and compared it to the current situation:

(a) The climate change or CC scenario, with 10% more frequent peak discharges (3750–9500 $m^3 s^{-1}$) according to recalculations of data provided by Van Deursen (2002).

(b) The situation with climate and upstream land-use change: the CLC scenario, which equals the CC scenario but has a 13% lower annual sediment load in the lower Rhine River as a result of a decrease in arable land and, consequently, lower soil erosion rates in the River Rhine basin (Asselman *et al*., 2003).

(c) The situation with flood plain rehabilitation: the FR scenario, reflecting the topographical changes indicated in Figs 2 and 3.

(d) The situation with the combination of climate, upstream land use and topographical change: the CLC + FR scenario.

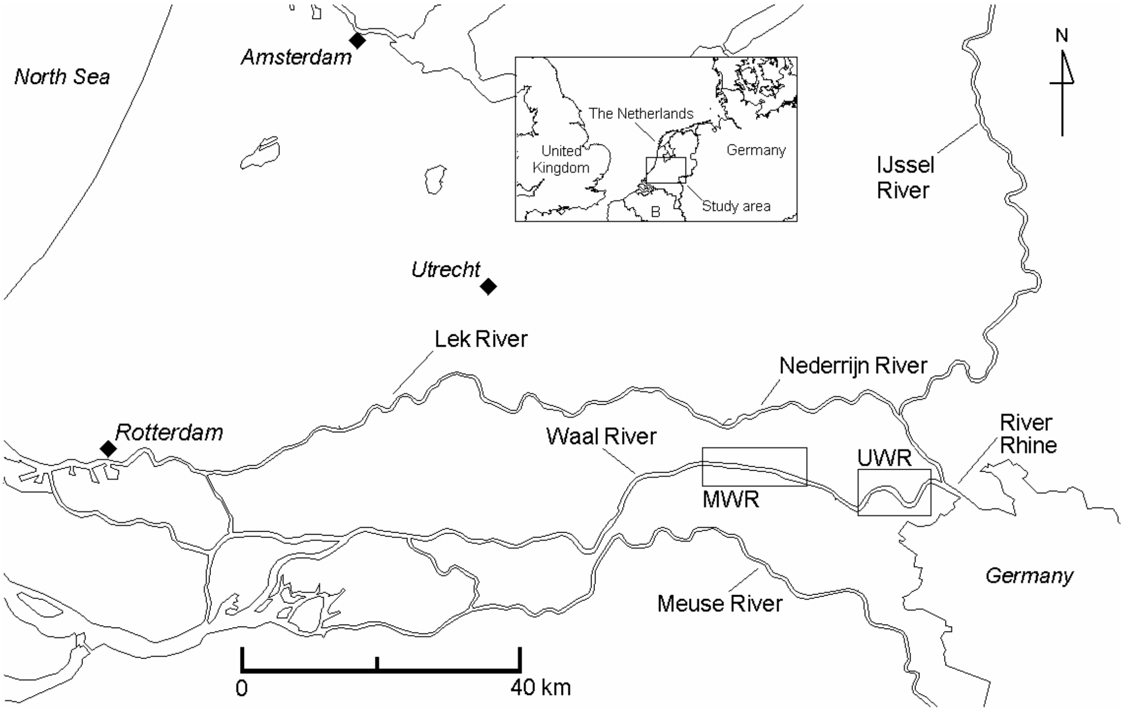

Fig. 1 Location of the studied river reaches.

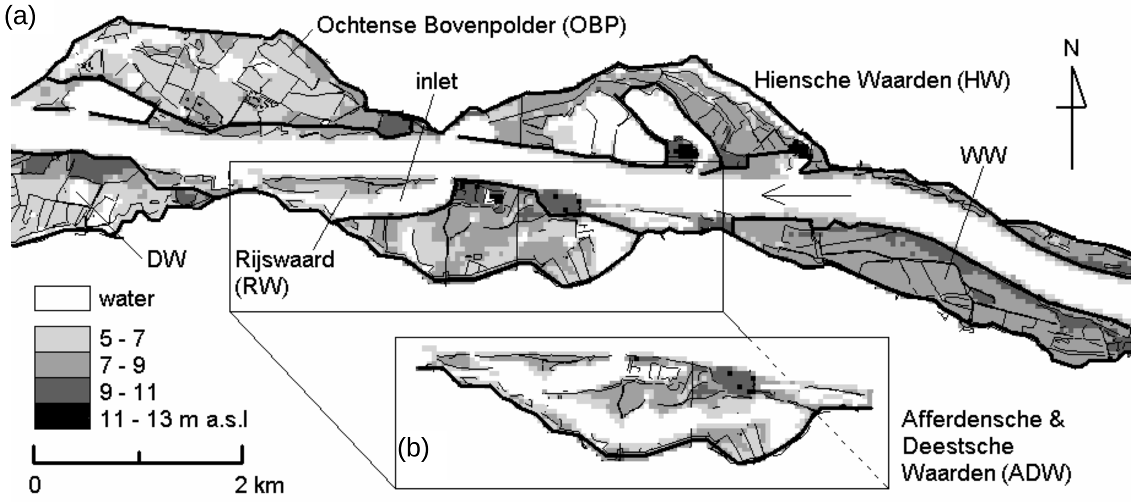

Fig. 2 Present (a) and future (b) layout of the MWR reach. DW = Drutensche Waarden; WW = Winssensche Waarden.

For the calculations of the present and future deposition rates we extended the sediment transfer model of Thonon *et al.* (2004) with a sedimentation (SED) module, hence obtaining the MoCSED model (Thonon *et al.*, 2006). We calculated the spatial pattern of suspended sediment concentrations and sediment deposition for eight discharge classes (representing discharges between 3750 $m^3 s^{-1}$ and 9500 $m^3 s^{-1}$). In the model calculations we used an effective settling velocity $w_{s,e}$ of 6.7 10^{-5} m s^{-1} (Thonon *et al.*, 2005), a critical shear stress for sediment deposition τ_{cr} of 2 Pa

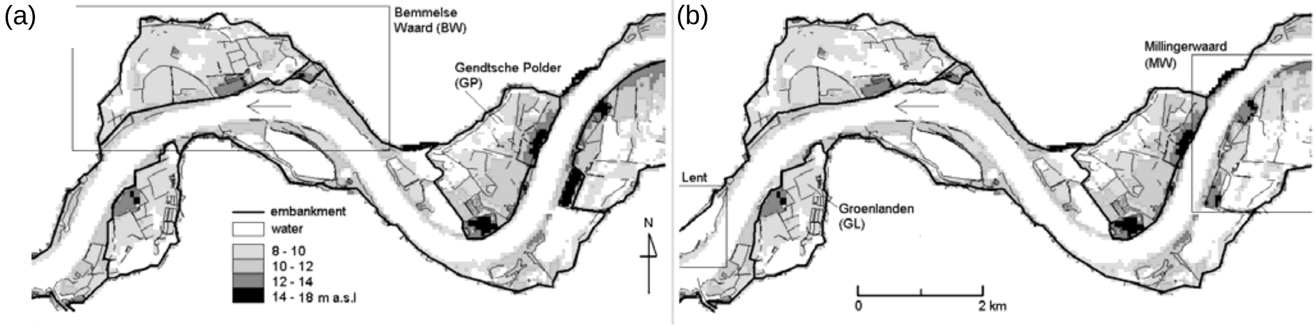

Fig. 3 Present (a) and future (b) layout of the UWR reach.

(Asselman & Van Wijngaarden, 2002). The suspended sediment concentrations (SSC) at the upstream model boundary were derived from sediment rating curves reported by Asselman (2000). We derived the deposition rate using the following equation:

$$D = \left(\sum_{i=1}^{8} w_{s,e} \cdot \left[\left(1 - \tau/\tau_{cr}\right) \cdot C_i \cdot T_i \right] \right) + \left(f_{pond} \cdot h_{pond} \cdot C_{pond} \cdot 10^{-3} \right) \tag{1}$$

where D is sediment deposition rate [kg m^{-2} year^{-1}], τ is flow shear stress [Pa], C_i is SSC derived from MoCSED [mg l^{-1}], T_i is average yearly duration of a discharge class [s year^{-1}], f_{pond} is flooding frequency of flood plain [year^{-1}], h_{pond} is water level at flooding of flood plain [m], C_{pond} is SSC at flood stage [mg L^{-1}], and i denotes a discharge class.

The first part of the right-hand side in equation (1) represents settling of sediment from flowing water. The second part represents settling from ponding. This is the amount of sediment that settles because water is trapped behind a minor embankment. T_i and f_{pond} follow from the frequency distribution of discharges. To derive the heavy-metal deposition rates we multiplied the sediment deposition for each discharge class by the metal concentration according to the metal rating curves in Middelkoop *et al.* (2002). The annual metal deposition rate was the sum of the metal deposition for the eight discharge classes. We obtained the conveyance losses by multiplying the average deposition rates for the two study reaches with the total surface of the Waal River flood plains (87 km^2) and dividing this by the total annual sediment and heavy metal transport through the Waal River.

RESULTS AND DISCUSSION

Figure 4(a) gives the average sediment and zinc deposition rates for the total Waal River branch for each scenario. Because the sediment and heavy-metal deposition rates are strongly correlated, we have left the results for the other heavy metals out. The current deposition rates are 1.5 kg m^{-2} year^{-1} sediment, 0.5 g m^{-2} year^{-1} Zn, 0.09 g m^{-2} year^{-1} Pb, 0.08 g m^{-2} year^{-1} Cu and 1.5 10^{-3} g m^{-2} year^{-1} Cd. These figures correspond to calculations with the more straightforward Silt-1D model by Asselman & Van Wijngaarden (2002), who found a sedimentation rate of 1.7 kg m^{-2} year^{-1} for the total lower River Rhine. Recalculated to conveyance losses, this means that nearly 7% of

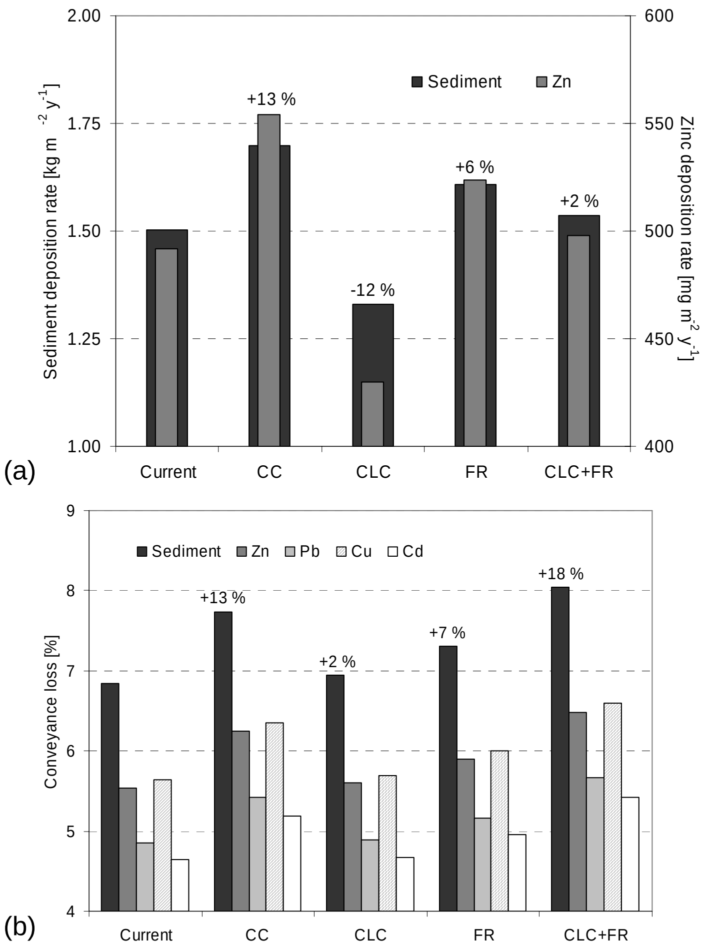

Fig. 4 Sediment and zinc deposition rates (a), and sediment and metal conveyance losses (b), for the Waal River branch according to the current situation and the different scenarios.

the annual sediment transport is sequestered by the flood plains (Fig. 4(b)). The conveyance losses for heavy metals (4–6%; Fig. 4(b)) are lower than for sediment. This is due to the fact that with increasing discharge, on average, suspended sediment concentrations increase (Asselman, 2000) but heavy metal concentrations in suspended sediment decrease (Salomons & Förstner, 1984; Middelkoop *et al.*, 2002).

In general, overbank deposition rates increase under the applied scenarios. The largest increase in overbank deposition rates takes place under the CC scenario: +13% (Fig. 4(a)). This is primarily due to more frequent and longer inundations of the flood plains, which result in increased average annual deposition rates of sediment (see Asselman, 1999; Narinesingh *et al.*, 2000) and heavy metals (see Dennis *et al.*, 2003). Only under the CLC scenario did the deposition rates decline, by 12%. This means that the impact of reduced soil erosion is greater than the impact of increased flooding frequency and duration. Local flood plain rehabilitation measures have a smaller albeit positive impact on the deposition rates (+6%) than the upstream changes. When the combined effect of all changes on the deposition rates (+2%) is considered, the local and upstream changes appear to almost cancel out each other's impact (Fig. 4(a)).

The conveyance losses provide a different picture to the deposition rates (Fig. 4(b)). Here, the combined effect of all the changes gives the largest increase in conveyance losses of all the scenarios considered: 18%. Despite the decreased sediment and metal conveyance, the increase in flood frequency and duration leads to an increase in conveyance losses. The CLC scenario, on the contrary, seems to result in a negligible change in conveyance losses (+2%). In this case the decrease in deposition rates almost equals the decrease in sediment transport.

CONCLUSIONS

The increase in inundation frequency and duration of the lower River Rhine flood plains due to climate change leads to an average increase of overbank deposition of sediment and associated heavy metals by 13%, whereas land-use changes in the upstream catchment lead to a decrease of deposition rates at the scale of the river branch. The combined effect of these upstream changes is a reduction of overbank deposition rates by 12%. Local changes in topography due to flood plain rehabilitation measures cause an increase in deposition by 6%. This causes the impact of local and upstream changes together on average flood plain deposition rates to be very small. It is remarkable that the conveyance losses are nevertheless most sensitive for this combination of changes in climate, upstream land use and flood plain topography and show an increase of almost 20%. This demonstrates that although the combined changes in climate, land use, and flood plain topography may barely cause changes in average absolute deposition rates of sediment and heavy metals, they may considerably increase the importance of flood plains for the budget of sediments and associated contaminants in river basins.

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