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CONCEPTS OF DYNAMIC EQUILIBRIUM OF INTEREST FOR RIVER MANAGEMENT IN THE LOWER MAAS CATCHMENT

JEF VANDENBERGHE*, GEMMA VENHUIZEN**, JOS DE MOOR***
* VU University, Institute of Earth Sciences, De Boelelaan 1085,
1081 HV Amsterdam, The Netherlands
E-mail: jef.vandenberghe@falw.vu.nl
** Nova Zemblastraat 23M, 1013 RJ Amsterdam, The Netherlands
*** EARTH Integrated Archaeology, Basicweg 19, 3821 BR Amersfoort, The Netherlands

Abstract: This paper discusses the interaction between climate change, land use, water management and internal evolution within a river catchment, applied to the Maas River catchment. It is based on the results of a project carried out as part of the Dutch research programme “Climate Changes Spatial Planning”, theme “Climate Scenarios”. These results were obtained by a combination of proxy reconstructions and by numerical modelling of past, present-day and near-future climate and river evolution. Since external factors like climate change and human impact influence the river system in such a way that they will have severe consequences for society, economy and public health, understanding of the cause-and-effect relations within a river basin appears to be of utmost importance. Therefore, a background framework for accurate water management strategies, based on the intrinsic factors and external driving factors (climate, human impact) influencing the Maas River, has been developed. Together with the simulations, which give a good overview of the trends in precipitation and discharge between 4000–3000 BP and 1000–2000 AD (as well as an outlook to the 21st century), the proxies help to gain insight into the long-term changes in climate and hydrology in the Maas River basin. It appears that the principles of the dynamic equilibrium in a river system provide most useful guidelines for such a background. From the reconstructed river evolution it is illustrated what kind of effects may be expected from each natural or anthropogenic distortion of that equilibrium for flood risks, changes in river course and morphology, and fluvial transport capacity. It is concluded that river management, including compliance with the recent European directives for maintenance of natural heritage of river systems, should find a balance between providing the possibility to the river to maintain a dynamic equilibrium, based on its reconstructed historical river behaviour, and necessary measures as directed by practical social and economic needs.

Key words: dynamic equilibrium, river management, climate change, water management, human impact, flooding, Maas River, Geul River, The Netherlands

INTRODUCTION

During the past decades it has been a common situation to see rivers flooding, sometimes dramatically, and often unexpected. This was the case for the Maas River in The Netherlands during the winters of 1993–94 and 1994–95. In January 2011, flooding of the Maas and its tributaries was also imminent, although with less vigor, especially in the Belgian Ardennes. Such flooding events are also relatively common in the lower

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reaches of other catchments in NW and central Europe, as for instance in the Rhine, Elbe and Oder-Nysa river catchments (Glaser and Hagedorn, 1990; Fink et al., 1996; Zielinski, 2003). Apart from distress across the local population, the financial damage rose up to several millions of euro in either case. For instance, the flooding of the Maas River during the winter 1993–1994 caused a financial damage to houses, factories and infrastructure of more than 100 million euro (Ward et al., 2008a). The loss of land as a cause of erosion is more local and might appear less spectacular. However, during that same flood disaster of 1993–94 erosion gullies of several metres deep and

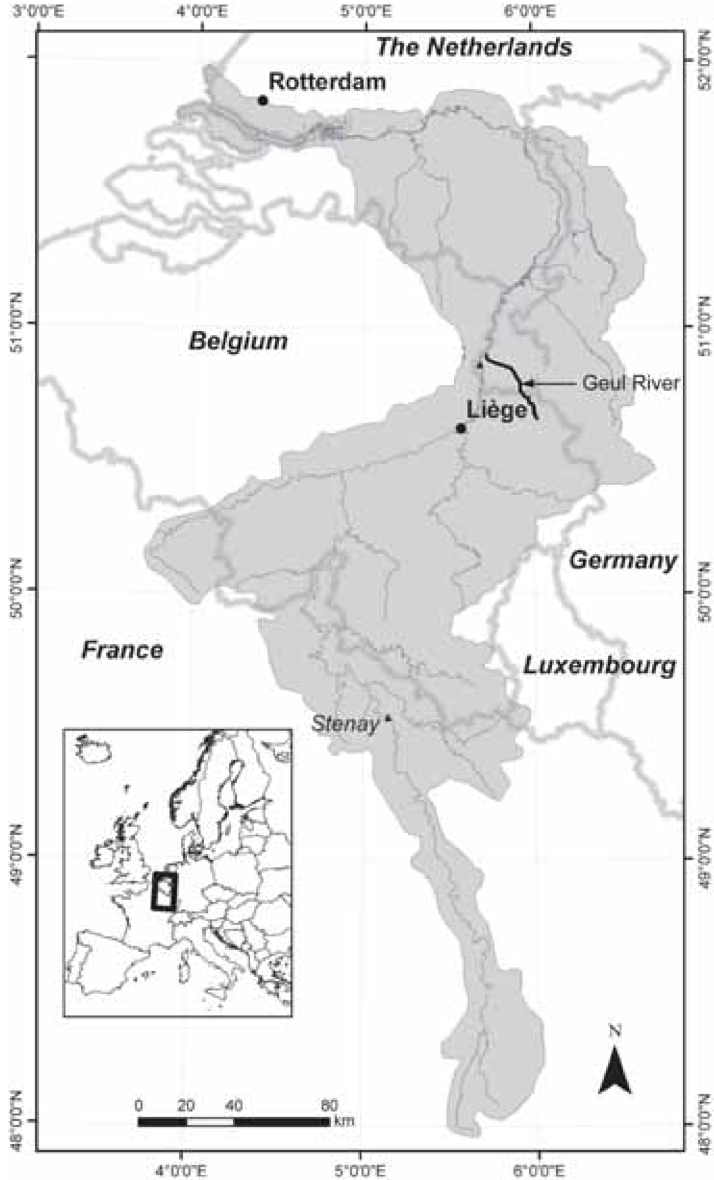

Figure1. Location map of the Maas and Geul river catchments (modified after Ward, 2009).

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a few tens of metres wide, were cut into the Holocene floodplain. Even less spectacular is the continuous lateral erosion by meander migration, especially in highly sinuous meander bends, for instance up to 2myear^{-1} in the Geul River as measured over tens of years (De Moor, 2006). Besides the loss of valuable soil, the removed sediment causes downstream obstruction of the channel. River basins may be drinking water reservoirs, on condition of good quality of soil and water. In regions with intensive rural activities the soil quality is often under pressure. The concentration of heavy metals, pesticides or nutrients may increase by soil erosion to values that are too high for drinking water consumption (Leenaers, 1989; Swennen et al., 1994; Wolfert, 2001).

Factors of different origin and magnitude may be considered to drive or enforce such flooding actions in the river system. They may be the expression of external forcing (people's activity, climate conditions, tectonic movements) or may simply be induced by internal evolution within the river system without interference from the outside. In addition, it should be kept in mind that rivers do not always respond immediately to all external forces, and the delay of their reaction may have substantial influences in the fluvial morphology (Gregory and Walling, 1973; Schumm, 1977; Vandenberghe, 1995).

Laws that govern the response of rivers to external and internal forcing are not new in fluvial geomorphology (e.g., Starkel, 1990, 2003). However, they are often not considered in river management. In this perspective, it is our objective to provide in this paper a framework for a better understanding of frequency and magnitude of flooding, and thus help in river management. As a case study, we deal with the lower Maas River valley and one of its main tributaries in The Netherlands, the Geul River (Stam, 2002; De Moor, 2006; for location see Fig. 1).

We focus on the impact of people's activities in the floodplains and their modifications of the river system. Therefore, the discussion is limited to relatively short time scales (decades, centennials). The ideas reported here result from a project that was carried out within the Dutch research programme "Climate Changes Spatial Planning" (<www.climateresearchnetherlands.nl>). In this project, the evolution of the Maas River as a response to climate change and human interference in the past four millennia was reconstructed. The outcome provides a framework for estimating (predicting) the effects of potential future changes of climate and human works in the river system. The project results are expressed in three PhD- theses at the VU University Amsterdam (Ward 2009; Versteegh 2009; Brader, in prep.), and for specific results we refer to these works and related publications. In addition, our results make also use of the advices of the European Water Framework Directive (EC, 2000).

Since our objective here is to provide a general framework, river responses are estimated qualitatively and expressed, for instance, in terms of increased or decreased river discharge, sediment deposition, flooding frequency, etc.

THE TEMPORAL SCALE

It appears that the nature and magnitude of river response to external forcing and the relative dominance of the involved processes within the river system depend on the concerned temporal scale (Vandenberghe, 1995). Obviously, this scale factor cannot be neglected in understanding river behaviour.

THE LONG-TERM SCALE

On a geological time scale, the evolution of river systems may be directed by natural extrinsic forces, such as tectonic movements, orbital climatic changes and base level fluctuations. Given the long-term scale, at which these forces normally interact with fluvial system evolution, in contrast with the temporal constraints imposed by forecasting at relatively short term, we do not deal with those forcing factors here. Even the faulting that occurred at the end of the last glacial in the southern Netherlands played only a rela-

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tively marginal role in shaping the Maas River valley in comparison with the present-day changes (Huisink, 1998b).

In this respect, the climatic change at the last glacial-interglacial transition was much more significant to the Maas River system (Huisink, 1998a; Kasse et al., 1995; Vandenberghe et al., 1994). It is an illustration of the general phenomenon of increased river activity at climatic transitions, in contrast to relative river stability in periods of uniform climatic conditions, especially induced by delayed response of the vegetation development to climate change (Starkel, 2003; Vandenberghe, 1995). However, climate changes as the ones that occurred at the Lateglacial- Holocene transition are not expected in the near future and are not of any significance either for our rivers.

THE SHORT-TERM SCALE

Steering of the fluvial system at decadal-to-centennial scale may be induced by relatively short-term climate changes at sub-orbital scale and human activity. However, even without such external forcing, rivers are not stationary at the same scale and are characterized by their own, independent (intrinsic or internal) evolution (Schumm, 1977).

SHORT-TERM EXTERNAL AND INTERNAL FORCING OF CHANGES IN THE RIVER SYSTEM

CLIMATE

To separate the effects of present-day human interventions from short-term climate fluctuations, we studied the evolution of the Maas River system from a period just before substantial human influence on river behaviour until the present time. Initial agrarian activity, accompanied with deforestation, started in the southern Netherlands around 3,000 years ago (Bunnik, 1999; De Moor et al., 2008). Before that time, Holocene landscape evolution and vegetation development were influenced by internal evolution and only to a minor extent by human activities and climatic fluctuations (e.g., Starkel, 1985; Hoffmann et al., 2010; Notebaert and Verstraeten, 2010).

However, it is not excluded that the magnitude of present-day global warming may have an impact on the river system that is unprecedented in Holocene times. In general, increase in temperature will lead to enhanced evaporation and thus lower runoff. The effect of predicted higher frequency and intensity of precipitation may be much higher. Extremes in precipitation amount may invoke increased probability of flooding and erosion. Such phases of extreme precipitation were more frequent already during the 20th century and will further increase according to model prediction (IPCC, 2007; Ward et al., 2008a, b).

INTRINSIC RIVER EVOLUTION

Holocene lowland rivers in tectonically stable regions, as in northwest and central Europe, may be considered to be near to equilibrium. In general, they appear to follow the principles of 'dynamic equilibrium' (Schumm, 1977). This means that changes in external conditions are internally compensated for by adaptation of the channel processes and energy conditions, which are expressed by the modification of channel dimensions and patterns. Rivers in dynamic equilibrium tend to keep balance between river's transport capacity and sediment transport (e.g., Lane, 1955). For instance, increased (decreased) sediment supply will need a steeper (weaker) river gradient to provide the precise quantity of required energy, or higher (smaller) discharges will invoke erosion (sediment accumulation) as they are the expression of superfluous (insufficient) energy. Erkens et al. (2009) demonstrated the importance of intrinsic evolution in the Rhine River valley during the Holocene, expressed by the formation of a terrace series.

HUMAN INTERFERENCE BY LAND USE CHANGE

Effects of river behaviour on population are obvious, but also men's influence on fluvial processes and morphology is clear. Until today people influence the river system indirectly by changes in land use. Since roughly

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1000 years ago, however, people have been interfering also more directly in the river management. Indirect influences on the catchment level, as land use, or direct interventions in the rivers, such as construction of ditches, have their specific effects on the fluvial landscape (e.g., Houben et al., 2006; Ward et al., 2008b; Vandenberghe et al., 2011). Soils may be eroded, land surfaces polluted and the ecology modified when water and sediment invade the floodplain. It is well known that forest growth induces lowered discharge due to higher evapotranspiration, and lower soil erosion due to increased soil infiltration capacity (e.g., Brown and Quine, 1999; Macklin and Lewin, 1989; Meybeck, 2003). In addition, pasture land provides a good protection against soil erosion. Eroded slope sediment may be stored along the slope, within the main channel and on the floodplain, or may be transported further downstream depending on the ratio between sediment supply and transport capacity (Rommens et al., 2006; De Moor and Verstraeten, 2008; Notebaert et al., 2009). Otherwise, a vegetation cover on the floodplain favours the deposition of sediment after flooding events (Verstraeten et al., 2006; De Moor and Verstraeten, 2008).

Before 4000 years ago, the Maas River catchment was fully forested. Large-scale deforestation took place especially between 1000 and 1800 AD and large areas of pasture or crop land were established. As a result, evapotranspiration decreased, leading to increased river discharges and flood frequencies (Ward et al., 2008a). In addition, slope erosion increased considerably (e.g., until 40 times in the Geul River catchment during the Middle Ages in comparison with the more natural conditions in the preceding period; cf. De Moor and Verstraeten, 2008). Around 1900, reforestation took place in the same catchment, and thus water and sediment discharges decreased also. In contrast, urbanization, in combination with a slight increase in precipitation, is held responsible for increased water discharge and sediment supply in the 20th century as evidenced by Stam (2002) and De Moor (2006).

Short-term effects of land-use changes on river activity, and especially the amount of eroded soil, are complex and cannot be defined only by the exact nature of those land-use changes but also their areal extent and local factors, such as relief, sensitivity of the soil for rain erosion, and the type of land use have to be considered. For instance, the transition from forest to crop land causes a much larger effect than the transition from forest to pasture (De Moor and Verstraeten, 2008). A complete transition from forest to crop land may lead to considerably decreased evapotranspiration and thus a higher water table. In contrast, the effect of the partial reforestation during the 19–20th centuries was relatively small in comparison with the effects of the increased precipitation (Stam, 2002; Ward et al., 2008c). Similarly, potential changes in land use during the 21st century will probably be of minor importance in comparison with the expected climate change as appears from model simulations. More particularly, it is expected that the present-day relative distribution of forest/ cropland/ urban land of 35/55/10 will remain at a rather constant level due to reasons of conservation of cultural heritance and the economical value of the agricultural land (Ward et al., 2008b).

It is also well known that urbanization may provoke accelerated and increased water runoff as a consequence of lower absorption capacity of the soils and lowered evapotranspiration. However, paved surfaces will lead to decreased soil erosion and thus sediment supply to the rivers. In urban areas, drainage of rain water should be well controlled. Rapid drainage would lead to excessive discharges and flooding and/or erosion and only a downstream movement of the problem (see examples, for instance, in Gregory and Walling, 1973 and Embleton et al., 1978)

Land use, as a main exponent of land-surface characteristics, is theoretically the principal external forcing factor of river behaviour at the very short time scale (Notebaert and Verstraeten, 2010; Houben et al., 2006). Starting from the forecasted

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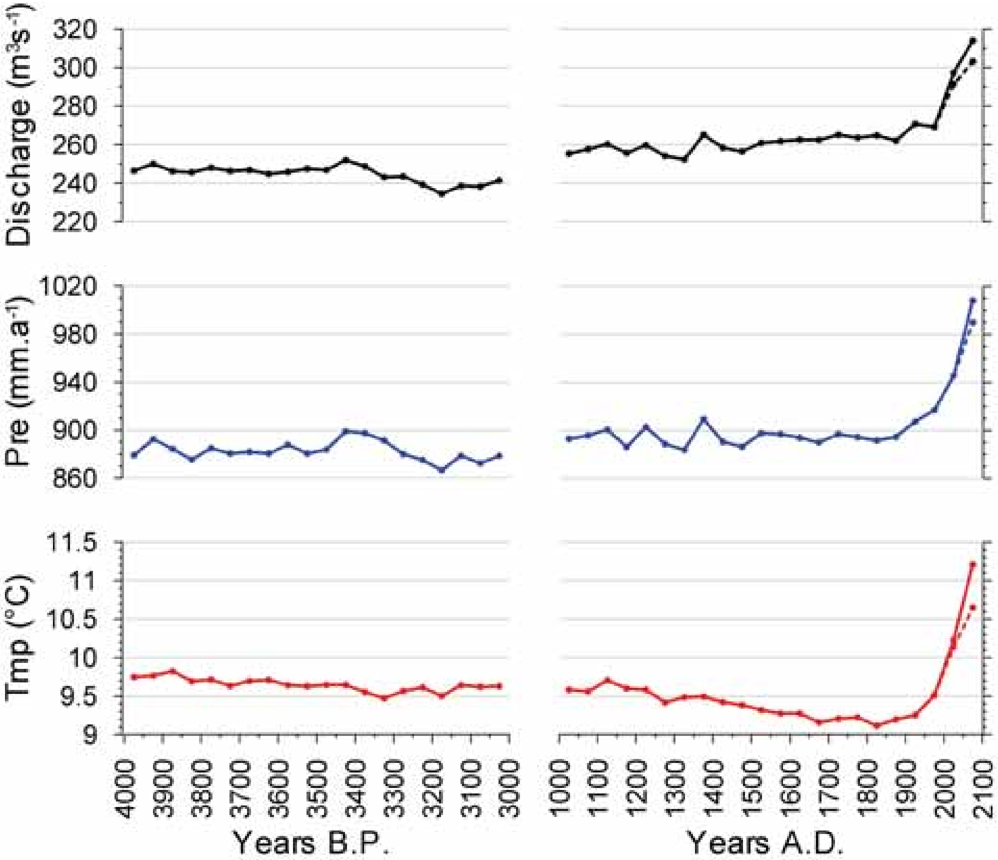

Figure2. Long-term changes in mean annual discharge at Borgharen (5 km downstream of Maastricht), basin averaged precipitation (pre) and basin averaged temperature (tmp). For the 21st century, the upper line represents scenario A2, the lower one scenario B1 (from Ward, 2009; Ward et al., 2011; with permission).

climate and expected land use in the 21st century, Ward et al. (2008b,c, 2011) predict by modelling experiments a significant increase in discharge due to both increased precipitation and changed land use for the near future. In addition, they predict that land-use changes may also have a substantial impact on sediment supply to the rivers. Therefore, it is important to consider the potentially significant efficacy of land-use planning as a tool to mitigate local effects of soil erosion and sediment delivery to rivers (Fig. 2). In addition, the effect of land cover will probably be enhanced by the forecasted increase in extreme climate events (peaked precipitation events with subsequent flooding).

HUMAN INTERFERENCE BY RIVER MANAGEMENT

River management has become an important steering factor in determining river activity since relatively recent times only. The first ditches were constructed in the Middle Ages, while large-scaled projects to protect against flooding only date from the past tens of years. Intentionally, their effects on river processes should play at short term. The applied measures are rather diverse: some of them attempt to reinforce the river bed and

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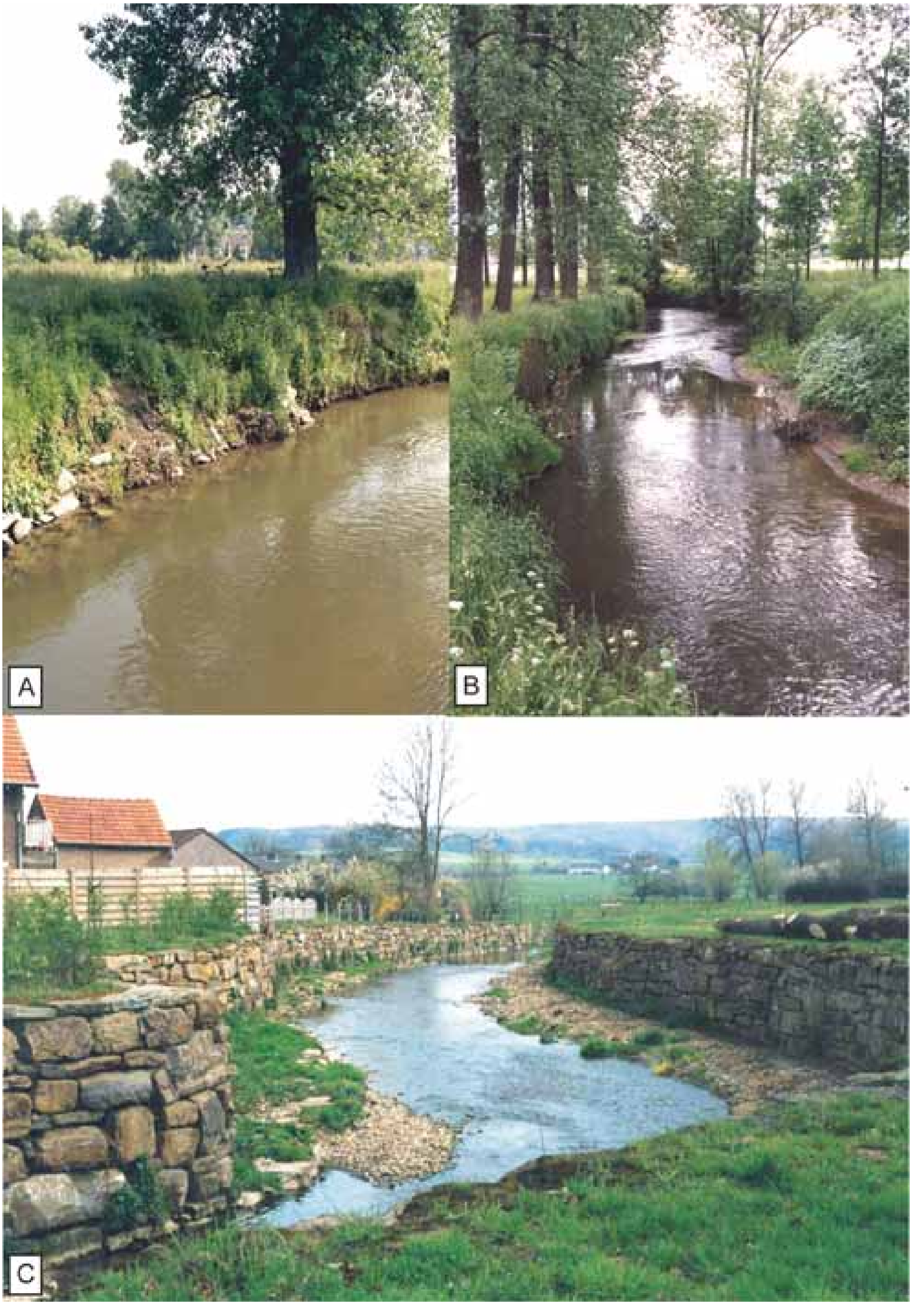

Figure3. Erosion reducing measures along the Geul River: bank toe protection using large boulders (a); planted poplar trees on the river bank in order to stabilise the bank (b); artificial walls replacing natural river banks to protect properties (c) (De Moor, 2006).

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thus counteract erosion, while others attempt to avoid a too high groundwater table and prevent flooding.

Several types of intervention that strive to decrease bank failure and general erosion were distinguished by De Moor et al. (2006) and papers referenced therein: bank stabilization, bank toe protection, channel straightening and flow retardation constructions (Fig. 3). Bank stabilization can consist of natural measures (e.g., tree plantation or riparian vegetation on the levees of the river) or artificial ones as the replacement of natural banks by stone or concrete walls. Trees remain vulnerable, protect only limited spots and may cause flow diversion. Artificial measures are more effective but visually less attractive and more expensive. They are applied preferentially at places where valuable buildings or infrastructure have to be protected. Bank toe protection measures may consist of wooden wattle structures, and boulders and/or concrete rubble placed at the foot of the river banks. They are not always successful in preventing erosion because discharge is variable. Wooden wattle structures are mainly used where the chance of severe erosion is not very high. Sometimes, wooden wattle structures lose their function when the banks behind the structures are eroded. Boulders and concrete rubble are much more common and successful. All these measures have different costs and provide different degrees of bank stability.

Straightening of rivers may have different reasons: lowering of the groundwater table or facilitation of ship navigation. A consequence of straightening is that the river stretch is shortened and subsequently the river gradient and flow velocity increase, in turn influencing the suspended sediment load (e.g., Nakamura et al., 1997).

Flood prevention measures consist of the construction of dikes, the creation of water retention basins and side channels, and the modification of the river bed (deepening or widening). Dutch regulations stipulate that flood recurrence is allowed to be once in 1250 year for the embanked floodplains and once in 250 years for the unembanked areas. This discharge of the Maas River may attain 3,800 m^3s^{-1} between the present dikes. According to model simulations for the 21st century (Ward et al., 2008b), a peak discharge with recurrence time of 1250 years is estimated at 4,137 m^3s^{-1}.

MANAGEMENT MEASURES AND THEIR EFFECTS IN A RIVER AT DYNAMIC EQUILIBRIUM

It seems likely that, apart from technical interventions in the drainage process, the *frequency of extremes* in discharge regimes and imbalances in the sedimentation/erosion rate may only be reduced to some extent by intervention in the land use. Its potential effects are described above. Measures to adapt to the *effects* of undesired discharge extremes and disturbances of the sedimentation/erosion budget may be more at hand. In that respect, it has to be stressed that natural floodplains are characterized by a morphology that is adapted to natural, changing discharges while keeping the equilibrium between sedimentation and erosion in a dynamic way and at the long term (Starkel, 1990).

Illustrative examples of such morphology are the occurrence of large backswamps and a number of secondary distributary channels. They may provide helpful inspiration for artificial constructions within the floodplain to regulate to some extent (extremes of) river activity, for instance by the creation of retention basins and side channels. Modelling of such scenarios will certainly contribute to quantify their respective effects (De Moor et al., 2007; Notebaert et al., 2011; Ward et al., 2008a). At the time of completion of this paper, results became available from a risk analysis by hydrological modelling for the river Rhine as a result of predicted global warming (te Linde, 2011). In general, artificial adaptation strategies are rather complex since river management may have conflicting consequences, especially

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with respect to the different functions of rivers and their valleys.

Ditches are the most obvious protection against flooding. Concerning sediment transport ditches may have a double effect. They keep all sediment within the channel (Lemin et al., 1987) and prevent sediment accretion on the floodplain On the other hand, ditches stop the supply of local sediment from the hillslopes to the river. These complex effects can only be evaluated by modelling and field measurements. Dikes at relatively large distance from the channel should mimic the most natural situation, but their impact would be less while maintenance costs would increase.

For large rivers, there are obvious reasons for *regulating the river course* due to the functionality as transport route of these rivers. For small rivers, straightening has often been applied for rapid drainage of the agricultural fields. In addition, lateral river erosion should be avoided, for instance for the protection of buildings and infra-structure or farm land (De Moor, 2006). In the case of *bed stabilization*, however, it should be kept in mind that according to the laws of dynamic equilibrium, as explained above, the natural sediment balance of the river will be distorted, depending on the grain-size of the supplied sediment (Dade et al., 2011). It means that aggradation of the river should not be prohibited as a compensation for sediment removal. In natural conditions, this aggradation takes place on the floodplain at times of flooding. If natural flooding is artificially reduced, downstream in-channel sediment deposition may be a consequence which should lead to extra costs of dredging that sediment.

The *shortening of the river course* obviously causes the steepening of the longitudinal gradient of the river, resulting in a distorted dynamic equilibrium (Schumm, 1977). The consequent extra stream power may be used for lateral bank erosion, incision or meandering within the river bed (e.g., Gregory and Walling, 1973). These are undesired effects in populated areas, which will require compensating measures of bed or bank protection or reducing stream power (for instance flow velocity retardation by dam constructions), thereby reducing bank erosion. The main disadvantages of these measures are that the river system cannot adapt adequately to high and low extremes of discharges and sediment transport is hindered (Parker and Andres, 1976; Brookes, 1988). The retention of sediment behind dams may provoke downstream channel erosion. In addition, retardation measures may provoke sedimentation at (extremely) low discharges. Therefore, it is often observed that straightened rivers tend to find back their naturally meandering course by lateral migration, and thus re-establishing their dynamic equilibrium (Parker and Andres, 1976).

Widening or deepening of the river channel may certainly be effective in preventing against flooding at high discharges, but will certainly give problems at low stage. More particularly, channel transect enlargement may obviously lead to decreased sediment transport capacity and thus sedimentation in the river bed at low discharges.

Moreover, a complete stop of flooding also has its consequences for the *natural ecology and morphological environment* of valley plains. The above described problems and the fact that naturally meandering rivers have more diverse flora and fauna and a higher aesthetic value, have in recent decades led to the restoration of many originally meandering rivers (e.g., Brookes and Shields, 1996; Wolfert, 2001). The reasons for a change in management policy towards restoration of mainly small rivers were the need for water retention and the recognition of the value of unique valley landscapes. Water retention was necessary because of flooding downstream. Water management and nature conservation should be combined according to the European Water Framework Directive (EC, 2000). Implementation of water management according to this European Directive will conserve or increase the ecological value of the area and also significantly contribute to reducing flood risk, as the flood retention capacity will increase.

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These principles were applied recently in the Geul River catchment where nature conservation is a main aim of the local water board. Practically, the sinuosity of the Geul River has been restored in an indirect way: bank stabilization and protection were removed and the Geul was allowed to meander freely. Evidently, lateral river erosion must be prevented at some places by bank reinforcement as indicated above. However, such costly measures may counteract the aesthetic value and biotic and abiotic attractiveness of a rural landscape with high touristic potential, as for instance this catchment. Once natural processes are operating, a geomorphologically more diverse river is developed with higher ecological value with higher biodiversity (De Moor, 2006). Although several stretches of the Geul River remain heavily modified, other stretches now show natural meandering processes that fulfil the requirements of the European Water Framework Directive (EC, 2000). Another example concerns the middle Ebro River in Spain where Ollero (2010) proposes the creation of a 'fluvial territory', a 'non-defended space in which the river can overflow and its course can have mobility' (Ollero, 2010).

SYNTHESIS AND CONCLUSIONS

The numerous and different functions of a river and its valley plain lead to different expectations and measures to comply with. As a consequence, the desired or required measures may sometimes be conflicting. Natural flooding will enable erosion at high stage and deposition at low stage, resulting in maintaining the dynamic equilibrium (Schumm, 1977; Brookes, 1988). However, social and economic functions require, at least locally, course fixation and regulation, protection against floods, and bank protection. It is clear that compromises have to be found. An integrated approach is required (Verstraeten et al., 2002; Van Rompaey et al., 2003; Ward et al., 2008c; Notebaert et al., 2011). It is shown here that prior to management decisions the river processes should be understood. The palaeohydrologic evolution is shown to be capable of providing important and relevant information to river managers in general (Starkel, 1993, 2004; Sear and Arnell, 2006) and specifically in the Maas River catchment (Ward, 2008a; Vandenberghe et al., 2011). In this respect, the principles of dynamic equilibrium provide a reliable framework in combination with numerical modelling. In practice, the effects of changing land-use and climate or different management measures should be conceptualized in specific scenarios and subsequently be quantified by appropriate modelling.

To conclude, all management measures involve distortion of the dynamic equilibrium. In a certain way, the river will always counteract such distortions. However, where management is required best results will be obtained when they mimic natural fluvial environments as much as possible. It is striking that also te Linde (2011, p. 149) came to the conclusion for the Rhine River that the reduction of flood probabilities should not only be addressed by flood protection measures, but also by adaptation options.

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