Geomorphological Change and River Rehabilitation

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Geomorphological Change and River Rehabilitation

Case Studies on Lowland Fluvial Systems in the Netherlands

H.P. Wolfert

ALTERRA SCIENTIFIC CONTRIBUTIONS 6

ALTERRA GREEN WORLD RESEARCH, WAGENINGEN

2001

This volume was also published as a PhD Thesis of Utrecht University

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Financial support for this thesis was given by The Ministry of Agriculture, Nature Management and Fisheries and by the Institute for Inland Water Management and Waste Water Treatment RIZA.

ISBN 90-327-0311-0

Abstract

Wolfert, H.P., 2001. Geomorphological Change and River Rehabilitation: Case Studies on Lowland Fluvial Systems in the Netherlands. Alterra Scientific Contributions 6, Alterra Green World Research, Wageningen (the Netherlands). 200 pp.

Integrated spatial planning for river rehabilitation requires insight in the geomorphology of river systems. Procedures are elaborated to implement a functional-geographical approach in geomorphology, in which a view of rivers as four-dimensional systems and the use of a process-based hierarchy of spatio-temporal domains is coupled to methods of land evaluation. Geomorphological mapping and map interpretation are important research techniques. Application is exemplified in case studies on lowland streams and rivers in the Netherlands, in which reference situations, process conditions to be fulfilled, suitability of areas and layout of measures are addressed. The natural developments of bedforms in the meandering sand-bed Keersop stream are strongly influenced by seasonal variations in discharge and aquatic macrophyte cover. Differences in the short-term recovery of the Tongelreep, Keersop and Aa streams to meander rehabilitation are caused by differences in bank material composition, but were also influenced through the design of cross-sectional dimensions and bend curvature. Riverine pastures along the small meandering River Dinkel depend on natural levee overbank deposition and in the long term on meander cutoffs, implicating conservation strategies must be based on geomorphological disturbance processes. Analysis of historical migration rates allowed areas suitable for re-meandering along the small River Vecht to be indicated, on the basis of the spatial variability of bank material resistance to erosion. In the embanked River Rhine depositional zone, four types of fluvial styles occurred before channelisation; landform development was related to the channel width–depht ratio values and the flow velocity over the floodplain. Insights in the Rhine river reach continuum could be incorporated in a cyclical planning procedure, characterised by phases of plan design and plan evaluation, at two different scale levels. Finally, similarities and differences between these case studies are set in a wider perspective and recommendations for river rehabilitation are discussed.

ADDITIONAL INDEX WORDS
Bedform configuration, Channel migration, Fluvial sediments, Historical maps, Meandering, River ecology, Spatial planning.

Cover photographs by P. Paris

Preface and acknowledgements

This thesis is about geomorphological research for river rehabilitation purposes. My involvement in this work started with a memorable trip to the UK in November 1990, where I visited Ken Gregory, Andrew Brookes, Colin Thorne and Geoff Petts. During these visits I not only learned about the methods and perspectives of this type of research but also became infected with their enthusiasm.

Since then many projects have been undertaken on small and large river systems and more recently on tidal rivers. As contract research, these probably would have been classified as applied geomorphology by university geomorphologists and as strategic research by those working for consulting agencies. Whatever it is called, to me, these studies are a very inspiring branch of science. Appealing aspects are the direct communication with stakeholders and the involvement of scientists from other disciplines. These types of cooperation often trigger original and challenging ideas worth examining in the research project at stake or valuable to the formulation of new, future studies. Besides, contract research guarantees a quick dissemination of results among those involved.

However, there are also some disadvantages. Study results are published in reports, which are written in the Dutch language. This hampers communication with colleagues abroad and the involvement in transboundary or international projects. Moreover, the scientific novelties do not reach the audience they deserve. Therefore, I am very grateful that the opportunity arose to combine some of my geomorphological work on river rehabilitation planning into a thesis, of which the central chapters would be submitted to scientific magazines. Writing this thesis provided the opportunity to work out details as well as to place the various studies in a broader context.

As usual in scientific studies, the cooperation of many individuals was indispensable. I would like to thank the following people:

- Promotor Ward Koster, for guidance on this project and careful comments throughout the text;
- Co-promotor Jan Klijn, for stimulating this work and continuous interest;
- Gilbert Maas; Arjan Koomen, Margriet Schoor, Hans Middelkoop, Patrick Hommel, Diana Prins and Marleen Stam, for professional cooperation in the projects underlying this thesis and co-authors’ advice;
- Bert Higler, Janrik van den Berg, Colin Thorne, Jef Vandenberghe, Bart Makaske, Hans Middelkoop, Henk Berendsen and Bert Harms, for valuable comments on drafts of one or more chapters;
- Colin Thorne, Bob Bunce and Derek Middleton, for corrections to the English of

drafts or final versions of chapters;
- Martin Jansen and Henk van Ledden, for design of the cover and drawing the excellent figures;
- Co Onderstal and Gilbert Maas for making the coloured maps;
- Mieke Pijfers for the lay-out of the thesis;
- Bert Harms; Kees Hendriks, Eric Marteijn, Wilfried ten Brinke and Peter Smeets, for help with finding funds to carry on with this work;
- Maja Kooistra, for temporarily being head of the Landscape Research Team to enable me to finishing writing this thesis;
- Bart Makaske, Gilbert Maas, Bert Higler, Arjan Koomen, Sabine van Rooij, Jan Klijn, Chantal Kandhai and Monique Smaak, for temporarily taking over some of the other jobs at Alterra;
- Piet Warmerdam, for hospitality, a room and desk at The Nieuwlanden office, where I wrote a large part of this thesis;
- Lia Wolfert, Simon, Roel, Lise, Thomas, Jaap and Hanna, for support and patience at home and asking the most intriguing question of all: *'Papa, wat hebben wij hier nou eigenlijk aan?' (Dad, what is the use of all this to us?)*, which put this work into the right perspective.

The writing of this thesis was financed by:

- the Netherlands Ministry of Agriculture, Nature Management and Fisheries;
- the Institute for Inland Water Management and Waste Water Treatment RIZA

Projects underlying the thesis were commissioned by the Province of Noord-Brabant, the Regge en Dinkel water board, the Department of Public Works and Water Management of the Netherlands Ministry of Transport, Public Works and Water Management, and the Province of Gelderland, and were in some cases co-sponsored by the Ministry of Agriculture, Nature Management and Fisheries or the Institute for Inland Water Management and Waste Water Treatment RIZA.

Henk Wolfert, Wageningen, August 2001

General introduction 1

THE CONTEXT: RIVER REHABILITATION

Rivers and their associated fluvial landforms are among the most universal features of the earth's surface (Strahler, 1975), but they are also highly diverse. Covering the entire continental gradient and occurring in most of the climatic regions of the world (Thornbury, 1969), the fluvial environment may vary from ephemeral headwater valleys carved in mountainous highlands to extensive marshy lowland deltas bordering seas and the oceans. Open to large fluxes of energy, the fluvial system is a physically dynamic environment in which both the channels and the adjacent floodplains continuously adapt to changes in water and sediment discharge over time.

The geomorphological variety in landforms and underlying processes makes natural rivers diverse and dynamic ecosystems (Mitsch and Gosselink, 1993; Petts and Amoros, 1996). The processes of erosion and deposition of clastic material release large amounts of nutrients, supporting a biomass production which is generally higher than that in adjacent areas from the same region. The frequently changing and diverse patterns of landforms and riparian wetlands provide a large diversity of habitats and land–water boundaries and consequently host a great abundance of wildlife. As a result, rivers are particularly important corridors along which many organisms may disperse through the landscape (Forman and Godron, 1986).

For the very same reasons, riverine valleys and deltas are among the most densely populated parts of the world: river systems provide water, fertile alluvial soils, fish for consumption and an easy transport route. Often, however, human involvement has resulted in a drastic modification of the physical structure of river systems, either directly or indirectly as a result of a changed discharge regime. This has led to biologically-degraded ecosystems, especially since the 19th century. Many rivers have been embanked, channelised, dammed and diverted for agricultural land drainage, flood mitigation, navigation, power production or storage of fresh water supplies. Dynesius and Nilsson (1994) calculated that 77% of the total water discharge of the largest river systems in the northern third of the world is strongly or moderately affected by fragmentation of the river channels by dams and water regulation works. Estimates of the percentage of channelised rivers in some of the north-western European countries vary from 74 to 99% for the counties in Denmark (Hansen, 1996) to 12 to 41% for water authority areas in England and Wales (Brookes et al., 1983).

In the 1970s awareness of the adverse effects of channelisation was raised by Keller (1976) and Nunnally and Keller (1979) in the USA. They adopted the 'design with nature' philosophy of McHarg (1969) and advocated using geomorphological processes for maintaining natural bedforms in river channels that had to be improved. The first handbook to further the conservation of wildlife in rivers was published in the UK soon after (Lewis and Williams, 1984) and the effects of river dams and channelisation were identified by Petts (1984) and Brookes (1988), respectively. The physical structure of previously channelised rivers was restored in projects on small streams in Germany (Glitz, 1983) and Denmark (Brookes, 1987). The first time specific goals were considered for the channel and floodplain morphology of a major transboundary river was in the Rhine Action Programme in 1987 (Van Dijk et al., 1995). Many other rehabilitation projects on both small streams and large alluvial rivers have followed. The strategies, the methods involved and, more recently, the results have been documented in several conference proceedings and other documents (International Commission for the Hydrology of the Rhine basin, 1992; Van de Kraats, 1994; Environmental Management Technical Centre, 1994; Brookes and Shields, 1996; Hansen, 1996; Holmes, 1997; Hansen and Madsen, 1998; Nienhuis et al., 1998; Zöckler, 2000; Nijland and Cals, 2001).

Rehabilitating the integrity of river systems requires space for geomorphological processes and associated landforms, which may function as a site or habitat for vegetation and wildlife. Increasing the area allocated to nature, however, may have serious impacts on other relevant functions of river systems, such as navigation, flood control and agriculture. Navigation on large lowland rivers, connecting sea harbours with important inland industrial areas, is vital for many national economies. Removing bank protection structures or re-opening secondary channels may result in deposition and an unacceptably shallow depth of the main channel. Several recent floods in Europe (the River Rhine in 1993 and 1995 and the River Odra in 1997) and in Northern America (the Mississippi River in 1993) have raised awareness once again that the discharge of water and flood control will remain a high priority issue. Enlarged areas vegetated by natural floodplain shrubs and forests will increase the flow resistance of the floodplain and may raise the water stages during high discharge events to unacceptably high levels. Also, there are still many agricultural parts of drainage basins which require appropriate drainage. Re-meandering may slow the flow velocity in streams, increase flooding in stream valleys and cause the water table of the surrounding area to rise. Thus, balancing conflicting interests from various sectors is one of the main challenges of modern, integrated water management.

The solution to many problems can be found in a careful and integrated planning process, in which the various river and land use claims are assigned to the most suitable parts of the river system. Scientists supporting the planning process will generally raise the following four questions where it concerns nature (Klijn and Harms, 1990):

- Are there reference situations for nature rehabilitation?
- What conditions must be fulfilled to realise such situations?
- Which areas are suitable for successful rehabilitation?
- What measures must be included in the spatial layout?

Reference situations are descriptions of past situations or relatively pristine river systems elsewhere, revealing the existence of more natural landscapes and biologically more diverse ecosystems (Ministerie van Landbouw en Visserij, 1989; Bisseling et al., 1994). The inspiration for river rehabilitation is usually derived from such situations. Besides, comparison of reference situations with the river system to be rehabilitated makes it possible to investigate which phenomena and processes have been degrading through time and consequently to identify the direction of change that has to be pursued (Kern, 1994; Pedroli et al., 1996). Process conditions that have to be fulfilled must be identified to set rehabilitation targets that are likely to be sustainable solutions at minimal costs for future management. Comparison with characteristics of the various parts of the river system, allows areas to be selected where these process requirements are met. This forms the basis for the design of measures that will create the new situation, or trigger the required process dynamics.

Answers to the four questions mentioned above should be based on sound knowledge of the disciplines involved, one of which is geomorphology. Although it has become clear since the mid 1980s that river rehabilitation requires improvements in physical site and habitat conditions, the role of geomorphology is only beginning to be addressed (Brookes, 1995a; Boon, 1997). Consequently, many geomorphological aspects of the planning process still require further development.

SCOPE OF THE STUDY: THE FUNCTIONAL-GEOGRAPHICAL APPROACH

In fluvial geomorphology there are basically two approaches to the study of fluvial systems: the functional approach and the realist approach (Richards, 1982). These intuitive attitudes towards reality form the basis for generating data, testing hypotheses and generating theory (Bennett and Chorley, 1978). In the functional approach, characteristics of river systems are viewed as phenomena with recurring and predictable regularities in which form and function can be assumed to be related. Theory derives from empirical scientific methods and aims to provide explanations and allow predictions to be made on the basis of observed regular relationships. The functional approach has its roots in the research of geomorphologists during the 19th and early 20th century, e.g. Davis, and is related to the modern geographical approach in which description and classification over a range of spatio-temporal domains is applied (Petts, 1995). In this study, the approach is called functional-geographical.

Central to the realist approach is the view that real explanation needs to penetrate behind the external appearances of phenomena to identify basic causal mechanisms. Realism usually addresses the smaller spatio-temporal domains of specific processes and relies heavily on the collection of high quality data to assist in the understanding of fluvial processes. Theory is firmly grounded in the general laws of physics and chemistry. Following recent methodological developments in geomorphology and the associated shift from extensive to intensive research design, Richards (1990) proposed that geomorphologists should consider adopting a realist approach. However, development of a realist model of the fluvial system in its entirety has been hampered by the many variables and the complexity of feedback mechanisms (Hickin, 1983).

Besides, such theoretical models may fail to account for the field evidence and the larger spatio-temporal domains (Baker and Twidale, 1991).

Instead, Rhoads and Thorn (1993) have argued that such debates centre around variations in the regulative principles adopted, the type of scientific argument and the characteristics of theory over different spatio-temporal domains. Whereas the realist approach can be associated with studying the steady state, contemporaneous deductive reasoning (i.e. a controlling state of affairs and a law are used to infer the resulting state of affairs), quantification and a large axiomic strength, the functional-geographical approach more often encompasses the study of directional change, retrodictive abduction (i.e. a resulting state of affairs infers a possible cause), and decreasing quantification and increasingly conjectural theory as temporal and spatial scales increase. Therefore, the two approaches can be seen as complementary and are both required in the river rehabilitation planning process. It is to be expected that the functional-geographical approach will be most successful in describing reference situations and selecting suitable areas for rehabilitation, while the realist approach will be most promising for analysis of process conditions. Problem-oriented studies may trigger the necessary cooperation among the different disciplines. A prerequisite to this is that those involved are able to see the advantages and necessity of both approaches. To date, however, the merits of the functional-geographical approach are little known to many hydraulic engineers and aquatic ecologists employed in water management, who are more familiar with applying detailed information on flow and sediment transport processes.

To develop further the applicability of the functional-geographical approach in river rehabilitation, two integrative concepts for studying rivers seem to be very promising. First, based on problem-oriented research activities on Oregon streams, Frissell et al. (1986) articulated a general approach for viewing stream systems in the context of the watershed that surrounds them, and proposed a framework for stream habitat classification. This has been extended by Kern (1994) to larger, alluvial river systems. Second, based on a number of studies on the effects of regulating the River Rhône in France (Bravard et al., 1986; Amoros et al., 1987a; Amoros et al., 1987b), Petts and Amoros (1996) introduced the fluvial hydrosystem concept as an integrative system for identifying ecosystems within the fluvial environment. Typical functional-geographical aspects of both concepts are viewing rivers as four-dimensional systems and the application of a nested hierarchy of spatio-temporal domains. Both systems are integrative as it is assumed that the structure and development of the river communities are largely determined by the structure and dynamics of the physical system. The fact that the various levels of ecosystems in both approaches are defined as distinct land units, makes them very suitable to the river rehabilitation planning process (Verstappen, 1983; Forman and Godron, 1986).

The application of these concepts in the river rehabilitation planning process has, however, received little attention to date. It is the purpose of this study to optimise this application for use in river rehabilitation studies, while emphasising the role of geomorphology.

STUDY AREA:
LOWLAND RIVER SYSTEMS IN THE NETHERLANDS

The research focused on fluvial environments in the Netherlands. The Netherlands is well suited as a study area for two reasons. First, as part of a new strategy for the conservation of nature, stream valleys and river floodplains in the Netherlands have been designated to be part of a National Ecological Network (Ministerie van Landbouw, Natuurbeheer en Visserij, 1990). The main feature of this new strategy is separation of the high-dynamic land use functions of rural areas (agriculture, infrastructure) from low-dynamic land use functions (nature, recreation), and the creation of large areas for both categories so that they can develop independently (De Bruin et al., 1987; Sijmons, 1990). The aim is to create a network of natural areas, that are connected to each other by smaller stepping stones, enabling migration of species. Various rehabilitation projects have been proposed. Within the 29,000 ha of River Rhine floodplains, for instance, the 8000 ha of designated nature at present are to be enlarged by another 8000 ha in 2018. In the definition of targets and selection of suitable areas, river managers exchange ideas with representatives of various public organisations and with scientists from various disciplines. This provides a realistic background for augmenting innovative and interdisciplinary research.

Second, the rivers of the Netherlands are lowland rivers, the geomorphology of which has been investigated mainly by Quaternary geologists and river engineers. It appeared that little knowledge was available to meet the specific demands of water managers in setting up reliable rehabilitation plans. For instance, in the first project designs for re-meandering, the dynamics of lowland streams were overestimated (Wolfert, 1991), and measures to rehabilitate secondary channels along the River Rhine distributaries did not account for the large diversity in landforms in the

Table 1.1.
Summary of characteristics of the three river types in the Netherlands

CHARACTERISTICS	RIVER TYPE		
	Stream	**Small river**	**Large river**
Geology	Intra basinal	Basin fringe	Extra basinal [1]
Geomorphology	Erosion zone; Non alluvial	Transfer zone; Alluvial	Deposition zone [2]; Alluvial-deltaic
Drainage basin (km^2)	< 500	500-10,000	> 10,000
Bankfull discharge (m^3 s^{-1})	< 10	10-200	> 200
Main water functions	Drainage; Nature	Drainage; Water supply; Nature	Water supply; Flood control; Navigation; Nature
Operational water management	Regional scale; Water board	Regional scale; Water board	National scale; Ministry

[1] *cf. Galloway, (1981);* [2] *cf. Schumm, (1977)*

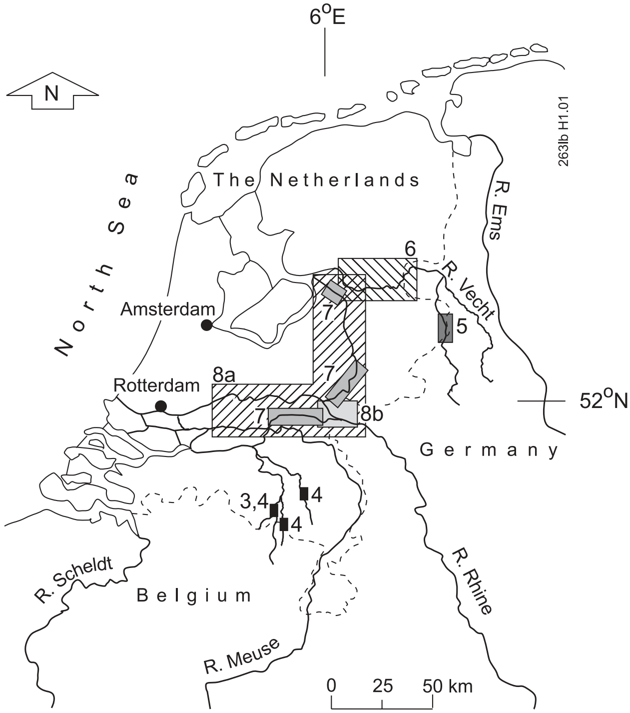

Fig. 1.1.
Location of the study areas. Numbers refer to chapters of this thesis

floodplains of various river reaches (Wolfert, 1992). The lack of relevant knowledge on the geomorphology of rivers in similar lowland environments was also indicated by Brookes (1995b).

The various types of rivers in the Netherlands' lowland area have been incorporated into one study, as it is assumed that important similarities and differences throw light on the conditions to be fulfilled and enable a better choice of areas suitable for river rehabilitation. The rivers, including channels and floodplains, have been divided into three groups: streams, small rivers and large rivers (Table 1.1). This simple classification scheme is primarily based on general physiographical characteristics, and is related to the size of the drainage basin and the volume of discharge. Consequently, the three classes reflect easily recognisable ecosystems and may well be compared with river systems abroad. In addition, the main water functions are very different and this influences the possibilities and constraints for river rehabilitation. The three river types are consistent with those distinguished in an existing aquatic ecological river typology for Dutch rivers by Higler and Mol (1984), although they separate large lowland streams from small lowland rivers. The following streams and rivers – or representative parts of them – have been studied here (Fig. 1.1):

- the Tongelreep, Keersop and Aa streams, tributaries to the River Dommel, representing streams;
- the River Overijsselse Vecht and one of its main tributaries, the River Dinkel, representing small rivers;
- the distributaries of the River Rhine system, the rivers Waal, IJssel and Neder-Rijn / Lek, representing large rivers.

AIM, OBJECTIVES AND STRUCTURE OF THE THESIS

Summarising, the aim of this study is to contribute to:
- application of the functional-geographical approach in the river rehabilitation planning process;
- knowledge of the geomorphology of lowland fluvial systems, with emphasis on rivers in the Netherlands.

Consequently, specific objectives of this study are to:

- recommend procedures to implement the functional-geographical approach in the river rehabilitation planning process;
- describe and explain the ecologically relevant landform configurations and related sediments in the various types of river systems, and their variability in space and time;
- detect the role of the various variables influencing the fluvial processes related to the formation of landforms, and their significance to management;
- identify areas where rehabilitation of geomorphological processes and subsequent formation of landforms is likely to be successful, and the required space;
- provide design guidance for effective rehabilitation measures.

The term landforms is used in a general sense, indicating all topographical features of the earth's surface. As usual in geomorphology, it is replaced by the term bedform in the context of the study of river channel processes. The term rehabilitation refers to (1) a return to a previous condition, as well as (2) a return to a normal functioning or (3) a return to a good condition or for a new purpose (cf. Ehrlich et al., 1980). Better than the term restoration, it denotes the awareness that not all rivers can return to a previous pre-channelisation state.

The thesis is divided into nine chapters. Following this general introduction. Chapter 2 deals with the elaboration of the methodological aspects of the chosen functional-geographical approach.

The next six chapters draw on a number of case studies on streams, small rivers and large rivers. Each type of river is studied in two chapters that together cover the four questions posed in the river rehabilitation planning process. Together, these chapters serve as examples of a functional-geographical procedure associated to rehabilitation planning. The chapters are arranged so that subsequent chapters deal with larger spatio-temporal domains of features and processes. These range from stream bedform patterns of several tens of square meters in size, changing each season, to the river reach landform patterns of the Rhine in areas of several hundreds of square kilometers in size, reflecting developments over a period of almost a millennium.

Chapters 3 and 4 investigate streams. In Chapter 3, the interactions between macro, meso and micro bedforms in the meandering Keersop stream are studied, and the influence of seasonal patterns of discharge and in-stream aquatic macrophyte growth, to provide a detailed, contemporaneous reference. In Chapter 4, the short-term geomorphological impact of meander rehabilitation in the Tongelreep, Keersop and Aa streams is monitored, to provide answers to design questions often posed in this context.

Chapters 5 and 6 deal with small rivers. In Chapter 5, the influence of natural levee overbank deposition on riverine grasslands along the small River Dinkel is examined, to provide a conservation strategy based on geomorphological processes. In Chapter 6, the historical meandering of the River Overijsselse Vecht is investigated, to identify relevant variables for selecting areas suitable for re-meandering in the near future.

Chapters 7 and 8 cover large rivers. In Chapter 7, historical developments of the River Rhine distributaries are analysed, to describe a pre-channelisation reference situation, emphasizing spatial change along the river gradient. In Chapter 8 the use of this type of geomorphological knowledge is demonstrated in both the design and evaluation stages of a cyclical planning procedure.

Finally, a synthesis is provided in Chapter 9. Similarities and differences between the various river systems studied are discussed and used to evaluate the use of the functional-geographical procedures in the planning process, and to indicate some general geomorphological principles and constraints for river rehabilitation in the Netherlands.

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Functional-geographical approach 2

USER REQUIREMENTS

Planning for river rehabilitation will generally aim at safe, multifunctional and ecologically sustainable rivers. In the preceding chapter it was argued that the planning process should be accompanied by research on the functioning of rivers to achieve these goals. Research yields relevant information for making the appropriate choices in the planning process. Peck (1998) mentioned various reasons for collecting this information: (1) to gain sufficient knowledge to make planning recommendations and decisions, (2) to test the outcome of models and hypotheses during the planning process, (3) to create baseline data for monitoring, (4) to indicate information gaps or areas that require specific research, and (5) to increase general understanding of river functioning. In reality, however, emphasis is on the first reason.

From a water management perspective, scientific information supporting the decision-making process in rehabilitation planning should meet the following requirements (Rademakers and Wolfert, 1994; Wolfert, 1996): (1) information must cover the entire plan area to enable comparison of its constituent parts, (2) the information should relate to results of research from other disciplines as part of an integrated approach encompassing the various river functions, (3) the type of information should be related to the measures proposed by water managers to enable the impacts of these measures to be assessed, and (4) information must be gathered efficiently, since the planning process generally is relatively short and research budgets are limited. These requirements define the type of research associated with the river rehabilitation planning process.

In this chapter an approach towards efficient river rehabilitation studies is elaborated, building on (1) methods of land evaluation applied successfully in spatial planning processes (e.g. Verstappen, 1983; Zonneveld, 1995) and (2) the hierarchical framework for habitat classification (Frissell et al., 1986) and the fluvial hydrosystem concept (Petts and Amoros, 1996) developed for studying river systems in an applied context.

LAND RESOURCE INVENTORY

Information covering an entire plan area is usually gathered in a resource inventory, with which most spatial planning processes start. Land resource inventories are adequate, because the planner is concerned with the designation of areas. Such an approach has a long tradition in rural land use planning. In the Australian land-systems survey, applied world wide in the 1950s and 1960s, the inventory was based on the recognition of land systems which contain a recurring pattern of various related aspects, such as geomorphology, soils and vegetation different from those of adjacent areas (see Verstappen, 1983; Cooke and Doornkamp, 1990). Similar methods are still being used in land resources surveys. With the emergence of landscape ecology as a science in the 1970s, emphasis shifted from the description of patterns to the study of functional topological (i.e. vertical) and chorological (i.e. horizontal) process relationships between the abiotic and biotic components (Leser, 1976). These inventories yield geographical data on patterns, processes and changes in space and time, which are usually stored and presented in maps, and more recently in Geographical Information Systems.

Land resource inventories require a classification system in which information of the land system studied is presented in a systematic way (Lotspeich and Platts, 1982). According to Cowardin and Golet (1995), the major objectives of a classification system are to: (1) describe units that have certain homogeneous natural attributes, (2) arrange these units in a system that will aid decisions about resource management, (3) identify classification units for inventory and mapping, and (4) provide uniformity in concepts and terminology. In physical land evaluation, land units are classified. Land units are defined as ‘a tract of land that is ecologically relatively homogeneous at the scale level concerned’ (Zonneveld, 1995). ‘Land’ may also encompass all water, lakes or rivers flowing from or across these lands (Lotspeich and Platts, 1982).

To approach naturally homogenous land units, two different methods can be recognised (Conquest et al., 1994, Zonneveld, 1995). Ideally, data on characteristics of land units are subjected to statistical techniques, such as cluster analysis and principle components analysis, to derive a posteriori patterns and indicate relationships. This bottom-up methodology is frequently applied in vegetation science and aquatic ecology, using much data on plants and invertebrates and their sites and habitats. An efficient alternative is to search for spatial patterns in land unit characteristics of the area studied, and a priori classify these land units based on logical rules. This top-down methodology is well known from physical land evaluation studies and landscape ecological research. It requires far less data, but can only be applied successfully when sufficient knowledge of the ecosystem functioning is available. Knowledge of river ecosystems is assumed to be sufficient to allow a top-down methodology to be used.

LANDFORMS AND GEOMORPHOLOGICAL PROCESSES

To provide a framework in which results from various disciplines can be integrated, the topological interactions between the abiotic and biotic components of land units are viewed in most land evaluation systems as a simple model of hierarchical influence (Fig. 2.1). A chain of asymmetric relationships is distinguished, from the subsystem climate to the subsystems geology, geomorphology, hydrology, soils, flora and fauna (e.g. Bakker et al., 1981; Klijn, 1995). In this sequence, fauna species are largely dependent on vegetation, vegetation on soils, soils on hydrology, and so on. At a regional level, geomorphology is considered to be the central and most meaningful abiotic system, as

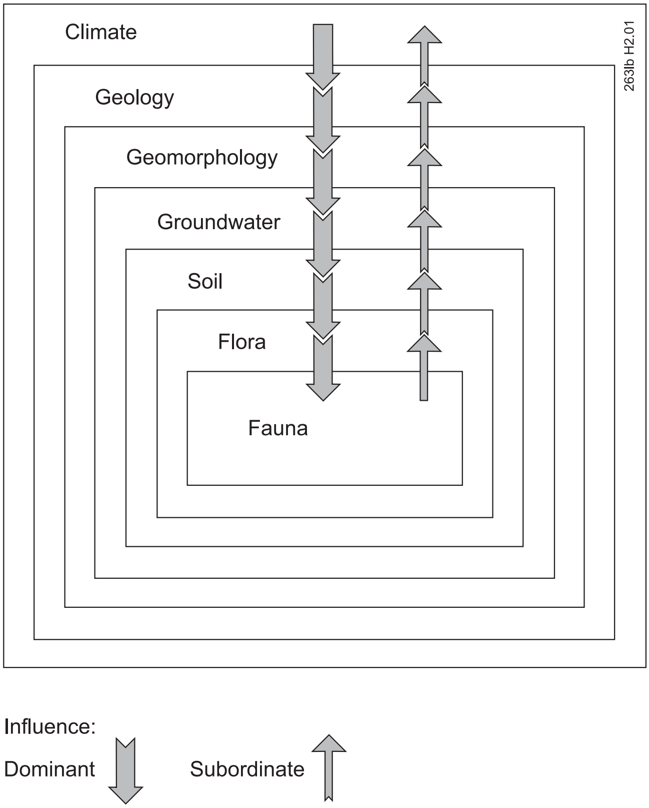

Fig. 2.1.
A hierarchical model of topological ecosystem relationships (from: Klijn, 1995)

it is closely correlated with geology and determines hydrological processes and subsequent soil developments. Landforms thus play a prominent part in the land inventory classification (Godfrey, 1977; Van Zuidam and Van Zuidam-Cancelado, 1985), especially as they are easily recognisable features which may be mapped relatively quickly, either in the field or using remote sensing techniques.

Landforms are central to most land inventory systems, which is clearly justified where the fluvial system is concerned. Its morphodynamics are responsible for a young topography that is generally more prominent than that of adjacent areas. The biological patterns of fluvial systems are assumed to be largely adjusted to and controlled by the physical patterns and processes. Consequently, most integrated classification systems for rivers are based upon the physical patterns (Lotspeich and Platts, 1982; Frissell et al., 1986, Kern, 1994). The influence of geomorphology on flora and fauna in river systems is related to morphodynamics and hydrodynamics (Knaapen and Rademakers, 1990). Morphodynamics include the mechanical and physical influences of flowing water on substrate, vegetation and animals, the most dominant processes being erosion and sedimentation. Morphodynamics are reflected in the geomorphological structure of the channel bed and floodplain. Hydrodynamics relate to the physiological and hydrological influence of water on site, vegetation and animals. It includes water depth, flooding duration and fluctuations of the groundwater level. These variables clearly depend on the channel bed and floodplain relief. Information on genesis and relief of landforms is usually provided by geomorphological maps, which are therefore valuable as tools for integrated river rehabilitation planning.

FUNCTIONAL HIERARCHIES

For efficient collection and dissemination of information for application by river managers, research must be attuned to the mission, legal powers and land under the responsibility of the organisations involved in planning and water management. Organisations may operate at a transboundary (e.g. European Union), internal (e.g. country, state), local (e.g. water board, municipality) or landowner level (e.g. nature reserve, farm). Each of these require their own level of information (Delft Hydraulics, 1992; Klijn, 1995). One way to define the appropriate scale is to match the level in the administrative or decision hierarchy with a relevant perspective of the organisation in the river system. The use of river system hierarchies in applied river research has been advocated by Frissell et al. (1986), Kern (1994), Amoros et al., (1987), Petts and Amoros (1996) and Newbury (1996), and explored successfully in various underlying disciplines, such as hydroclimatology (Hirschboeck, 1988), sedimentology (Allen, 1983; Miall, 1985; Weber, 1986) and geomorphology (Jackson, 1975; Schumm, 1988). However, the hierarchies proposed differ in the levels distinguished, in the weights given to the abiotical and biotical aspects and in terminology.

An interesting point in this context is that the smaller phenomena in river systems are often used to describe the difference between the larger ones. For instance, various types of bars have characteristic patterns of ripples and dunes, and different fluvial styles are characterised by specific bedform assemblages. Moreover, the larger these phenomena are, the longer they exist. Thus, Jackson (1975) introduced a unifying, hierarchical model of macro, meso and micro bedforms, mainly based on bedform size, time-span of existence and superposition. Similarly, a process-functional hierarchy is proposed here for use in river rehabilitation studies, of which the levels can be detected in all types of river systems and together form a consistent nested hierarchy. These levels are: (1) the river domain, composed of a characteristic set of river reaches, (2) the river reach domain, characterised by recurring patterns of macro bedforms, and (3) the river macroform domain, showing superimposed small-scale bedform patterns (Fig. 2.2). A comparison of nomenclature is given in Table 2.1.

The river domain comprises all surface waters within the drainage basin. Theoretically, in each river system a zone of erosion, a zone of transfer, and a zone of deposition may be distinguished (Schumm, 1977; 1988), but generally a much larger variety of river reaches can be observed. River reaches are often characterised by certain species of invertebrates, fish and vegetation (Mosley, 1987; Naiman et al., 1992; Large

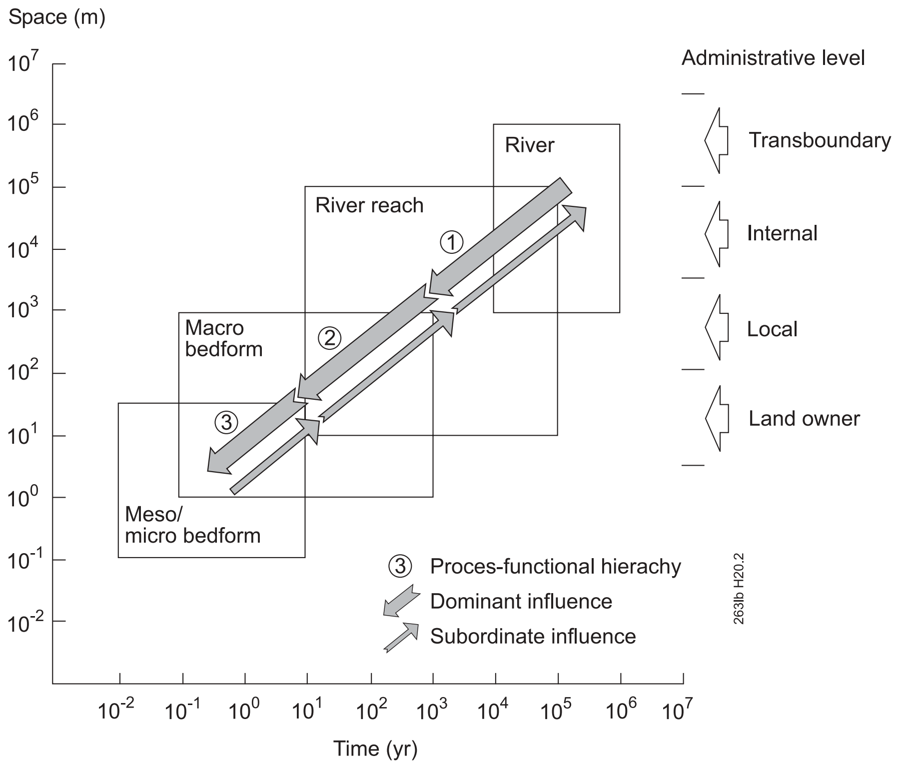

Fig. 2.2.
A model of process-functional hierarchies in river systems compared to the levels of the administrative hierarchy. Envelopes of spatio-temporal domains are derived from Frissell et al. (1986), Kern (1994) and Petts and Amoros (1996)

et al., 1996; Roux and Copp, 1996), while reach discontinuities were observed to result in distinct changes in aquatic species assemblages and in a lower floodplain biodiversity (Hughes et al., 1994; Statzner and Higler, 1986; Stanford et al., 1996). Examples of macro bedforms are pools and riffles in streams, and bars, sloughs and natural levees in large alluvial rivers. Many classifications of typical macro bedform assemblages have been developed (e.g. Miall, 1985; Nanson and Croke, 1992; Rosgen, 1994; Downs, 1995; National Rivers Authority, 1996.). Macroforms are the basic units in river ecological classifications, for example the functional unit of Amoros et al. (1987) and the river ecotope of Rademakers and Wolfert (1994). The small-scale bedforms encompass features such as dunes and ripples (Reineck and Singh, 1980) but also minor channels and bars. The variability of small-scale bedforms is related to the behaviour and life history adaptation of stream organisms (Frissell et al., 1986).

In hierarchical models of river systems, the various independent variables are assigned to specific levels in the hierarchy, because what appear to be the most controlling or constraining variables often changes according to the time-frame in

Table 2.1.
Comparison of nomenclature used to indicate the spatio-temporal domains in fluvial systems

REFERENCE	DISCIPLINE	SPATIO-TEMPORAL DOMAIN			
		River	**River reach**	**Macro bedform**	**Meso and micro bedform**
Miall, 1985	Fluvial sedimentology	Depositional system	Fluvial style	Architectural element	Lithofacies
Frissell et al., 1986	River ecology	Stream system	Segment system; reach system	Pool/riffle system	Microhabitat system
Weber, 1986	Fluvial sedimentology	Basin scale	Reservoir scale	Genetic unit scale	Grain size scale
Amoros et al., 1987	River ecology	Drainage basin	Functional sector	Functional unit	Functional describer
Schumm, 1988	Fluvial geomorphology	River system	River reach	Meander; sand bar	Bedforms (ripples and dunes)
Kern, 1994	River ecology	Gewässersystem	Gewässerabschnitt / Talboden; Gewässerstrecke / Überschwemmungsaue	Bettstructure / Auenhabitate	Microhabitate
Petts and Amoros, 1996	River ecology	Drainage basin	Functional sector	Functional unit; functional set	Mesohabitat
Newbury, 1996	Stream hydraulics	Catchment scale	Stream reach scale	Habitat scale	Microhabitat scale

which the system is viewed (Frissell et al., 1986). This allows a selection to be made of the variables most relevant to the organisations involved in rehabilitation planning. Independent and dependent variables often mentioned in relation to the three levels in the process-functional hierarchy are listed in Table 2.2. In Fig. 2.2, these levels are compared to the areas covered by the various administrative levels. Assuming that the internal and local administrative levels are the most relevant in spatial planning, comparison shows that some of the independent variables cannot be influenced since their spatial domain far exceeds that of the area of jurisdiction of the water manager. Besides, it appears that the variables at the river reach–macro bedform level are right in the middle of the sphere of influence of rehabilitation planners. Thus it can be concluded that the domain of the river reach characterised by recurring patterns of macro bedforms is especially suited for use in studies for river rehabilitation purposes. River reaches and their characteristics are the result of large discharge events and require many decades to develop. Historical studies, therefore, are considered extremely relevant to rehabilitation research.

CONCLUSIONS

Starting from the hierarchical framework for habitat classification (Frissell et al., 1986)

Table 2.2.

Independent and dependent variables often mentioned in relation to the three levels in the process-functional hierarchy

LEVEL	INDEPENDENT VARIABLES	DEPENDENT VARIABLES
River with river reaches	Climate Tectonics Geological setting Basin relief Land cover	Valley type Longitudinal profile Channel pattern
River reach with macro bedforms	Discharge of water Discharge of sediment Valley slope Bank material Bank vegetation	Channel dimensions Bedform types and configuration Architectural elements
Macroforms with meso and micro bedforms	Flow velocity Stream power Sediment grain size Aquatic and bank vegetation	Bedform dimensions Bedform types and configuration Lithofacies

and the fluvial hydrosystem concept (Petts and Amoros, 1996) some user requirements typical of the spatial planning process were used to define research procedures for river rehabilitation purposes. (1) Compared with previous work by the authors mentioned, the four-dimensional approach is expanded through the addition of land resource inventories using a top-down classification method. (2) Like both concepts, information on physical patterns and processes is considered to be the most meaningful, but more emphasis is put on the use of geomorphological maps (3) The proposed approach differs from the hierarchies of Frissell et al. (1986) and Petts and Amoros (1996) in the use of a process-functional hierarchy, in which the central domain of river reaches characterised by recurring patterns of macro bedforms is considered the most appropriate to organisations involved in river rehabilitation planning.

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3

Aquatic macrophyte growth and seasonal bedform pattern changes in a lowland sand-bed meandering stream

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Submitted to Catena

ABSTRACT

The interactions between macro, meso and micro bedforms, seasonal variations in discharge and aquatic vegetation cover in a small sand-bed meandering stream are described. A two-bend reach of the Keersop stream in the Netherlands was studied by means of detailed geomorphological mapping and cross-sectional surveys in March, July and November, for a period of three years. Macroforms (pools, erosional channels, point bars and platforms) were related to the flow paths of the two pairs of alternating helical flow cells. The development of mesoforms (chute channels, obstacle bars, chute bars) was related to the obstruction of flow by the submerged species *Elodea spp.* and *Callitriche spp.* Microforms (sand ripples) occurred superposed on both these groups. Establishment of submerged macrophytes was inhibited in pools because of attenuation of light and in erosional channels because of permanently high flow velocities. Maximum coverage of the stream bed by macrophytes was 47%. An expanding cover was associated with an increase in the area of gravel lags and exposed peat layers in between solitary plant stems. A high density of plants induced the deposition of silts and particulate organic matter. A cyclical sequence of events is described. In winter, when macrophyte cover is relatively small, large discharge events activate the macroforms. Since stream banks are stable, point bars along convex banks are eroded while chute channels at crossovers were filled with sand. In summer, smaller discharges and expansion of plant cover, led to the formation of mesoforms and the sand eroded from chute channels was used to restore the point-bar surface. This indicates that point bars and mesoforms are the main sediment storage features and sediment is exchanged between them. A model of seasonal change is considered useful in both the design and evaluation of meander rehabilitation strategies.

KEY WORDS
Aquatic macrophytes, Bedform configuration, Helical flow, River rehabilitation, the Netherlands

INTRODUCTION

The spatio-temporal variation of channel bedforms in streams and rivers is an important item in integrated river management. Bedforms have traditionally been relevant to determining flow resistance and cross-sectional channel dimensions and their importance in ecological assessments is recognised (e.g. National Rivers Authority, 1996). Being the result of the interaction of water flow and channel substrate, bedforms provide the physical habitats for aquatic macrophytes (Westlake, 1973) and for aquatic fauna species (Tolkamp, 1980; Kershner and Snider, 1992). The diversity of bedforms partly determines biodiversity, as the various species encountered in pristine rivers require specific circumstances to become established or for feeding, shelter and reproduction. Where many fauna species need different habitats close to each other, others require habitat characteristics to change because their life-cycle is adapted to pulsing of water discharge (Junk et al., 1989; Greenwood and Richardot-Coulet, 1996). Hence, increasing the bedform diversity in space and time is an important aim of many stream and river rehabilitation projects.

Jackson (1975) introduced a unifying, hierarchical model of macro, meso and micro bedforms, mainly based on bedform size, their time-span of existence and superposition. Macroforms, such as point bars and sand flats, are the major geomorphological features. They develop in response to the discharge regime and geomorphological setting of the river system. Macroforms interact with and condition the mean flow pattern, but are relatively insensitive to the changes in the flow regime during a flood event. Compared with such events, the time-span of existence of macroforms is much longer. Mesoforms, such as dunes and antidunes, evolve in response to flow conditions in the entire turbulent boundary layer. As the flow varies throughout a flood event, mesoforms typically have a time-span of existence that equals the duration of such an event. Microforms, such as ripples, develop in response to the flow structure within the lowest zone of the turbulent boundary layer, which is relatively insensitive to changing water depths, and are therefore formed during all discharges. The response time of microforms is short relative to the major changes in flow characteristics. From the many descriptions of fluvial styles (e.g. Miall, 1996) it appears that the three groups of bedform types are not equally important in all types of rivers. This is because the hierarchy of bedforms varies with the mean particle size of the bed material and with the mean water depth (Jackson, 1975). Macroforms dominate the bedform configuration in gravel-bed rivers (Church and Jones, 1982; Hey and Thorne, 1986). Bed load transport is mainly restricted to low-frequency, high discharge events, of the order of bankfull or greater. Consequently, the bedform configuration is stable during the entire period between succeeding flood events. In contrast, all three groups of bedforms usually occur in superposition in sand-bed rivers. Here, flow transverse mesoforms develop upon the macroforms, while microforms partly characterise the surface of the mesoforms (Boersma et al., 1968; Jordan and Prior, 1992). Transport of the sandy bed load is not restricted to large discharge events, but is continuous, and so the bedform configuration continues to change. This favours an increase in the area covered by mesoforms and microforms at decreasing discharge.

Plant growth has additional effects on the formation and distribution of bedforms (Kopecký, 1965, Hickin, 1984). Stems and leaves obstruct the flow, which disturbs the regular interaction between the water and the bare channel bed. In general, solitary plants induce scour around stems and exposed roots followed by local downstream deposition, whereas a dense vegetation results in reduced flow velocities and enhanced deposition of bed load. Well-known examples are the formation of pools and associated downstream gravel bars around tree roots and large woody debris (Gregory and Gurnell, 1988; Keller et al., 1995), the stabilization of mid-channel bars due to colonization by herbs and willow saplings (Hooke, 1986), and point-bar and scroll-bar formation in woody riparian zones (Hickin, 1984; McKenney et al., 1995). The influence of vegetation is considered to be relatively large in small rivers and streams. The shallow water depth and low specific stream power make streams highly suitable for submerged and floating-leaved plants, especially when unshaded (Westlake, 1973).

The interactions between macroforms, mesoforms, microforms and aquatic macrophytes in small sand-bed streams, however, have not been documented very well. A better understanding of these interactions is valuable for ecological assessments, which guide the many stream rehabilitation projects being executed or planned at present throughout Europe and North America (Brookes, 1995; Kondolf and Micheli, 1995; Newbury, 1996). This paper investigates the spatio-temporal variability of bedforms in the Keersop, a small sand-bed meandering stream with abundant growth of aquatic macrophytes in the Netherlands. The research objectives are to increase our knowledge of (1) the spatial distribution and evolution of macro, meso and micro bedforms and (2) their relationships with seasonal patterns in discharge and aquatic plant growth. The opportunity to monitor the dynamics of channel bedforms was provided by a post-project appraisal in which meander rehabilitation was evaluated. The response to re-meandering is described in Chapter 4.

MATERIALS AND METHODS

Physiography and hydrology

The Keersop is a tributary of the River Dommel and is located in the south of the Netherlands (Fig. 3.1). It drains an area of approximately 85 km2, ranging in altitude from approximately 40 m above mean sea level near the drainage divide to 21 m near the confluence with the River Dommel. The undulating topography is underlain by gravelly and sandy deposits of fluvial and marine origin, locally covered by Pleistocene fluvio-periglacial and aeolian sands (Bisschops et al., 1985). In the shallow valleys, Holocene peat as well as sandy fluvial deposits occur. Mid-19th century topographic maps indicate that the Keersop was at that time characterised by an irregularly meandering planform. The Keersop was channelised in 1880 as part of a land development project to reclaim peatlands and improve the drainage of agricultural land.

During the period 1961–1990, mean annual precipitation was 750-800 mm and

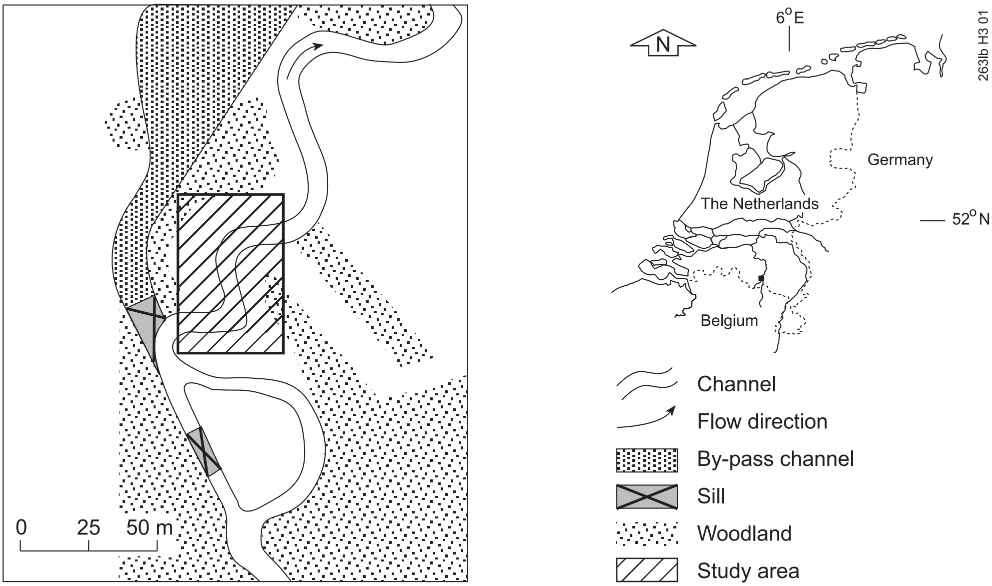


Fig. 3.1.
Location of the study site

mean annual evapotranspiration 550–575 mm (Meinardi et al., 1998). Evapotranspiration exceeds precipitation in the period April–August. The stream discharge hydrograph generally shows large volumes of runoff occurring in winter and base flow discharge in July and August. Mean winter and summer temperatures are 2.0–2.5 ^{o}C and 17.0–17.5 ^{o}C, respectively. Maximum temperatures are below 0 ^{o}C for an average of 7–8 days per year.

Study reach characteristics

Meandering has been rehabilitated in a 1.2 km long reach of the Keersop, close to its confluence with the river Dommel. Remnants of the formerly meandering Keersop were re-connected to each other, using an excavated channel with a trapezoidal cross section. The cross-sectional dimensions were derived from the historical channel, based on information from soil profiles. To compensate for the present hydrological regime, which was assumed to lead to higher stream stages compared with the historical one, the channelised reach was transformed into a by-pass channel (Fig. 3.1). Cobble sills within the former channel direct the flow into the new meanders, but are overtopped just before flow exceeds bankfull discharge in the meandering reach. Sand traps were installed at the beginning and at the end of the rehabilitation reach to compensate for the enlarged input of sediment to the stream, which was expected during the initial year(s) following rehabilitation. The stream rehabilitation works were completed in

Fig. 3.2.
The study reach in July 1995

April 1994. No weed cutting or other stream maintenance was carried out afterwards.

The study site is located in the middle part of the rehabilitated reach (Fig. 3.1). A site has been selected which (1) incorporates a sharply curved bend and a less sharply curved bend separated by a crossover in between, (2) has banks with an undisturbed, non-reinforced soil profile, and (3) is located as far away as possible from the upstream sand trap, assuming this distance is large enough to accommodate the sediment load deficiency occurring in the upstream part of the rehabilitation reach.

At the study site, the meandering channel has a slope of 0.00067, a mean bankfull width of 8.1 m and a mean bankfull depth of 1.6 m (Fig. 3.2). The ratio radius of channel curvature to channel width of the tightly curved bend is 0.7, and that of the gently curved bend is 1.6. The stream banks are mainly composed of Holocene peat with some sand lenses. The top soil is densely rooted. The stream bed is underlain by Weichselian fluvio-periglacial deposits: slightly gravelly sands and peat layers. The median grain size (D_{50}) of the sediment load was estimated to vary from 150 to 400 µm. Nutrient availability in the sediment is low (NO_3^-: 0.53 mg kg^{-1}; NH_4^+: 5.5 mg kg^{-1}; PO_4^{3-}: 71.9 mg kg^{-1}; data from Mesters, 1997), as are concentrations in the water (NO_3^-: 10.30 mg l^{-1}; NH_4^+: 0.31 mg l^{-1}; PO_4^{3-}: 0.04 mg l^{-1}; data from Mesters, 1997). Water in the Keersop is clear at low flows and, as water depth of the thalweg at mean discharge varies from 0.6 m at the crossover to 1.2 m in the deepest pool, most of the bedforms can be observed regularly.

Field surveys

Seasonal changes in substrate and aquatic macrophyte cover in Dutch streams have been illustrated in maps by Tolkamp (1980) and Mesters (1997), respectively. Accordingly, the main technique used to register the bedform configuration was a detailed mapping survey. The geomorphological mapping system applied had been developed for monitoring geomorphological and geo-ecological changes in the small and shallow streams in the Netherlands (Koomen et al., 1997). All mapping units were identified in the field at a scale 1:100 using a network of poles along the banks, placed within 2 m of one another. Bedforms were distinguished on the basis of their morphology and delineated on the basis of breaks of slope. Bedform substrates were indicated on the maps as observed by visual inspection. The occurrence of aquatic macrophytes was also mapped. Nine cross sections were measured to monitor changes in cross-sectional morphometry. Data on bedform configuration and cross-sectional data were processed using the software package ARC/INFO (ESRI, Redlands, CA). Changes in the cross-sectional dimensions were calculated by means of overlay procedures.

The field surveys were repeated in March, July and November for a period of three years. In March, the effects of high winter discharges on the channel banks and bedform patterns are documented; macrophyte coverage of the bed is minimal. In July, the effects of base flow in summer are recorded; by then the area of macrophytes has expanded to such an extent that the influence on bedforms is clearly noticeable. In November, in-stream vegetation cover is just over its maximum. It is also not too late to analyse the effects of late summer thunderstorms on the morphology. The mapping survey always preceded measurement of cross-sectional dimensions, because taking these measurements can disturb the bedform pattern.

During the monitoring period, water discharge was registered continuously at a gauge located approximately 1.3 km upstream from the study site. Flow velocities were measured over various bedforms at three different water depths, at medium flow. Flow patterns at the water surface were sketched in the field.

RESULTS

Discharge and macrophyte distribution

The variability in discharge during the monitoring period is shown in Fig. 3.3. Mean discharge during the period May 1994 to July 1997 was 0.77 $m^3 s^{-1}$. The 1994/1995 winter season was exceptionally wet, which caused flooding in all streams and larger rivers in the region in January. At the Keersop study site, bankfull level was reached and overtopping of the banks resulted in a small deposit of sandy overbank material along the convex bank of the tightly curved bend. The maximum discharge registered at the gauge was 5.8 $m^3 s^{-1}$, of which approximately 25% was conducted through the by-pass channel. In contrast, the 1995/1996 winter season was relatively dry and maximum

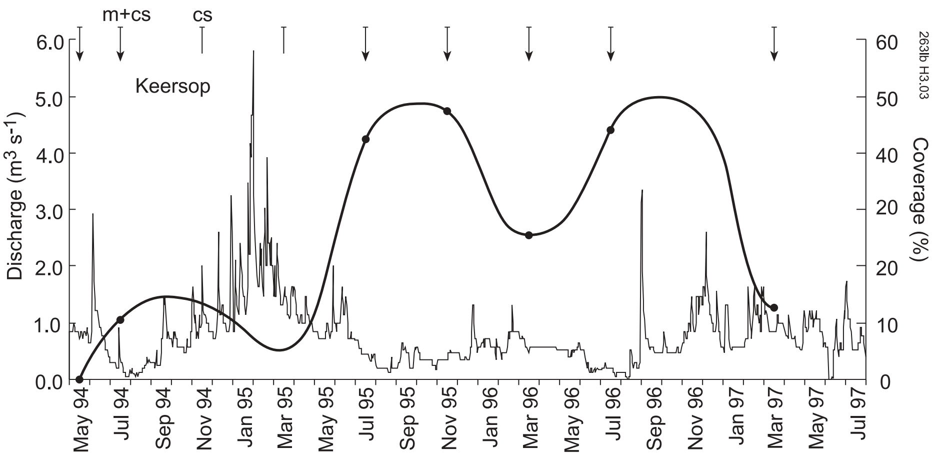


Fig. 3.3.
Daily discharge hydrograph and channel bed coverage by aquatic macrophytes during the study period, together with survey dates (arrows: m, geomorphological map; cs, cross sections)

runoff values did not even exceed some of the higher discharges occurring during the summer. Nevertheless, mean runoff in both winter seasons was clearly different from that occurring during the summer seasons, when discharge values are approximately 0.5 $m^3 s^{-1}$ or less. Base flow occurred in all the three summer seasons relevant to the study. The minimum value of runoff registered was 0.06 $m^3 s^{-1}$ in July 1994. A local summer thunderstorm caused a relatively large discharge event in August 1996, but bankfull water levels were not reached.

The changes in in-stream macrophyte cover are summarised in Fig. 3.3, and the spatial distribution of aquatic plants is shown in Fig. 3.4. During the first summer after the rehabilitation works were completed the macrophyte coverage was still limited in extent. Typically, coverage increased during the growing season from April to October and decreased during the winter season. The abundant presence of macrophytes is comparable with many Dutch lowland streams (Querner, 1993; Mesters, 1997), which generally have relatively low flow velocities and are unshaded. The length of the growing season is related to the available light and water temperature. Maximum obstruction of flow usually occurs around August. The most important plants in the Keersop were the submerged species Canadian waterweed (*Elodea spp.*) and water-starworts (*Callitriche spp.*), which both grow in large clumps (Fig. 3.5). Both plant types established during the first summer after the rehabilitation works were completed. The plants are mainly rooted in the exposed peat layers or in pieces of peat eroded upstream and deposited here, probably because this peat is a nutrient rich and a stable habitat. As *Elodea spp.* is typical of disturbed habitats, it gradually disappeared during the monitoring period, being immediately replaced by *Callitriche spp.* Floating-leaved pondweeds (*Potamogeton natans*) were registered at several locations. Both *Callitriche spp.* and *Potamogeton natans* are typical of the relatively faster-flowing

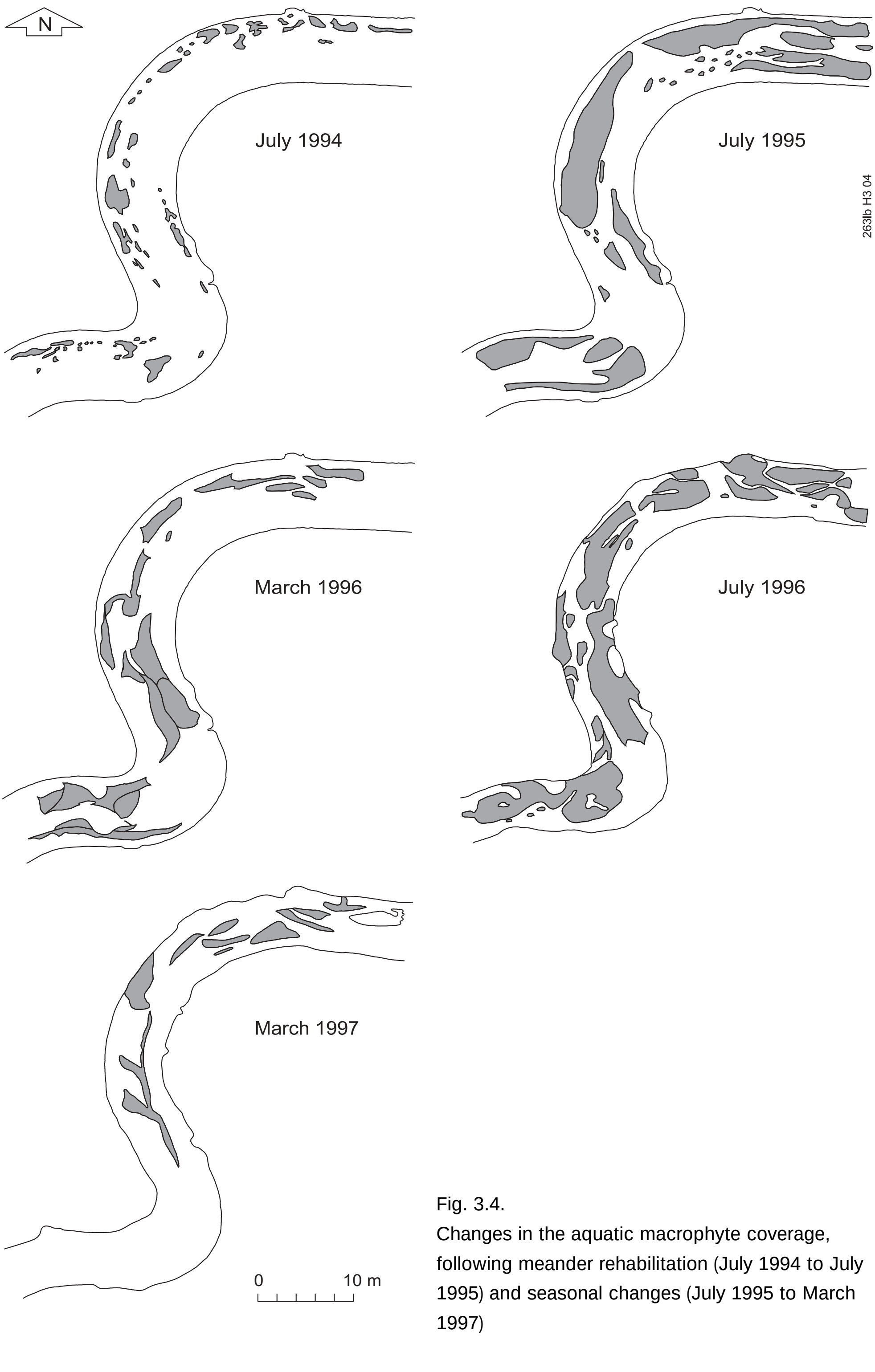


Fig. 3.4.
Changes in the aquatic macrophyte coverage, following meander rehabilitation (July 1994 to July 1995) and seasonal changes (July 1995 to March 1997)

Fig. 3.5.
Obstruction of flow by submerged macrophytes (here *Callitriche spp*.), growing in large clumps

reaches in Dutch lowland streams. Fringed water-lily (*Nymphoides peltata*) was also found and some emergent species were observed, such as water-cresses (*Rorippa amphibia*), arrowhead (*Sagittaria sagittifolia*), water plantain (*Alisma plantago-aquatica*), bulrush (*Typha spp.*) and reed sweet-grass (*Glyceria maxima*). These species, however, were far less abundant, and mainly occurred along the stream banks.

Bedform pattern characteristics

Pools and major erosion channels were observed to be the most prominent bedforms in the Keersop (Fig. 3.6; Table 3.1). Major channels originated in the area near the crossover and gradually increased in size in downstream direction until they merged with the pool. The channels continued downstream from the pool, gradually decreasing in size until they vanished near the next crossover. Pools were associated with asymmetrical cross sections and undercut banks in bends (Fig. 3.6: cross sections 3 and 7), but near the crossovers, cross sections were typically symmetrical (Fig. 3.6: cross sections 5 and 9). The pattern observed is very similar to the model by Thompson (1986), which describes two alternating pairs of surface convergent helical flow cells exist within a stream channel caused by the resistance of bed and banks to flow, experiencing repeated decay and regeneration. In sinuous streams, decay of the one and

Table 3.1.
Summary of bedform characteristics

BEDFORM	MORPHOLOGY	MATERIAL	GENESIS
Pool	Concave upward; plane bed	Slightly gravelly sand with gravel lag on top, covered by particulate organic matter	Temporary scour due to convergent flow with strong secondary component in bends
Major erosional channel bottom	Concave upward; plane bed	Slightly gravelly sand, with gravel lag on top	Continuous erosion, due to a convergent flow, and some armouring
Major erosional channel floor	Flat; plane bed	Exposed peat layer, or slightly gravelly sands with gravel lag on top	Continuous erosion, due to convergent flow, and some armouring
Major erosional channel slope	Steeply sloping; plane bed or rippled surface	Exposed peat layer or slightly gravelly sand with residue of gravel or coarse particulate matter on top	Continuous erosion, due to convergent flow
Chute channel	Concave upward; plane bed	Slightly gravelly sand	Chute erosion due to convergent flow along macrophytes
Point-bar platform	Flat to gently sloping; rippled surface or plane bed	Sand, partly covered by fine particulate organic matter	Deposition due to outward-only flow in bends
Point-bar slope	Steeply to gently sloping; rippled surface or plane bed	Sand, partly with a residue of gravel or coarse particulate organic matter on top	Deposition due to strong secondary circulation in bends
Obstacle bar	Convex upward; plane bed	Sand	Deposition due to retardation and divergent flow behind macrophyte stems
Chute bar	Flat with distal slipface; plane bed or rippled surface	Sand	Deposition due to divergent flow at the distal side of chute channels
Sand ripples	Rippled surface, mainly straight crested	Sand	Temporary storage during continuous transport
Platform	Flat to gently sloping; plane bed	Silt and fine particulate organic matter mainly	Deposition due to divergent flow and low flow velocities
Concave bank bench	Flat to gently sloping; plane bed	Silt and fine particulate organic matter mainly	Deposition due to divergent flow and low flow velocities

regeneration of the other pair of cells typically occurs near the inflection point. In the Keersop, flow velocity was highest in the erosional channels (Fig. 3.7), so that erosion continued there during all seasons. A thin gravel lag and exposed peat layers in particular resisted erosion. The latter resulted in a stepped longitudinal profile of the pool–channel unit and erosion rims along the pools. Water depth in the pools at mean discharge is 1.2 m in the tightly curved bend and 0.9 m in the gently curved bend. Few macrophytes were found in the pool–channel units.

Point bars, platforms and a concave bank bench were observed along the stream banks. Along convex banks in bends, point-bar slopes were covered by a residue of gravel or peat particles, or rippled sands and avalanche faces, indicating intermediate

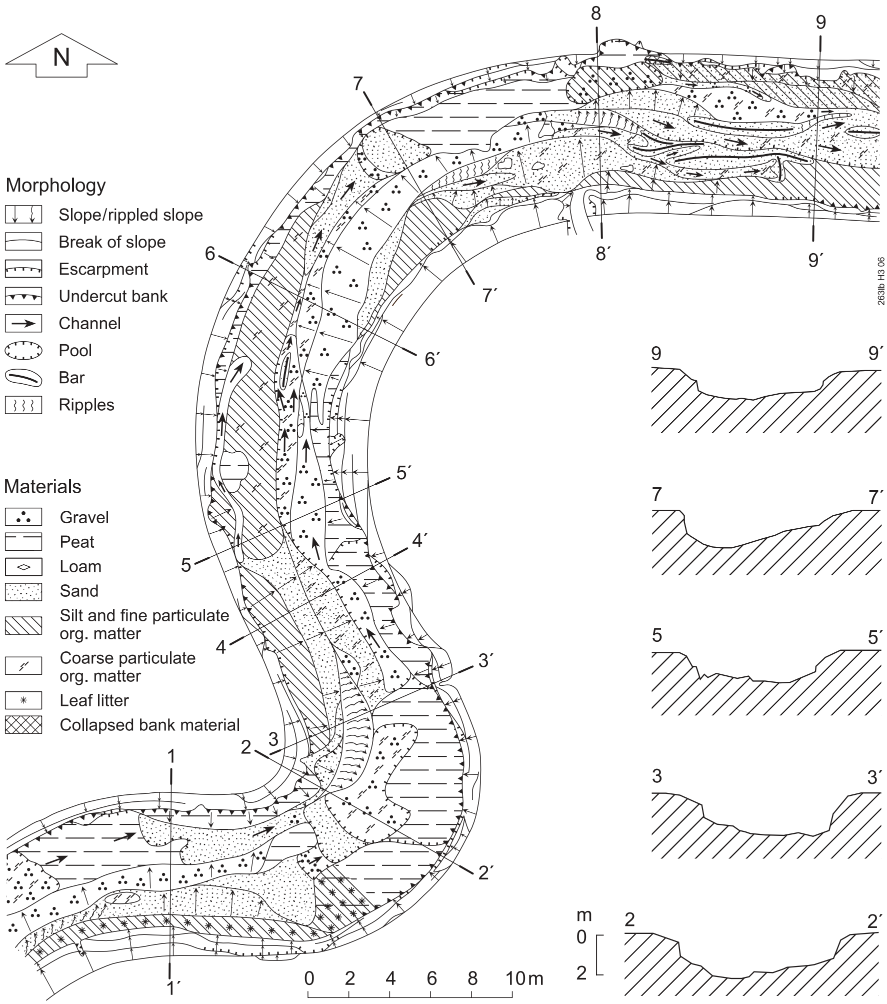


Fig. 3.6.

Geomorphological map and some cross sections showing the bedform configuration and stream dimensions in July 1995

flow velocities. Part of the point bar in the tightly curved bend emerged at low discharge. Elsewhere in the study reach, terrace-like bedforms existed along the bank toes, which here are referred to as platforms, analogous to point-bar platforms. The platforms were covered by fine material such as silts, fine particulate organic matter and – in November – leaf litter. Flow velocities are very low here. A comparison of Figs. 5 and 6 shows that the existence of most of these platforms is due to the dense vegetation cover of *Elodea spp.* and *Callitriche spp.*, which can reduce flow velocities substantially (e.g. along the concave bank between cross sections 5 and 6 in Fig. 3.6). One of the

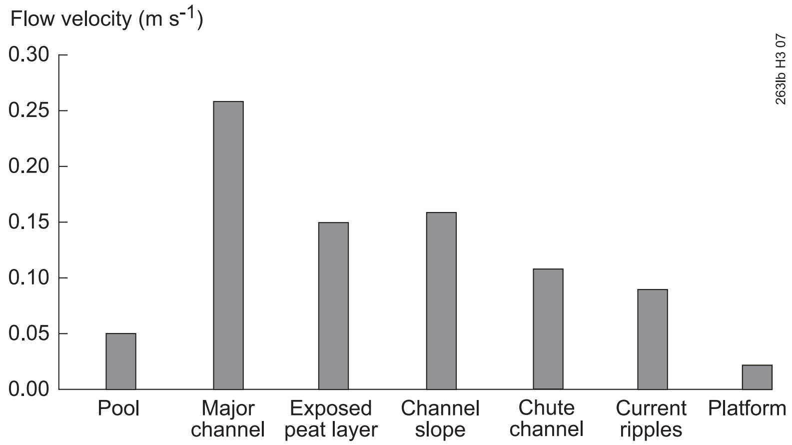


Fig. 3.7.
Mean flow velocities associated with some of the bedforms, at approximately mean discharge in July 1995

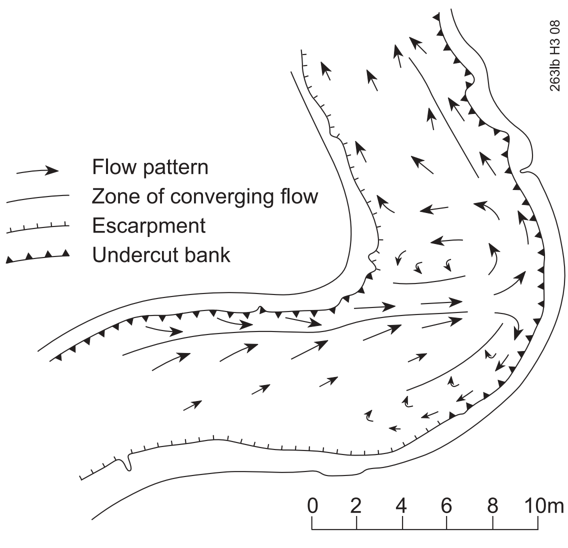


Fig. 3.8.
Surface flow pattern in the tightly curved bend at mean discharge

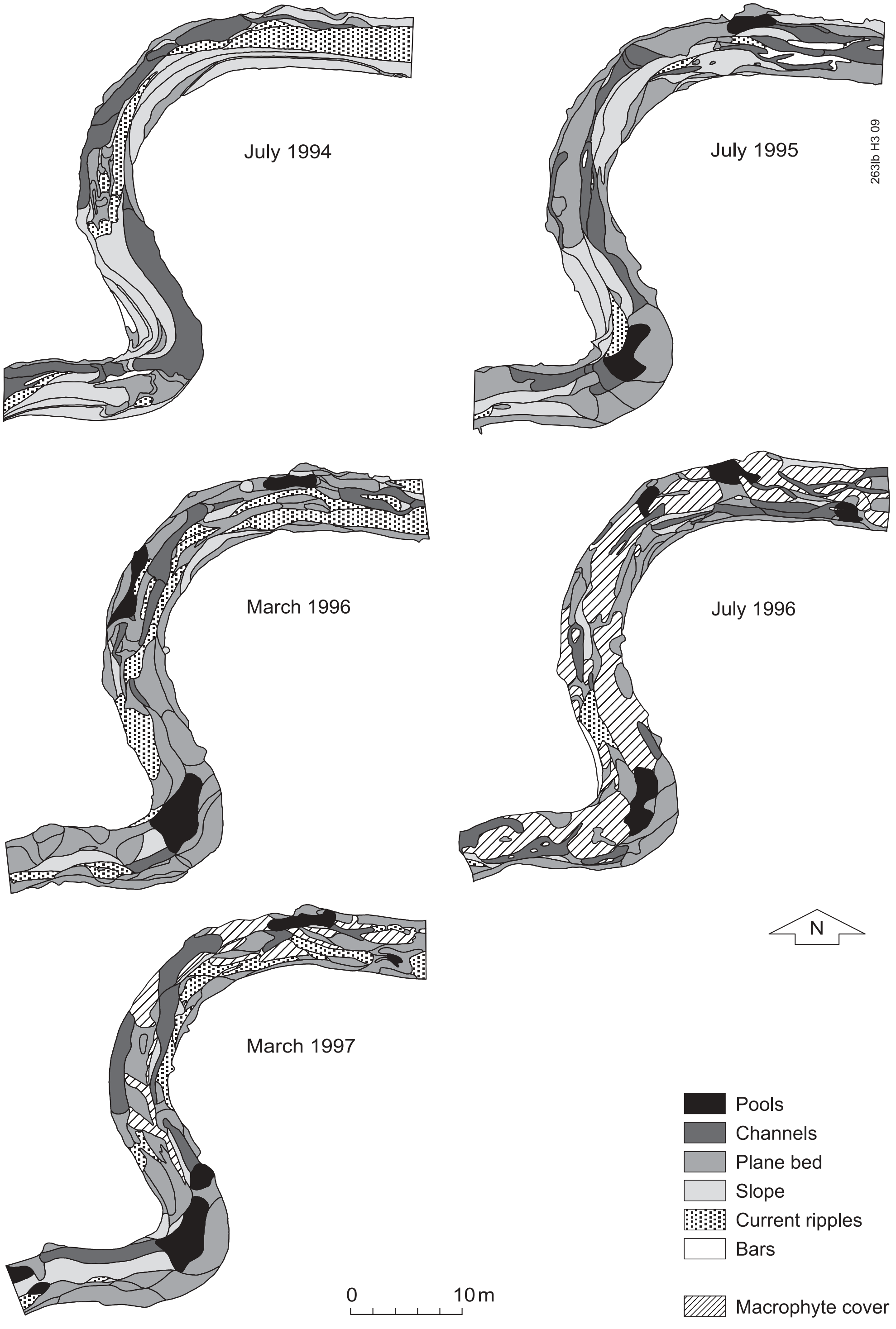
platforms is interpreted as a concave bank bench because its development was related to the flow pattern in the tightly curved bend (cf. Page and Nanson, 1982). This bend is immediately preceded by the upstream bend, so that decay of the helical flow cell of that bend could not fully occur. The flow enters the tightly curved bend at full strength where it impinges on the concave bank, causing two reverse currents (Fig. 3.8).

Obviously, the strong convergent flow where both reverse flows are re-united with the main flow is responsible for the relatively large depth of the pool and its location in the middle part of the stream, a process similar to the formation of circular meander pools (Andrle, 1994). The eddy along the point bar causes erosion of the point-bar slope (Fig 6: between cross sections 2 and 3). In the reverse flow along the concave bank, flow velocities generally are very low and lead to deposition of fine clastic material and particulate organic matter (Fig. 3.6: just upstream from cross section 2). Here, as well as on the higher parts of the other platforms, the emergent plants *Rorippa amphibia*, *Sagittaria sagittifolia*, *Alisma plantago-aquatica*, *Typha spp.* and *Glyceria maxima* became established.

Chute channels, obstacle bars and chute bars were the smaller bedforms observed. Minor channels were smaller than the major channels in length, width and depth, and often ran somewhat more obliquely to the stream banks. These channels were mainly located in the middle part of the stream channel, developing near the crossover, where several minor channels sometimes existed next to each other (e.g. between cross sections 8 and 9 in Fig. 3.6). The channels developed mainly along or between patches of *Callitriche spp.* and *Elodea spp.*, and are interpreted as chute channels since they are formed in previously deposited stream sediments. The flow velocity in these channels is lower than in the major channels. The evolution of the chute channels is related to two types of minor depositional bedforms. The obstacle bars were found to be distinct, longitudinal sand ridges in between the chute channels, where sand accumulating behind stems of aquatic plants retarded the flow and caused deposition of material. These are called obstacle bars, in a reference to obstacle marks (Reineck and Singh, 1980). Such bars were also formed on the downstream part of the point bar, interpreted as the bar tail as defined by Thompson (1986). The material eroded from the chute channels was partly deposited at the end of these channels, where expanding flow resulted in the formation of lobate slipface-bounded bars, which may be interpreted as small chute bars, conforming to the bars downstream of convex bank chutes (McGowen and Garner, 1970). The proximal side of the chute bars was generally covered by rippled sands, with an avalanche face on the distal side.

Bedform pattern dynamics

During the period from May 1994 to March 1995 the excavated channel developed into a more natural one. Channel widening prevailed during this period (Table 3.2). Aquatic vegetation was still scarce and the influence of the helical flow pattern on bed topography and bed material was clearly reflected in the maps made in July 1994 (Fig. 3.9 and Fig. 3.10). Scouring of gravel lags, formation of pools and undercutting of banks reached maximum intensity during the first bankfull flow in January 1995. Afterwards, the rates of sediment production declined, and the balance between sediment input and output was restored. A complete sequence of bedforms was observed, similar to that of natural sand-bed rivers. It was concluded that the response to meander rehabilitation in the Keersop was mainly limited to the first year after rehabilitation and that the developments in the next two years reflect the usual seasonal



July 1994
July 1995
263lb H3 09
March 1996
July 1996
N
March 1997
Pools
Channels
Plane bed
Slope
Current ripples
Bars
Macrophyte cover
0
10 m

Table 3.2.
Changes in cross-sectional dimensions (in m^2 ; positive values indicate deposition; negative values indicate erosion)

CROSS SECTION	PERIOD								
	May 94 – Jul 94	Jul 94 – Nov 94	Nov 94 – Mar 95	Mar 95– Jul 95	Jul 95 – Nov 95	Nov 95 – Mar 96	Mar 96 – Jul 96	Jul 96 – May 97	Totals
1	- 0.37	0.06	- 0.78	0.24	0.14	- 0.34	0.11	0.17	- 0.77
2	- 0.39	- 0.03	- 2.47	0.75	- 0.64	0.20	0.15	0.39	- 2.04
3	- 0.37	- 0.22	- 2.16	- 0.36	0.60	0.38	- 0.42	- 0.56	- 3.11
4	- 0.19	0.07	- 0.08	- 0.32	0.22	- 0.05	- 0.39	0.76	0.02
5	- 0.24	0.32	0.45	- 0.25	- 0.07	- 0.32	- 0.13	0.99	0.75
6	- 0.30	0.12	0.59	- 0.06	0.03	0.49	0.12	0.60	1.59
7	- 0.14	0.04	- 0.37	0.03	- 0.14	- 0.21	- 0.84	0.17	- 1.46
8	- 0.09	- 0.31	0.31	- 0.08	0.02	- 0.15	-.0.58	0.84	- 0.66
9	0.03	- 0.18	0.20	0.17	- 0.01	- 0.14	- 0.11	0.34	0.30
Totals	- 2.06	- 0.13	- 4.93	0.12	0.15	- 0.14	- 2.09	3.70	- 5.38

Table 3.3.
Changes in bed-material distribution (in % of total area of bedforms in the study reach)

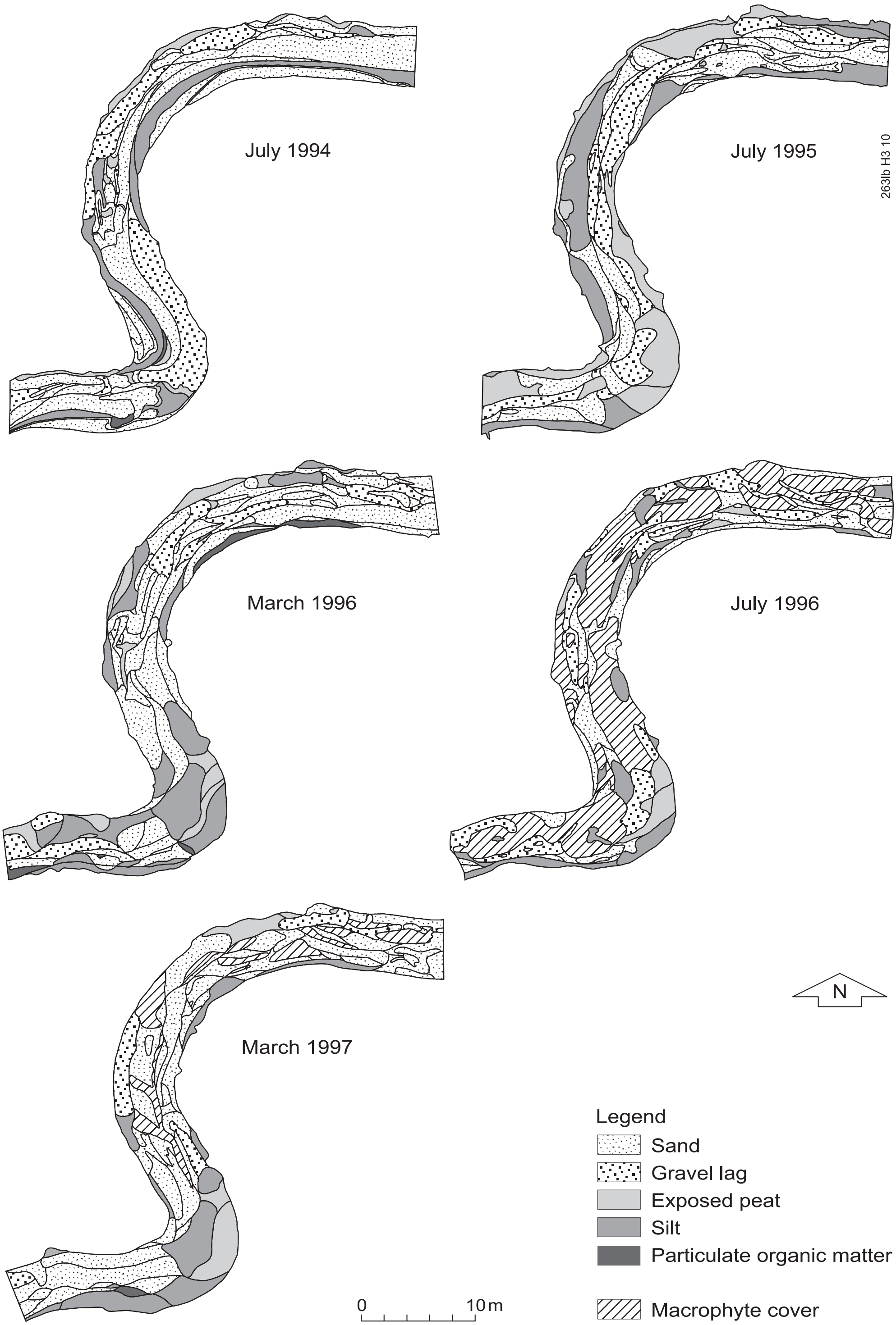
BED MATERIAL	JULY 1994	JULY 1995	MARCH 1996	JULY 1996[1]	MARCH 1997[2]
Exposed peat	5	23	8	9	8
Gravel lag	22	21	12	28	9
Sand	57	33	52	40	63
Silt	15	22	25	21	18
Particulate organic matter	1	1	3	2	2

[1] *exclusive 43% macrophyte coverage;* [2] *exclusive 12% macrophyte coverage.*

changes in lowland streams.

The most conspicious changes from March 1995 onwards occurred in bends, especially in the tightly curved bend. A large part of the initial point bar in this bend was eroded during the bankfull event, after which the gradual formation of a new point-bar surface was observed (Fig. 3.11). The sediments probably were derived from the areas in between the bends, where bed scour dominated local deposition. This degradation took place in a period of low discharges and is assumed to be related to the retardation of water flow by growing macrophytes, initiating new flow paths around stems, where convergent flow gradually gained the power to scour channels. An increase in chute channels, minor bars, gravel lags and exposed peat layers was the result (Fig. 3.12; Table 3.3). Where the vegetation was very dense, fine material was

Fig. 3.9.
Changes in bedform configuration showing a larger bedform diversity as a result of macrophyte establishment (July 1994 to July 1995) and seasonal changes due to small discharges and larger macrophyte coverage during the growing season (bedforms obscured by the aquatic vegetation cover were not mapped in July 1996 and March 1997)



July 1994
July 1995
263Ib H3 10
March 1996
July 1996
March 1997
N
Legend
Sand
Gravel lag
Exposed peat
Silt
Particulate organic matter
Macrophyte cover
0
10 m

Table 3.4.
Classification of bedforms in the study reach

BEDFORM GROUP	BEDFORM	FORMATIVE EVENT	TIME-SPAN OF EXISTENCE
Macroforms	Pool; Major channel; Point bar; Platform	Bankfull discharge	Years – decades
Mesoforms	Chute channel; Obstacle bar; Chute bar	Medium to low discharges; Macrophyte growing season	Weeks – months
Microforms	Sand ripple	All discharges	Hours – days

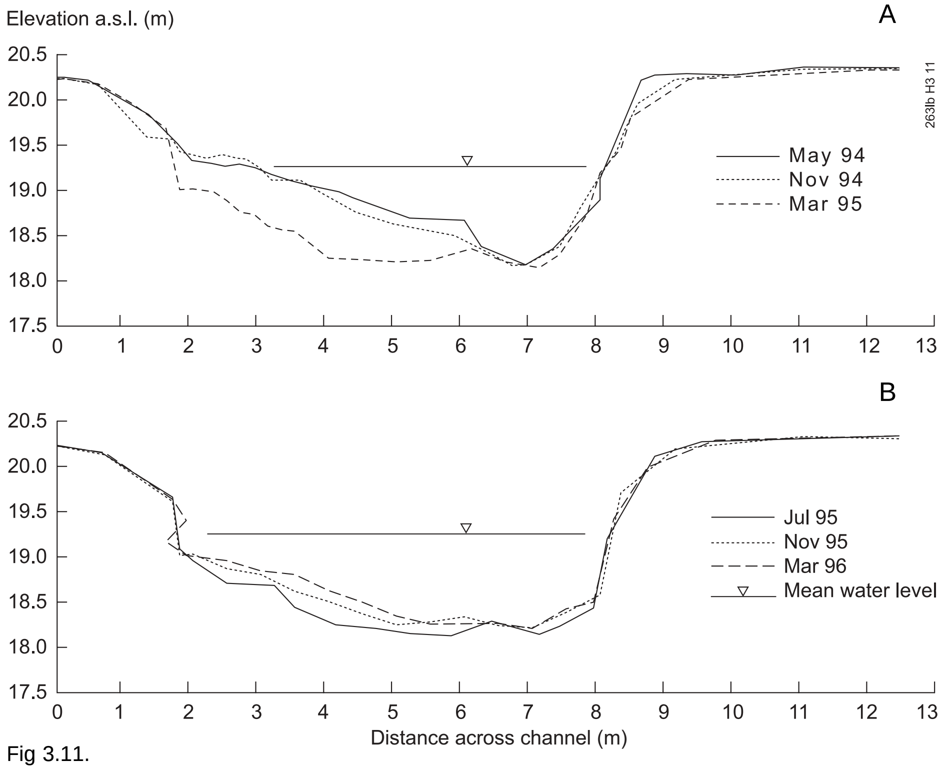


Fig 3.11.
Degradation of the point bar due to the bankfull flow event of January 1995 (A) and subsequent aggradation in the period thereafter (B) at cross section 3

Fig. 3.10.
Changes in bed material composition, showing a decrease in area with sand during the growing season (July 1995 and July 1996) associated with an increase in area with gravel lags, exposed peat, silt and organic matter (bed material obscured by the aquatic vegetation cover was not mapped in July 1996 and March 1997)

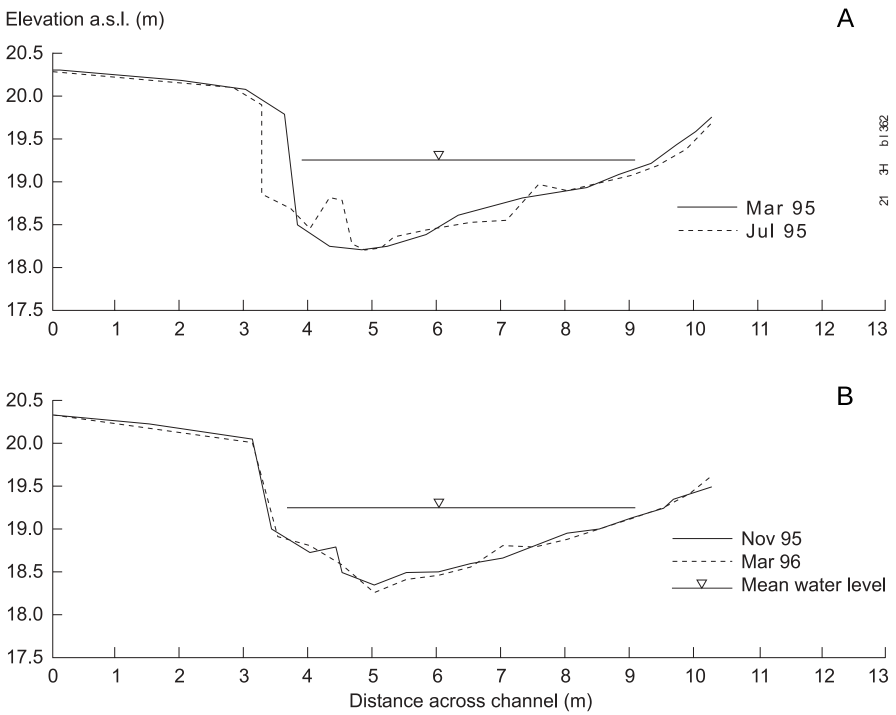


Fig. 3.12.

Formation of chute channels between aquatic macrophytes and associated obstacle bar formation during the period of plant growth (A) and levelling during the period of plant cover decay (B) at cross section 8

deposited underneath the branches and leaves (Fig. 3.13). The growth of dense patches of plants in and downstream of the gently curved bend led to a shift of the thalweg from the left bank towards the right bank and a gradual decrease in the influence of the helical flow cells in the meandering stream. Some of these processes were reversed as the vegetation cover decreased during the next winter season. The new channel bed topography of chute channels and obstacle bars was partly levelled (Fig. 3.12), and the depositional areas, associated with a dense cover of plants during the summer, were slightly eroded (Fig. 3.13).

The same processes were observed during the 1996 summer and 1996/1997 winter seasons. The thalweg of the stream was obstructed by plants during the summer, but was found in March 1997 in a position comparable with that of March 1996 again. However, more chute channels were formed during the growing season, to be filled with sand after the decline of the vegetation cover in winter. The bed material composition again showed marked differences between March, at the start of the growing season, and July when macrophyte coverage was almost at its largest (Table 3.3). A dense cover was not only associated with larger areas of eroded substrate, but

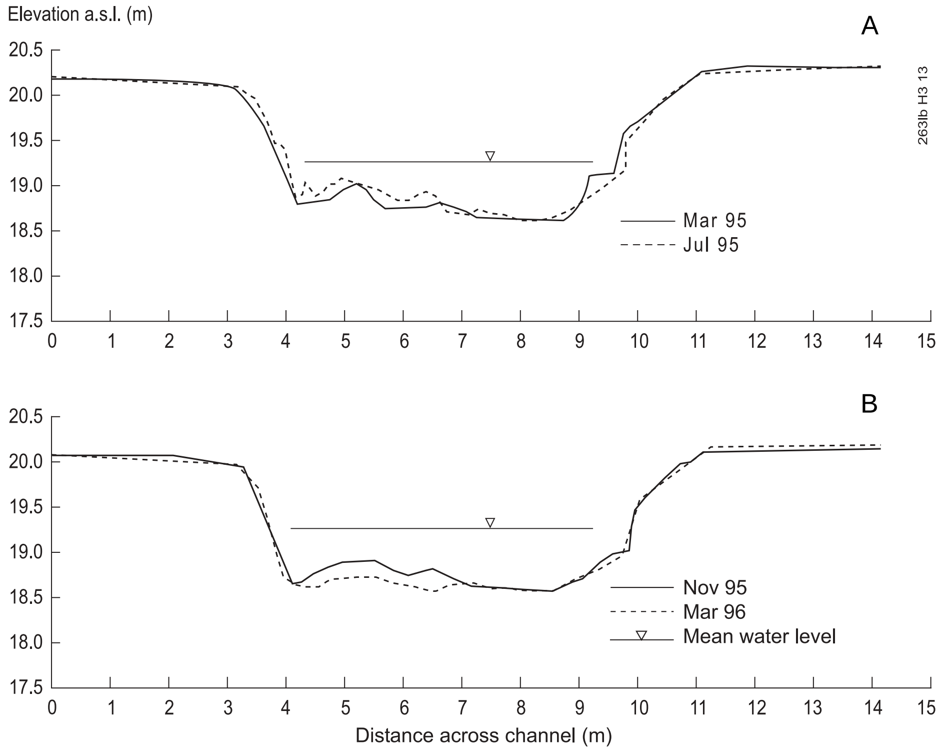


Fig. 3.13.

Deposition under a dense cover of aquatic macrophytes during the period of macrophyte expansion (A) and bed degradation during the period of plant cover decay (B) at cross section 5

also with smaller amounts of sands, silts and particulate organic matter. The relatively high amount of sand observed in May 1997, however, was not only related to the decay of the vegetation cover, but also to an enlarged input of sediment caused by the summer thunderstorm in August 1996.

DISCUSSION

Macrophyte–bedform interactions

The growth strategies of floating-leaved *Potamogeton natans* L. and submerged water-crowfoots (*Ranunculus peltatus* ssp. *heterophyllus* Schrank) were studied by Mesters (1997) in a channelised, low sinuosity reach of the Keersop, situated approximately 4.5 km upstream from the present study area. The percentage cover of macrophytes increased from a total of 30% in March to 73% in May and 96% in September, whereas the maximum coverage observed in the Keersop was 47% (November, 1995).

The increase was mainly caused by the shoot biomass growth of *Ranunculus*, which dominated the stream vegetation from March onwards. *Ranunculus* was, therefore, more dominant than in the reach studied here. This difference in species composition may be part of the natural longitudinal zonation of macrophytes in the Keersop, since *Ranunculus* is typical for the faster flowing upstream reaches of lowland streams. The difference in coverage may be caused by the rehabilitation works as well as by differences in channel planform and in bedform composition. The first aspect was especially dominant during the first year of monitoring (1994), during which the macrophyte roots had not yet been able to develop a maximal storage capacity. However, the pools – especially the one in the tightly curved bend – as well as the major and minor channels also remained devoid of macrophytes in 1996. The water depth in the pools was 0.9-1.2 m at mean discharge. This depth obviously causes so much attenuation of light that photosynthesis is hardly possible anymore (Querner, 1993). In the major channels, the helical flow cells persist throughout the year and the associated shear stress and turbidity probably reduces the growth of submerged species and submerged stages of (juvenile) floating-leaved species there (Mesters, 1997). These examples clearly demonstrate that bedform diversity influences the distribution of aquatic macrophytes.

Conversely, the coverage by aquatic macrophytes has also been shown to influence the bedform configuration. Plant growth from April onwards disrupts the flow pattern of paired helical cells, which declines during the spring but has been shown to persist throughout the year in a meandering stream without macrophytes – i.e. in the summer season immediately following the completion of the rehabilitation works. Once established, plants create areas of low shear stress immediately behind their stems. The increased obstruction to the flow causes higher flow velocities and convergent flow between the various plant stems. This results in local bed scour and the formation of minor, chute channels. Flow divergence occurs behind the stems, where sand deposition causes the formation of longitudinal bars, and at the distal side of the minor channels where chute bars are formed. In the case of (*Elodea spp.* and *Callitriche spp.*, both growing in large clumps, continuing growth leads to large areas with low flow velocities, where silts and particulate organic matter are deposited in large amounts. Thus, plant growth induces the evolution of very different stream habitats close to each other which is favourable to many stream organisms. The characteristics of river planforms, however, are generally assumed to be determined by the independent variables discharge, valley slope, bed load, bank material and bank vegetation (Hey and Thorne, 1986). As the in-stream bedform configuration is closely related to the river planform, these variables are often used to explain or model the in-stream characteristics of river reaches, for instance when determining resistance to flow. From the above observations, however, it appears that it may be necessary to incorporate the in-stream vegetation as an independent variable as well.

Bedform classification and sediment exchange

In general, the division of bedforms into macroforms, mesoforms and microforms is only applied to the sedimentary features of river channels (e.g. Reineck and Singh, 1980; Church and Jones, 1982). Erosional bedforms are seldom incorporated, with the exception of the pool in the pool-riffle unit. However, it appears that erosional forms are just as characteristic as the depositional ones. A classification of all bedforms is proposed in Table 3.4. Following Jackson (1975), criteria for classification are mainly based on bedform size, time-span of existence and superposition. Pools, major channels, point bars and the platforms distinguished, have been shown to survive throughout all seasonal events and thus are typical macroforms. Their configuration is adapted to the helical flow pattern of the meandering reach. Minor channels and sand bars are the result of a typical river regime event occurring in summer: low discharge – approximately 1.5 m^3 s^{-1} or less – accompanied by macrophyte growth. These are classified as mesoforms. As was expected, typical mesoforms such as dunes or antidunes have not been encountered in the study reach because these features require a larger channel depth and width. Surprisingly, the area covered by microforms remains very small throughout the year. This is not only due to the meandering planform and associated helical flow – in straight, channelised reaches ripples may cover almost the entire bed – but also to the presence of macrophytes, increasing the area with local convergent flow during the growing season.

Point bars and the mesoforms developed near the crossover and on point-bar tails are the main sediment storage features in the Keersop. Along the convex banks, alternate erosion and deposition caused height differences of 0.5–0.9 m, and the net changes at the crossover measured 0.2–0.5 m. In contrast, the variation in the thalweg and the pools (since March 1995) was much smaller, and negligible at the concave bank bench. The direction of development in the point bar was often found to be opposite to that of the crossover. Obviously, the point bars and the mesoforms exchange sediment. The formation of chute channels in the summer season yields material for the extension of point bars and, conversely, the material eroded from point bars in winter fills the chute channels. Anthony and Harvey (1991) also described erosion during the rising limb of the annual hydrograph of point-bar sediments deposited at low flows in the sand-bed meandering Fall River, which has rigid banks like the Keersop. The type of direct sediment exchange described here may, therefore, be typical for meandering rivers that do not actively migrate and, therefore, have to accommodate larger flows entirely within their channels.

Model for stream rehabilitation studies

A conceptual model for the seasonal developments in the Keersop is given in Fig. 3.14. Assuming the occurrence of at least one frost period and a near bankfull event in winter, and base flow in summer without any significant thunderstorm discharge, a cyclical sequence of events may be envisaged. The cycle starts with a period of relatively

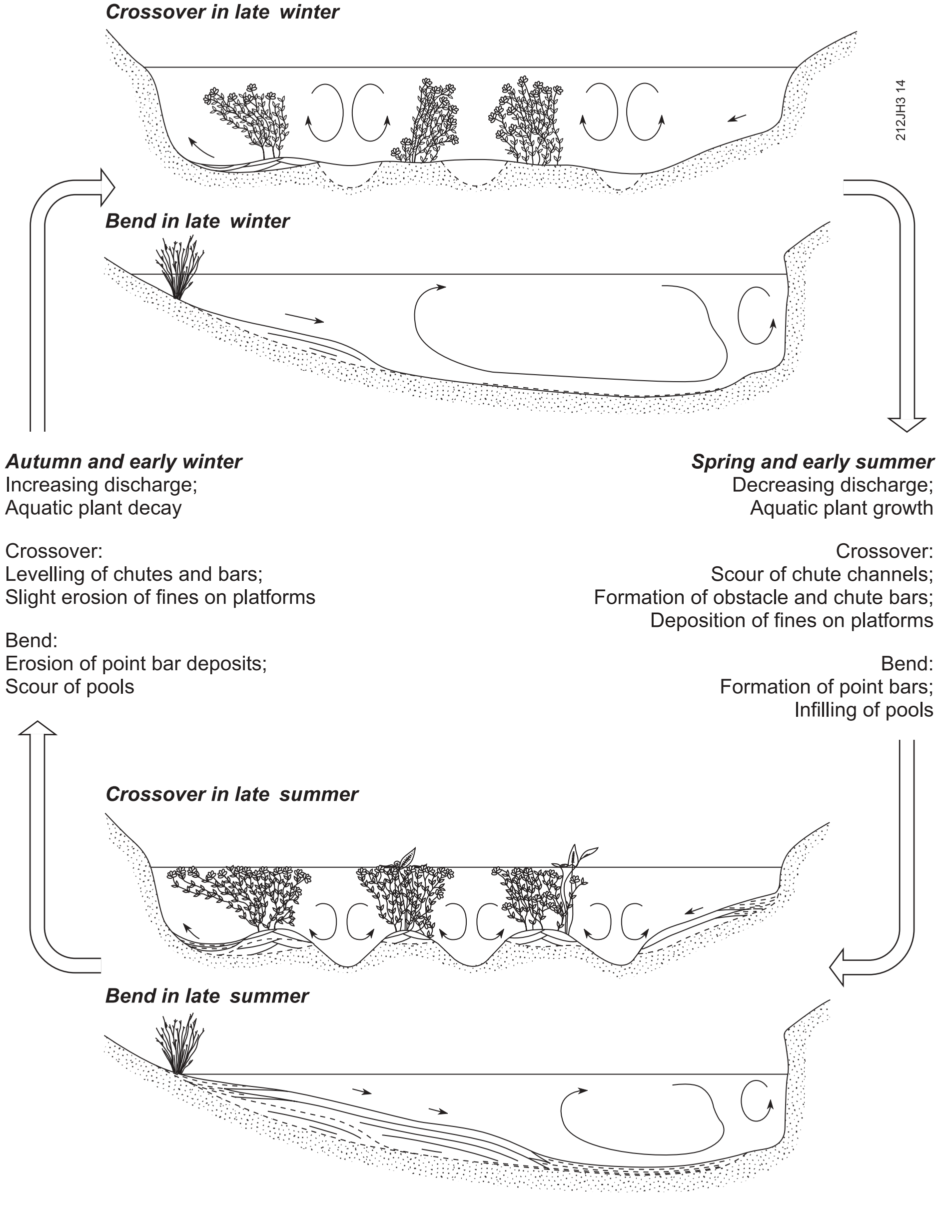


Fig. 3.14.

Conceptual model of seasonal bedform pattern changes, influenced by changes in discharge and aquatic macrophyte coverage high discharge in winter. High flow velocities enable the stream bed to accommodate: the macroform pattern of pools and alternating major channels is activated and minor channels near the crossover are filled with sediment. Flow velocities are lower during spring and summer. Macrophytes cause a shift in the channel thalweg near the crossovers through the formation of small chute channels and the associated bars. Simultaneously, the stream bed in bends responds as material is deposited along the convex banks. In the next winter season a new near bankfull event will restore the original bedform configuration. This cycle does not occur every year since it depends on the occurrence of a relatively large discharge event.

It has been acknowledged that rehabilitation projects require clearly described geomorphological goals (Boon, 1997; Sear et al., 1998). The Keersop provides a reference situation for present and future, rehabilitated streams. The results of the present study can be used as a reference to (1) assess what type of geomorphological features and processes are lacking in the present channelised streams, and (2) which of these need attention in rehabilitation design. Since very detailed guidance developed for one set of environments is not to be applied to other types (Brookes, 1995), the Keersop can only serve as reference reach for rehabilitation projects in similar physiographical settings. The conceptual model of seasonal change, however, has wider implications for design methods and post-project appraisals. Seasonal changes in discharge and macrophyte cover imply changes in the bedform configuration and the resistance to flow as well as the habitat function. Insight into this temporal variability is considered useful to both the design of stream dimensions and to ecological assessments.

CONCLUSIONS

Erosional as well as depositional bedforms have been shown to exist at a range of spatial and temporal scales in the lowland sand-bed meandering Keersop. Based on bedform size, time-span of existence and superposition, the pools, major channels, point bars and platforms are classified as macroforms. The macroform configuration is adapted to the flow paths of the two pairs of alternating helical flow cells in the meandering stream. Chute channels, obstacle bars and chute bars are classified as mesoforms. These bedforms occur mainly near the crossovers and their development is related to the obstruction of flow by aquatic vegetation. Microforms – sand ripples – are found superposed on both the other bedform groups.

The interactions between bedforms and macrophytes are twofold. First, bedform diversity influences the distribution of macrophytes: establishment of plants was inhibited in pools because of attenuation of light and in erosional channels because of permanently high flow velocities. Second, the establishment and growth of aquatic plants disrupts the flow pattern of paired helical cells, resulting in local bed scour, leading in turn to the formation of chute channels in between stems and the formation of the associated obstacle bars and chute bars. Also, a high density of plants induces the deposition of silts and particulate organic matter. Thus, plant growth induces the evolution of very different stream habitats close to each other, which is favourable to many stream organisms.

The influence of seasonal changes in discharge and plant coverage are reflected in the bedform configuration and associated bed substrate. In winter, when macrophyte cover is relatively small, large discharge events activate the macro bedforms. Point bars along convex banks are eroded and chute channels near crossovers are filled with sand. In summer, smaller discharges and expansion of plant cover result in the formation of mesoforms, and the sand eroded from chute channels is used to restore the point-bar surface. Thus, point bars and the mesoforms are the main sediment storage features and sediment is exchanged between them. This model of seasonal change is considered useful in both the design and evaluation of meander rehabilitation strategies.

ACKNOWLEDGEMENTS

This research was financed by the Netherlands Ministry of Agriculture, Nature Management and Fisheries and by the Province of Noord-Brabant. We gratefully acknowledge the cooperation of De Dommel water board, who collected and provided the data on discharge, flow velocities and cross-sectional dimensions. Valuable comments on a draft of this paper were made by Janrik van den Berg, Bert Higler, Jan Klijn, Ward Koster and Colin Thorne.

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4

Channel and bedform response to meander rehabilitation in lowland sand-bed streams

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Submitted to Earth Surface Processes and Landforms

ABSTRACT

The short-term impact of artificial re-creation of a meandering channel in small, sand-bed lowland streams in the Netherlands is described. The geomorphological responses of the Tongelreep, Keersop and Aa were studied in two-bend reaches by means of cross-sectional surveys and detailed geomorphological mapping in March, July and November, during a period of 2 to 3 years. Bedform adjustments in the Tongelreep and Keersop included local scouring of pools, undercutting of banks, coarsening of bed material and the formation of depositional bedforms. Initial responses led to a strong increase in the diversity of bedforms and associated bedform materials. The largest sediment production rates, however, were associated with the first bankfull discharge event. Differences in bank materials had a major influence on rates of bank failure and consequently on the amount of sediments stored in the channel. Both the balance between sediment input and output and a bedform configuration similar to that of natural sand-bed rivers have been restored in the Keersop, but not yet in the Tongelreep, because of the greater stability of the banks of the Keersop. The application of various cross-section types and the excavation of a by-pass channel had no effect, but channel migration rates decreased and the depth of pools increased with an increasing ratio of radius of bend curvature to channel width, due to a different flow pattern. The response in the Aa was almost nil because of oversized cross-sectional dimensions. The increase in diversity of bedforms in the Tongelreep and Keersop was expected to enhance the stream habitat function, but an associated increase in macroinvertebrate species richness could not be demonstrated, probably because this takes longer to occur. It is argued that this type of monitoring is important for developing effective strategies in river rehabilitation.

KEY WORDS
Bank erosion, Bedform configuration, Channel cross section, Macroinvertebrates, River rehabilitation, the Netherlands

INTRODUCTION

Troughout Europe and North America small lowland streams have been channelised over the last few hundred years, mainly to improve agricultural production (Brookes, 1988). Stream channels have been straightened, cross-sectional dimensions enlarged and in many cases headwaters have been extended further upstream in the drainage basin. As a result, the physical variety in bedforms and bed materials has been destroyed and the natural value of most stream ecosystems has seriously declined. Nowadays, most water management authorities have adopted new concepts for sustainable management of water resources and many projects have been initiated to rehabilitate the ecosystems of lowland streams (e.g. Brookes and Shields, 1996; Hansen and Madsen, 1998).

One of the most promising measures to be considered in the planning of these projects is the rehabilitation of meanders (Glitz, 1983; Brookes, 1987; Madsen, 1995, Verdonschot, 1995; Hansen, 1996; Vivash et al., 1998), defined here as the re-creation of a sinuous channel planform. Meander rehabilitation, or re-meandering, is important for three main reasons. (1) A meandering channel possesses a large heterogeneity in flow characteristics, bedforms and bed materials. This diversity is essential for the return of many fish and macroinvertebrate species in the stream ecosystem, which often need different physical habitats for feeding, shelter and reproduction. Erosion of stream banks and associated deposition within the channel sustain this habitat diversity in a natural way. (2) Meandering implies a relatively long retention time of water in the fluvial system. As a result, meander rehabilitation raises the groundwater level within the surrounding parts of the drainage basin and increases the flooding frequency in the stream valley. It can, therefore, be considered a measure for the conservation of water in areas with shortages of fresh water during the summer season (Kwakernaak et al., 1996). A raised groundwater level in stream valleys may support riparian wetland vegetation, which raises nutrient retention, thereby reducing nutrient concentration in the streams channels. An increase in flood frequency might also enhance the river-channel–floodplain interaction, which is important for the food chain in the downstream reaches, since much of the biomass is derived from the highly productive floodplain wetlands. (3) As well as generating a greater diversity of vegetation, meandering and natural stream banks are recognised as important factors in the perception of river landscapes by the public (House and Sangster, 1991). In landscape policy terms, meandering streams may be considered of earth-science value, as one of the few places exhibiting natural geomorphological processes in some of the cultural landscapes of Western Europe.

Many of the lowland streams to be rehabilitated drain agricultural land and built-up areas, so that river managers have to negotiate with farmers or other residents when planning a stream rehabilitation project. Those involved are often anxious to know the effects of re-meandering in terms of rates of bank collapse or the amount of sediment deposited downstream, which influences flooding frequency in the stream valley. Such aspects determine the amount of riparian land to be purchased and/or the financial compensation to be awarded for the decrease in agricultural productivity. Also, planners themselves are anxious to obtain restoration design criteria that indicate the type of bedform response, enabling them to assess correctly the impacts of design choices on the future stream habitat function. However, these questions often remain unanswered since geomorphology, in contrast to hydrology and aquatic ecology, is not frequently involved in this planning process. Practical knowledge of the effects of re-meandering can be obtained in monitoring projects. Until now, however, few studies have been published documenting the short-term physical impact of meander rehabilitation on lowland streams (Friberg et al., 1998, Sear et al., 1998, Kronvang et al., 1998). In this paper the short term geomorphological impact of meander rehabilitation in three small, sand-bed lowland streams in the southern part of the Netherlands will be described: the Tongelreep, the Keersop and the Aa. Research objectives are to compare (1) the changes in channel cross-sectional dimensions and related sediment production caused by processes of bank collapse, aggradation and degradation, and (2) the changes in channel bedform configuration and associated bed materials relevant to the stream habitat function.

REHABILITATION PROJECTS

Physiography and hydrology

The Tongelreep, Keersop and Aa are tributaries of the River Dommel (Fig. 4.1). The

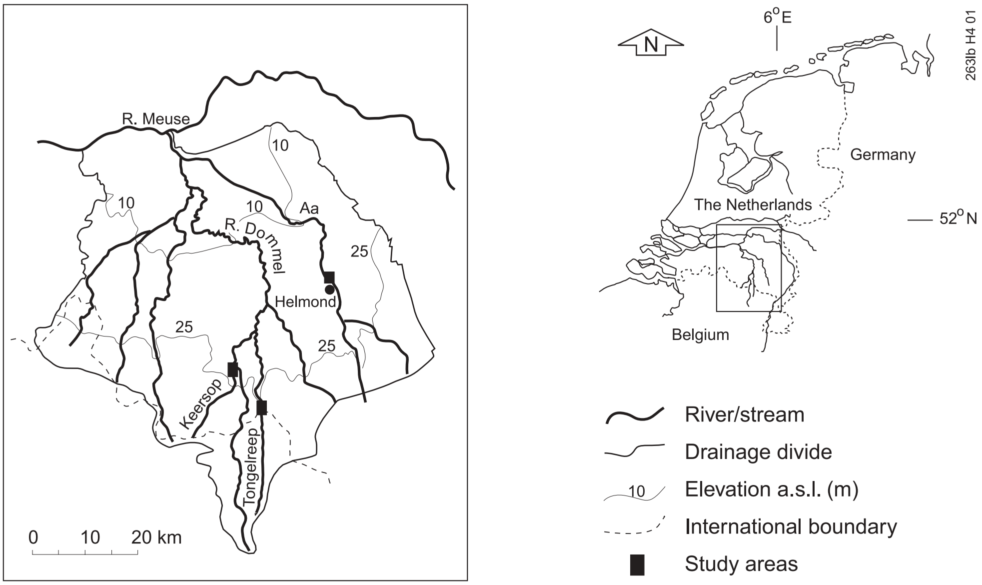


Fig. 4.1.

Locations of the Dommel drainage basin and the rehabilitation reaches in the Tongelreep, Keersop and Aa

Dommel drainage basin has an undulating to flat topography and is underlain by gravelly and sandy deposits of fluvial and marine origin, mainly covered by Pleistocene fluvio-periglacial sands or loams and by aeolian sands (Bisschops et al., 1985). In the shallow valleys, Holocene peat and sandy fluvial deposits occur. Mid-19th century topographic maps indicate that the three streams studied were at that time characterised by an irregularly meandering planform. The streams were eventually channelised in 1880 (Keersop), 1890 (Tongelreep) and 1935 (Aa) to reclaim peatlands and improve drainage of agricultural land.

During the period 1961–1990, mean annual precipitation was 725–800 mm and mean annual evapotranspiration 550–575 mm (Meinardi et al., 1998). As a result, the stream discharge hydrographs generally show large volumes of runoff occurring in winter and base flow discharges in July and August.

Rehabilitation design

Since the Tongelreep was one of the first stream rehabilitation projects in the Netherlands, many difficulties had to be overcome. Concerns existed about supposed hazards caused by bank collapse and upstream flooding with polluted water due to instream deposition. A new design was produced for the Tongelreep, which clearly deviates from the irregularly meandering channel in the past. The final design was chosen out of several scenarios which were tested using hydraulic models (Van Acht et al., 1992). A 2.1 km long sinuous channel was created, with smoothly curved bends and long straight sections in between (Fig. 4.2 and Fig. 4.3; Table 4.1). Various cross-section types were applied. To accommodate the flooding problem, the most upstream part of the rehabilitation reach was oversized and a separate by-pass channel was excavated along its most downstream part. The cross-sectional dimensions were gradually reduced in size in the downstream direction and the sinuosity increased. Sand traps were installed at the beginning and the end of the rehabilitation reach to compensate for the enlarged input of sediment in the stream, which was expected during the initial year(s)

Table 4.1.

Channel dimensions at the study sites, observed at the beginning of the monitoring period

STREAM	E (m)	P (-)	S (-)	w_{bf} (m)	d_{max} (m)	d_{mean} (m)	$r_m\ w^{-1}$ (-)
Tongelreep	Bend 1: 24.4 Bend 2: 24.0	1.84	S_b: 0.00066	9.62	1.62	1.10	Bend 1: 2.15 Bend 2: 2.16
Keersop	18.9	1.44	S_w: 0.00067	8.06	1.64	1.17	Bend 1: 0.71 Bend 2: 1.60
Aa	12.7	1.40	S_b: 0.00019	14.13	1.96	1.02	Bend 1: 0.85 Bend 2: 1.55

E, elevation above sea level; P, sinuosity; S_b, bed slope; S_w, water surface slope; w_{bf}, bankfull width; d_{max}, maximum bankfull depth; d_{mean}, mean bankfull depth; $r_m\ w^{-1}$: ratio radius of curvature to width.

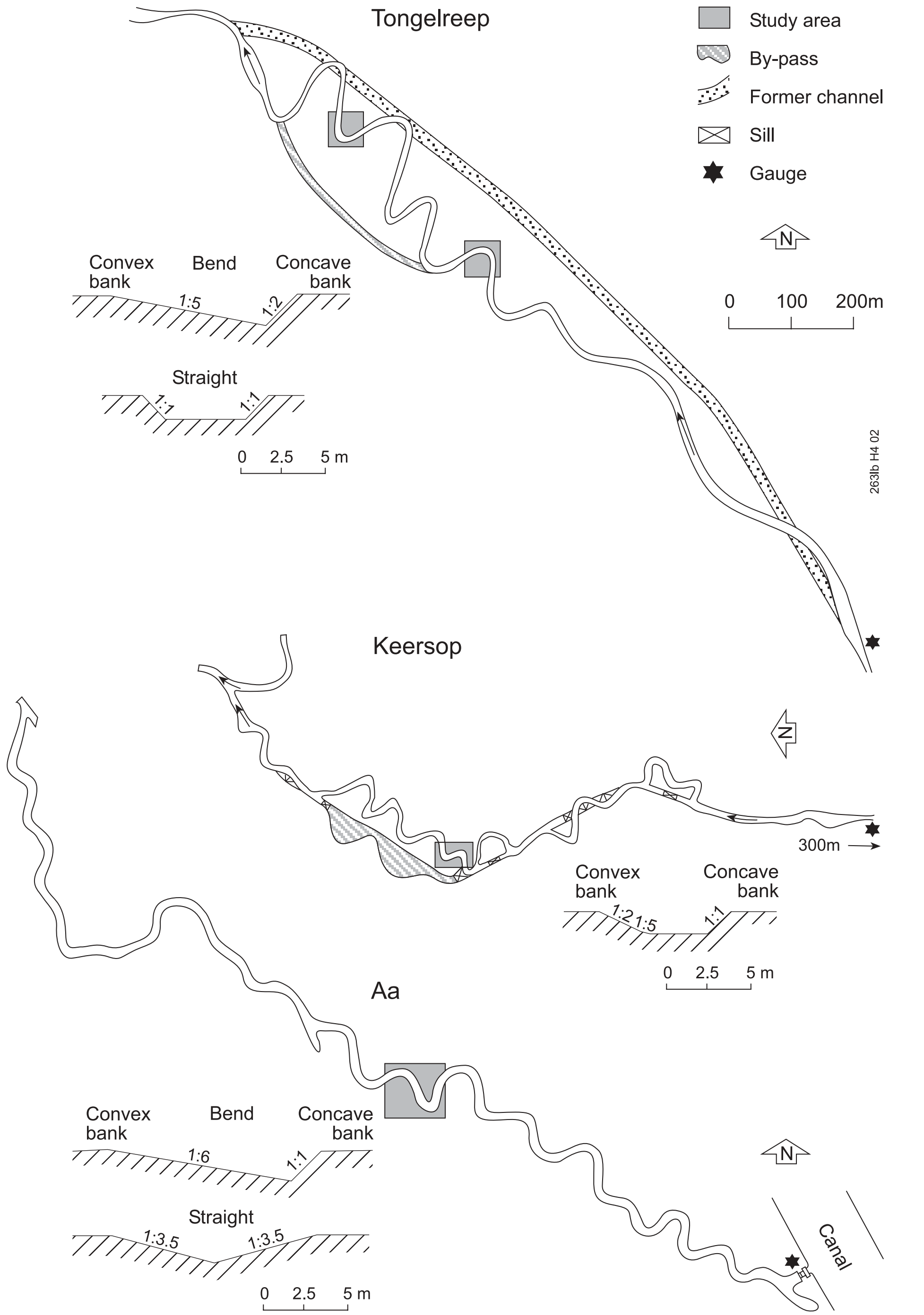


Fig. 4.2.
Layout of the rehabilitation reaches, dimensions of cross sections excavated and the locations of the study sites

Fig. 4.3.

The rehabilitated meanders at the study sites at the Tongelreep (upper), Keersop (middle) and Aa (lower), 1–2 months after completion of the excavation works following rehabilitation. The project planning took six years because of resistance by some local farmers and residents. The stream rehabilitation works were completed in September 1995.

In the Keersop, the stream rehabilitation design made use of remnants of the former meanders, which were still present as artificial oxbow lakes in the vicinity of the straightened stream. These oxbow lakes were reconnected to each other over a length of 1.2 km. The cross-sectional dimensions of the new meandering channel were adopted from the historical ones, using information from soil profiles. A channel with a trapezoidal cross section was excavated, assuming the flow itself would be able to form the desired in-channel habitat diversity. To compensate for the present hydrological regime, which was assumed to lead to higher stream stages compared with the historical ones, the normalised reach was transformed into a by-pass channel. Stony sills within the former channel direct the flow into the new meanders, but are overtopped just before flow exceeds bankfull discharge in the meandering channel. Sand traps were installed at both the upstream and downstream parts of the rehabilitation reach, which has a total length of 1.5 km. The stream rehabilitation works were completed in April 1994.

The Aa runs along the edge of the town of Helmond and for that reason the aim of stream rehabilitation was not only the ecological recovery of the stream system, but also an enhanced scenic quality. Moreover, a new discharge regime had to be designed. Some years prior to the stream rehabilitation project, the stream was isolated from its drainage basin by the construction of a large navigation canal. As a result, the downstream part of the Aa was connected only to the discharge system of the urban area. For rehabilitation purposes, a weir with a variable overflow device was installed in the banks of the new canal to re-water the rehabilitated Aa. The new discharge characteristics and the new cross-sectional dimensions of the Aa are based on the discharge hydrograph of the Bakelsche Aa, one of its former tributaries which flows near the rehabilitation reach. Cross sections have been excavated in a V-shaped form. The meandering planform is a new design but was partly based on information contained in 19th century topographical maps. The rehabilitated reach is 2.2 km long and was completed in November 1994.

Monitoring programme

In each of the rehabilitated reaches a study site was selected, which (1) incorporates a sharply curved bend and a less sharply curved bend separated by a crossover reach, (2) has banks with an undisturbed, non-reinforced soil profile, and (3) is located as far away as possible from the upstream sand trap, assuming this distance is large enough to accommodate the sediment load deficiency occurring in the upstream part of the rehabilitation reach. Two separate meanders of the Tongelreep were studied, to allow a comparison of channels with and without a by-pass.

Water discharge was measured at gauges located near the entrance of the rehabilitation reach. In the Keersop, however, the gauge was located 300 m further upstream. The discharge of the Tongelreep was measured daily, while those of the Keersop and Aa were observed continuously.

Nine or ten cross sections were measured at each of the study sites. Because of the relatively long straight sections in between the bends of the Tongelreep, 5 cross sections were located in each bend.

Changes in bedform configuration were mapped by detailed geomorphological surveys. Mapping has been advocated by Newbury (1996) as a basic tool in the study of stream hydraulic conditions and habitats. In this study a mapping system was applied, that had been developed for monitoring geomorphological and geo-ecological changes in small and shallow streams in the Netherlands (Koomen et al., 1997). The legend was derived from an existing mapping system developed by De Graaff et al. (1987). Different bedforms and bank features were distinguished according to their morphology and delineated on the basis of breaks of slope. All units were mapped in the field using a network of poles along both banks of the streams, placed within 2 m of each other. Sediments associated with bedforms were indentified by means of visual inspection and delineated on the basis of the bedform morphology. The occurrence of aquatic macrophytes was also mapped. A mapping scale of 1:100 was chosen as most suitable for the size of the features to be represented.

The surveys started soon after the rehabilitation projects were completed and lasted for a period of 2 years. In the Keersop, an additional survey was carried out approximately three years after rehabilitation. Measurement were taken in (1) March, (2) July, and (3) November. The measurements taken in March document the effects of high winter discharges on the channel banks and bedform patterns. The distribution of habitats in early spring is considered to be crucial for the development of the juvenile instream macroinvertebrate community (W.B. Higler, pers. comm.). In July, the effects of base flow in summer and the impacts of in-channel aquatic macrophyte growth are recorded. In November, the instream vegetation cover is just over its maximum. This is also a suitable time to analyse the effects of summer thunderstorms on the morphology. The mapping survey always preceded measurement of cross-sectional dimensions, since making these measurements can disturb the bedform pattern. During the project, it was decided to map the Aa less frequently, since only minor changes occurred.

The data on cross sections and bedform configuration were processed using the software package ARC/INFO (ESRI, Redlands, CA). Changes in the cross-sectional dimensions were calculated by means of overlay procedures.

RESULTS

Discharge events

Two events of bankfull discharge occurred during the period from November 1994 to July 1997 (Fig. 4.4). The first event was related to the exceptionally wet winter season in 1995, which caused flooding in all streams and larger rivers in the region in January. At the Aa study site, however, the artificial canal water inlet was shut down just before

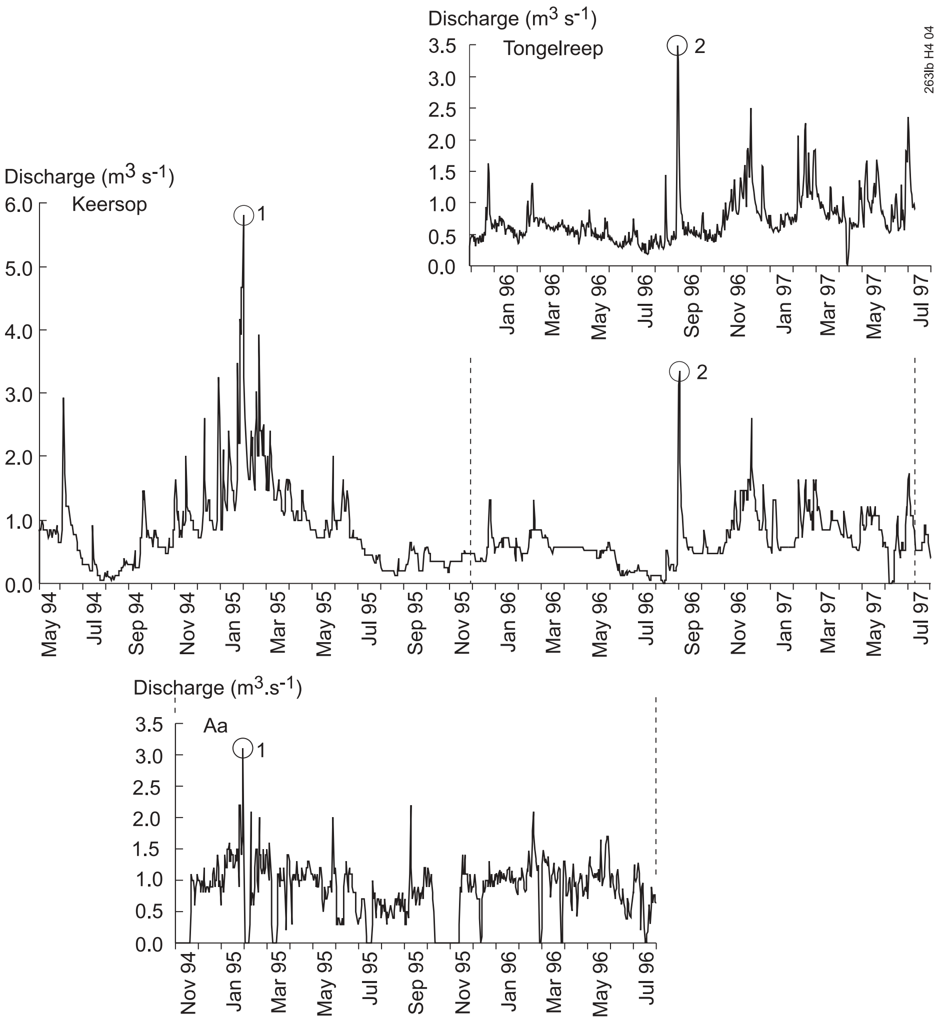


Fig. 4.4.
Discharge hydrographs, recording the two bankfull flow events during the monitoring period caused by prolonged precipitation during the winter season (1) and a summer thunderstorm (2)

bankfull was reached to prevent a further rise in water levels downstream. In contrast, the 1995/1996 winter season was relatively dry. The second event of high discharge was caused by a local summer thunderstorm in August 1996. It resulted in a bankfull event in the Tongelreep. The drainage basin of the Keersop, however, was not fully covered by the storm so that bankfull water levels were not reached.

Mean and maximum discharges are presented in Table 4.2. Maximum discharge in the Keersop study site is 75% of the total discharge measured at the upstream gauge, since the by-pass receives 25% during bankfull events. The discharge of the by-pass

Table 4.2.
Discharge characteristics and maximum values of flow velocity and specific stream power during the monitoring period

STREAM	Q_{mean} ($m^3\ s^{-1}$)	Q_{max} ($m^3\ s^{-1}$)	V ($m\ s^{-1}$)	Ω ($W\ m^{-2}$)
Tongelreep, bend 1	0.58	3.4	0.33	2.16
Keersop	0.77	4.4	0.46	3.59
Aa	0.83	3.2	0.22	0.42

Q_{mean}, *mean discharge;* Q_{max}, *maximum discharge (estimated);* $V = Q_{bf}/wd$, *mean flow velocities;* $\Omega = \rho g Q_{bf} S/w_{bf}$, *specific stream power, where* $\rho = 1.0\ kg\ m^{-3}$, *density of the water;* $g = 9.8\ m\ s^{-2}$, *acceleration due to gravity.*

along the Tongelreep is unknown. Assuming that the maximum discharges observed more or less equal bankfull discharge, flow velocity and specific stream power during bankfull could be estimated (Table 4.2). At that time, only a few, small aquatic macrophytes had established. It appears that flow velocities and especially specific stream power in the Tongelreep and Keersop were far greater than those in the Aa.

Bank retreat

Within a few months after completion of the rehabilitation works, scour at the bank toes resulted in various breaks in slope and in escarpments. Groundwater seepage in winter and spring also caused such features. Gradually, as higher discharges occurred, many of these escarpments were transformed into undercut banks (Fig. 4.5). Along the Tongelreep, undercutting was more severe in bend 1 (the most upstream bend). A marked increase in the rate of undercutting was initiated by the thunderstorm event in August 1996, after which the rate of formation of undercut banks remained high in bend 1. In this bend, undercutting was not restricted to the outer bend but occurred in both banks at the bend entrance and exit as well. In bend 2 (the most downstream bend) rates of undercutting decreased after the bankfull event. In the Keersop, both concave banks were severely undercut, but rates of erosion also decreased after the bankfull event in January 1995. In contrast to the Tongelreep and Keersop, the Aa experienced few changes in the morphology of its banks. Initially, some small erosional escarpments were observed in concave banks, but these soon were buried beneath a layer of clay. Moreover, a dense vegetation dominated by common reed (*Phragmites australis*) obscured most of the small bank features from the summer of 1995 onwards.

Severe undercutting led to channel migration. Retreat of the break of slope, excavated at the top of the concave banks, was observed in the Tongelreep and in the gently curved bend of the Keersop (Table 4.3). In bend 1 of the Tongelreep, undercutting not only resulted in the largest lateral migration observed, but also affected the largest concave bank length. Slab-type and cantilever failures resulted in bank retreat over a bank length of 23 m by July 1997, which was approximately 2/3 of the concave bank, whereas in bend 2 retreat was restricted to a 1 m length of bank. Two

Table 4.3.
Maximum channel migration rates

STREAM BEND	PERIOD	MAXIMUM MIGRATION (m)	M (m yr^{-1})	M/w (yr^{-1})
Tongelreep 1	Nov 95 – Jul 97	1.6	0.87	0.09
Tongelreep 2	Nov 95 – Jul 97	0.4	0.22	0.03
Keersop 1	Jul 94 – Mar 97	0.0	0.00	0.00
Keersop 2	Jul 94 – Mar 97	0.5	0.17	0.03
Aa 1	Nov 94 – Mar 96	0.0	0.00	0.00
Aa 2	Nov 94 – Mar 96	0.0	0.00	0.00

M, migration rate; M/w, relative migration rate; w, bankfull width.

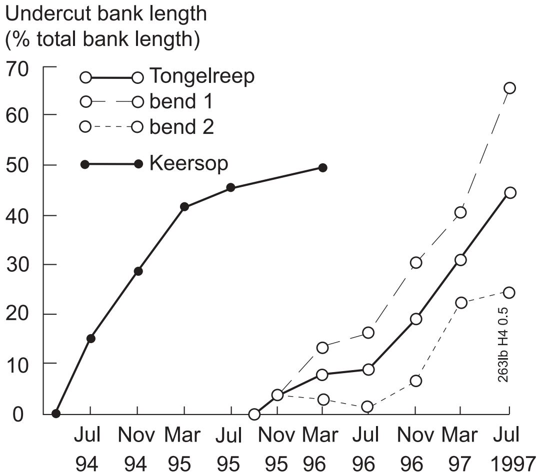


Fig. 4.5.
Changes in the length of undercut banks

spots of bank retreat occurred along the Keersop, both approximately 3.5 m in length. Here, failure was of the cantilever type. In both streams, bank retreat was triggered by the bankfull events in January 1995 (Keersop) and August 1996 (Tongelreep), but continued locally in the periods thereafter. In all bends maximum retreat occurred downstream from the bend apex. In the tightly curved bend of the Keersop, no retreat was observed during the study period, despite undercutting.

Cross-sectional change

The changes in cross-sectional dimensions of the Tongelreep, Keersop and Aa are shown in Fig. 4.6. The net change is the sum of the changes observed at the various cross sections within a study reach. The changes observed on the successive measurement dates are cumulated. On most measurement dates it was observed that

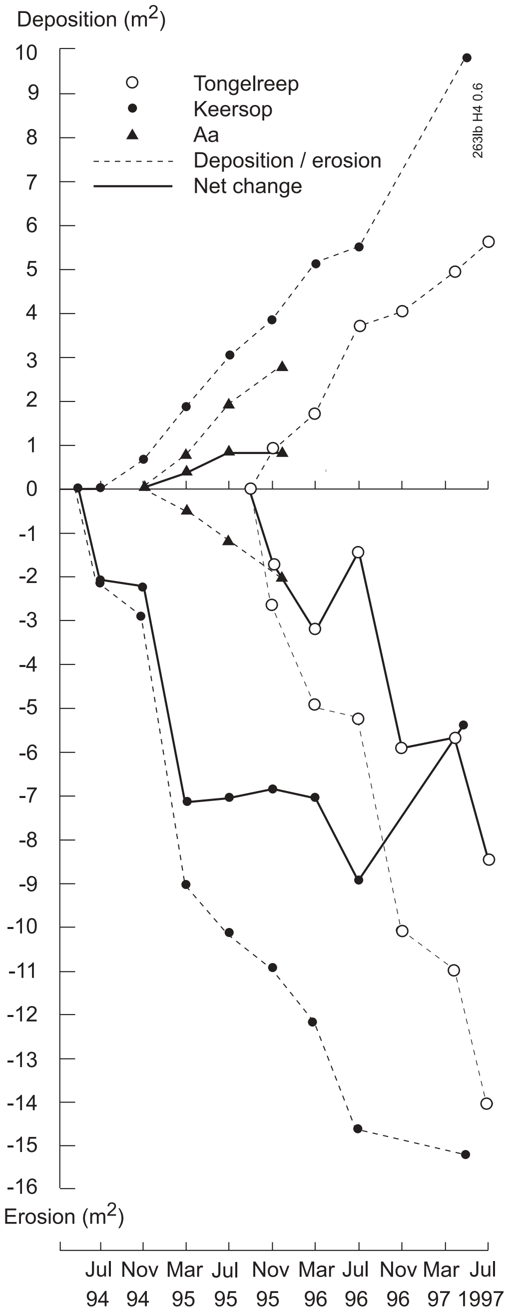


Fig. 4.6.
Changes in cross sectional dimensions

some cross sections had been degrading while others had been aggrading. To indicate the relative importance of erosion and deposition, these changes in degrading and aggrading sections are depicted separately in Fig. 4.6, and referred to as gross change from now on. Gross change due to erosion is considered to be an indication of the total sediment production in a reach. Therefore, differences due to erosion and deposition within one cross section are neglected here to facilitate comparison between streams.

Initially, after completion of the rehabilitation works, erosion prevailed in the Tongelreep and the Keersop. Erosion rates were large but declined after a few months, until a bankfull discharge induced high rates of erosion again. In the Tongelreep both local erosion and deposition in bend 1 were larger than in bend 2. After these flood events, however, developments were different. The process of widening continued in the Tongelreep, but erosion declined in the Keersop and came into balance with deposition. In the Keersop, degrading cross sections were observed in bends and aggrading cross sections at the crossover. The total sediment production observed during the entire monitoring period in the Tongelreep and Keersop is presented in Table 4.4. These data show that most sediment was produced in bend 1 of the Tongelreep, due to the high rates of bank retreat. In the Aa, the changes in cross sectional dimensions were small, and deposition was the dominant process. A soft, unripened clay, rich in organics, was deposited in a layer up to 50 cm thick in the channel bed and 10 cm thick on the lower parts of the stream banks. The clay may originate from scour where the canal water falls more than 1.5 m from a weir into a pool which is

Table 4.4.
Sediment production during the monitoring period

STREAM / BEND[1,2]	TOTAL SEDIMENT PRODUCTION (m^3)	SEDIMENT PRODUCTION RATE (m^3 yr^{-1})	SEDIMENT PRODUCTION RATE PER UNIT AREA (m yr^{-1})
Tongelreep, bend 1	84.7	46.2	0.09
Tongelreep, bend 2	39.7	21.6	0.04
Keersop	57.8	19.3	0.04

[1] *investigated area: Tongelreep 1, 527 m^2; Tongelreep 2, 572 m^2; Keersop, 532m^2*
[2] *monitoring period: Tongelreep, 22 months; Keersop, 36 months*

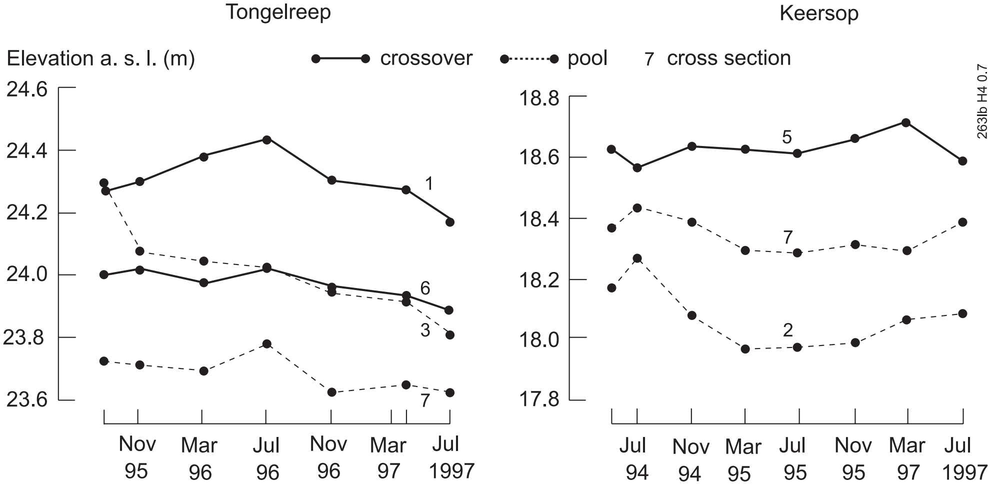


Fig. 4.7.
Developments of pools and crossovers, measured at the deepest part of cross sections

drained by the Aa.

Pools were formed by the flow in the Tongelreep and the Keersop almost immediately after rehabilitation works were completed (Fig. 4.7). In the Tongelreep, scouring occurred during the entire study period. Within one year, the depth of the pool in bend 1 was approximately 40 cm, measured from the top of the crossover, whereas the pool in bend 2 was 30 cm deep. At the same time, deposition occurred in the thalweg near the crossover. Since August 1995, however, the entire thalweg has been degrading. Change has been more pronounced in bend 1 than in bend 2. In the Keersop, the pool in the tightly curved bend was scoured to a depth of 60 cm, whereas pool depth was 30 cm in the gently curved bend. In the Keersop, however, scour stopped in July 1996 and the pools were partly filled by sediment. The depth of the thalweg near the crossover was relatively stable, but the position of the thalweg frequently changed due to the growth and decay of submerged macrophytes.

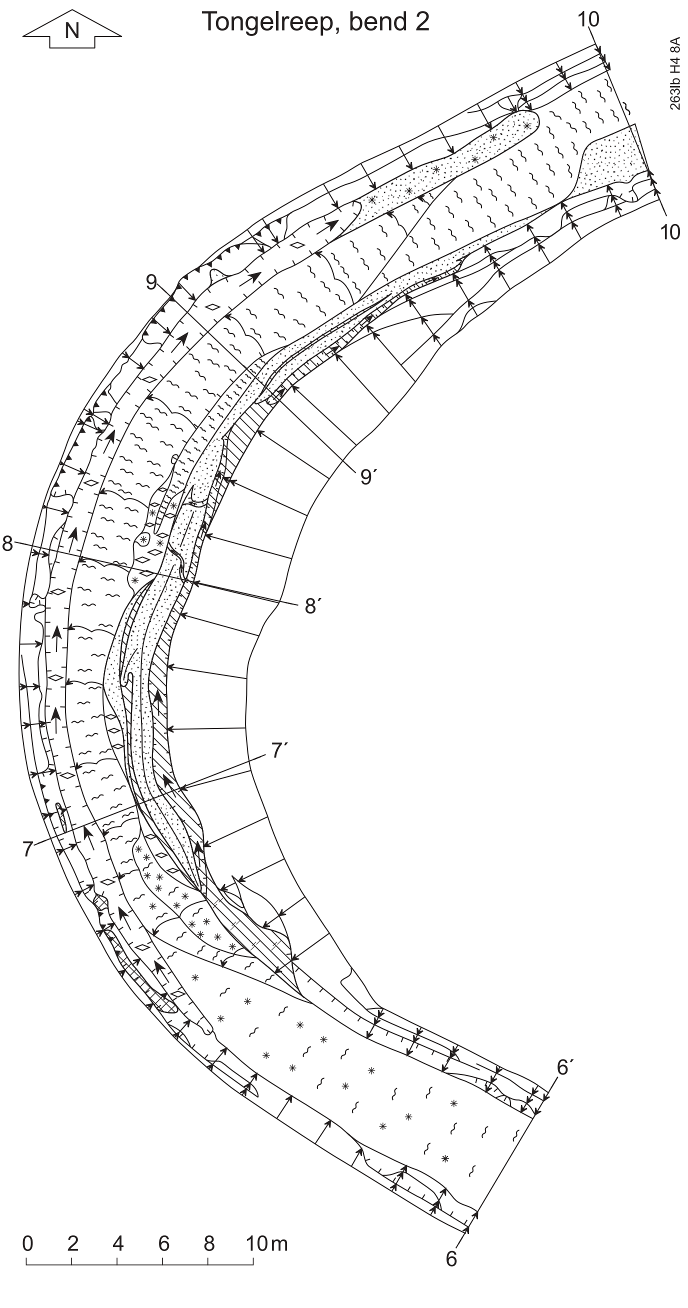
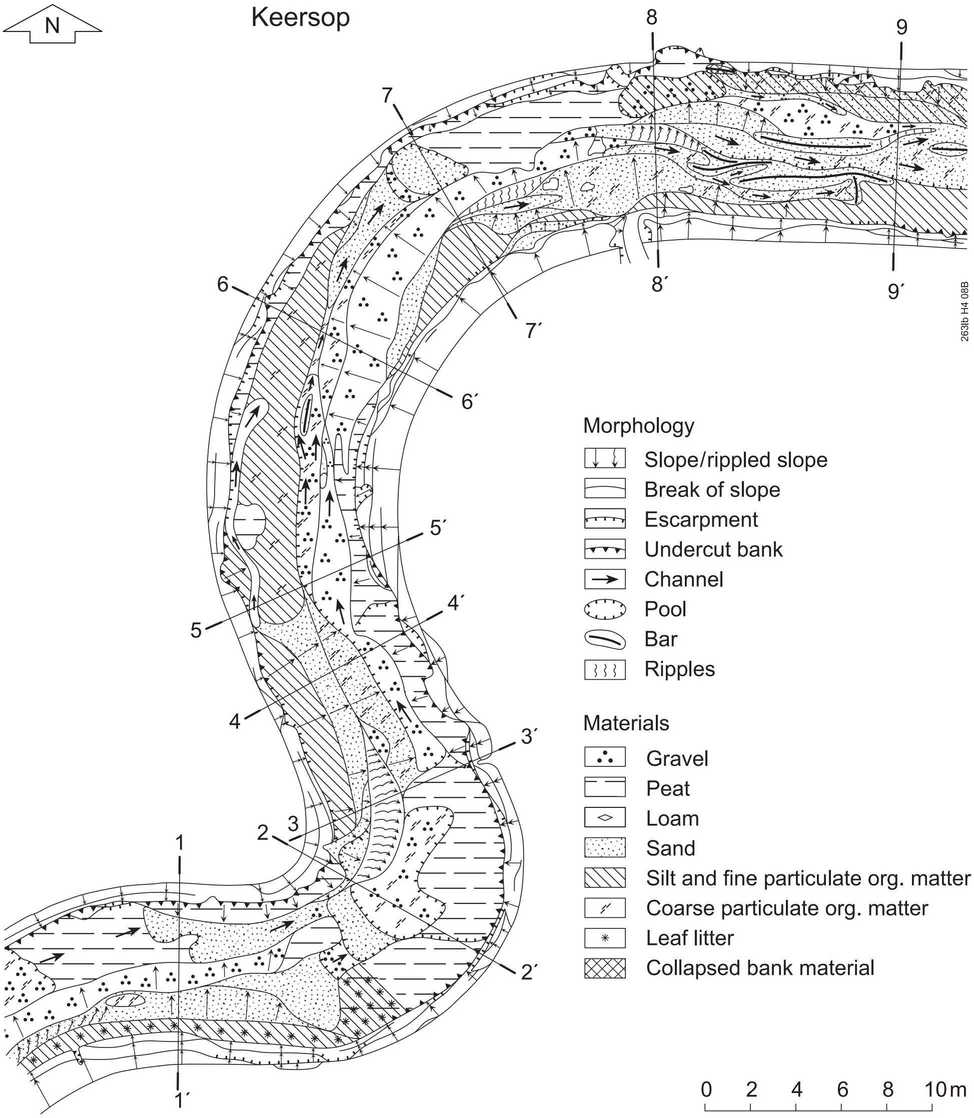


Fig. 4.8.

Geomorphological maps indicating bank features, bedforms and bedform materials during the first summer season following rehabilitation (Tongelreep: July 1996; Keersop: July 1995)


N
Keersop
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263lb H4 08B
Morphology
Slope/rippled slope
Break of slope
Escarpment
Undercut bank
Channel
Pool
Bar
Ripples
Materials
Gravel
Peat
Loam
Sand
Silt and fine particulate org. matter
Coarse particulate org. matter
Leaf litter
Collapsed bank material
0 2 4 6 8 10 m

Bedform development

In the Tongelreep, initially, shallow, elongate channels – or pools – developed along the concave banks as a result of slight erosion of the loamy substrate. The majority of the channel bed in between the bends was covered by sand. Once larger discharges occurred, rippled sands invaded the bends (Fig. 4.8) and some silt and fine particulate organic matter accumulated on the convex bank toe. Whereas bed topography remained rather monotonous in bend 1, the establishment of some aquatic macrophytes in bend 2 induced the development of small chute channels and elongate obstacle bars behind plant stems. Following the August 1996 summer thunderstorm, collapsed bank material was found fringing the pools in bend 1. In bend 2 this event induced the formation of elongate sand ridges along the convex bank, indicating initial point-bar deposition. Here also, plants established in the summer of 1997. Throughout the monitoring period, bedforms remained rather inconspicuous and rippled sands dominated the bed substrate (Fig. 4.9).

In the Keersop, a more complex bedform configuration and a greater diversity of bed materials were observed (Fig. 4.8). Initially, in response to the pattern of helical flows, shallow channels developed in bends and near the crossover some lobate sand bars were formed. Since the bankfull discharge in January 1995, however, other bedforms were observed too. Small, but relatively deep pools were scoured in bends, and material was stored in distinct point bars and near the crossover. In the tightly curved bend, a reverse current initiated the formation of a concave bank bench on which silts and organic matter were deposited. Erosion of channels resulted in exposed peat layers and gravel lags. From 1995 onwards, the growth of submerged Canadian waterweed (*Elodea spp.*) and water starworts (*Callitriche spp.*) resulted in the formation

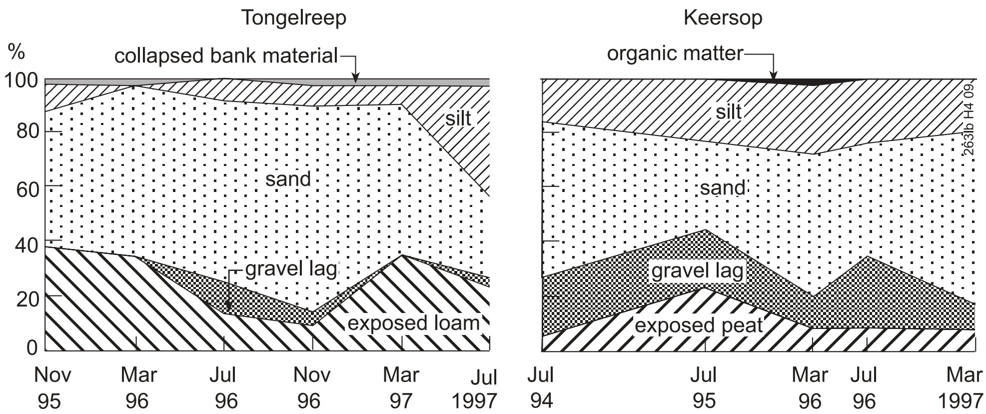

Fig. 4.9.
Differences and changes in bed material

of many chute channels, obstacle bars and chute bars, especially in between the bends. Despite undercutting, collapsed bank material was scarce.

Morphological mapping in the Aa was strongly restricted by the turbid water. However, since the dynamics of the Aa are almost negligible, and only a thin layer of clay was deposited, not many bedforms features were formed. On the lower parts of the convex bank of the upstream bend, a small, elongate ridge has been formed by deposition of coarse organic material and clay. This was enhanced by the growth of rushes (*Juncus effusus*) at this location. In between the bends deposition of clay has resulted in the formation of a terrace-like body of sediment. This deposit was soon invaded by common reed (*Phragmites australis*) and bulrush (*Typha latifolia*), reducing flow velocities and thereby increasing deposition rates once more.

DISCUSSION

Initial adjustments

Immediately after rehabilitation works the channel bed and banks are generally smooth and devoid of vegetation. This unnatural situation is altered by a widening of the stream and the formation of hydraulic roughness elements, increasing the flow resistance. Widening increases the wetted perimeter and scour results in a coarser bed material and the formation of depositional bedforms. These adjustments will stop once an equilibrium condition has been established in which flow forces and resistance are in balance. A conceptual model of these adjustments and the associated sediment yields is discussed by Sear et al. (1998). The model describes an initial phase of erosion and high sediment yields during construction and immediately thereafter, followed by a phase of stabilisation, with lower rates of sediment yield due to retarded degradation by armouring, and a final phase in which vegetation on the banks has recovered and sediment yields return to a normal rate. As channel widening was the dominant process of adjustment in the Tongelreep and Keersop, the discharge hydrographs (Fig. 4.4) and the data on gross change due to erosion of the study reaches (Fig. 4.6) in these streams can be used to calibrate the timing of sediment production in this model and to indicate the volume of sediment produced in the various phases. Gross change due to erosion is taken to be an approximation of the total sediment production. Consequently, sediment production rates are linked to discharge events by calculating the sum of changes that occurred during periods in between measurement dates, characterised by large or small peak discharges or base flow. In Fig. 4.10, changes in sediment production rates following a hypothetical sequence of discharge events are shown, expressed as a mean of the range of distinct production rates observed per event in the Tongelreep and Keersop.

Comparison of the discharge hydrographs and gross erosion rates shows that most entrainment of material occurs during peak discharges. An initial phase of erosion and relatively high sediment yields may occur almost immediately after rehabilitation, but may also be delayed until such an event occurs. In the Keersop this phase lasted

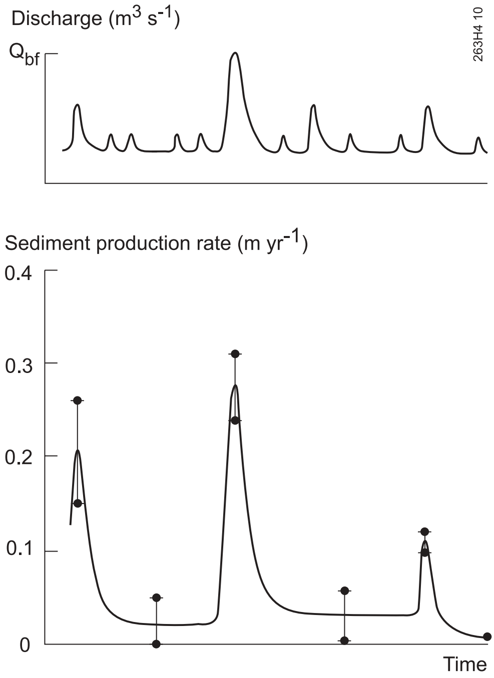

Fig. 4.10.
Conceptual model of changing gross sediment production rates in time, as the short term response to meander rehabilitation and discharge events

approximately 2 months, whereas it ended only after 6 months in the Tongelreep. It is followed by a phase of stabilisation in which sediment production is very low. The first bankfull discharge, however, is the major sediment production event, because scouring of gravel lags, pool formation and bank failure reach maximum intensity for the first time. In the period afterwards, sediment production is low again, but because of local reworking of bedload deposited during the waning of the bankfull event, rates of sediment production remain higher than those during the preceding period. Peak flows of smaller magnitude than bankfull were found to have no impact on the sediment production for a period of 5 to 7 months after the bankfull event. Later events will erode sediments again, but rates of production gradually decline as the balance between sediment input and output is gradually restored. The Keersop is the only stream in which deposition approached a balance with erosion during the monitoring period (Fig. 4.6).

The magnitude of adjustment, especially that of bend 1 in the Tongelreep, is typical of the first few years following rehabilitation works. Although lower than in many natural rivers (Fig. 4.11), migration rates, for instance, are much higher than those usually found in lowland stream settings. Brookes (1987) found that Danish streams having a specific stream power of 35 W m-2 or less had not responded to channelisation. Kuenen (1944), in a study on the meandering of streams on the Drenthe subglacial till plateau in the northern part of the Netherlands, concluded that the majority of streams did not show signs of lateral migration. This conclusion was

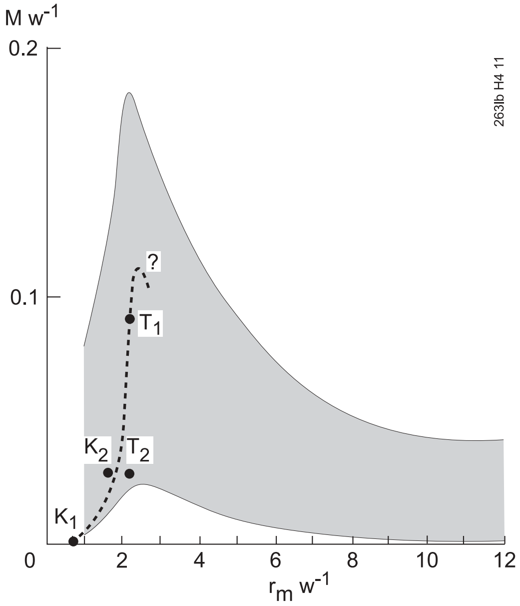

Fig. 4.11.
Relationships between channel migration rate and the radius of bend curvature to channel width ratio for the Tongelreep and Keersop compared with those of other rivers (M, migration rate; r_m radius of bend curvature; w, channel width; T1, Tongelreep bend 1; T2, Tongelreep bend 2; K1, Keersop bend 1; K2, Keersop bend 2; shaded area, envelope of data on other rivers from Hooke, 1997)

confirmed for streams in the southern part of the country by soil surveyors (W.H. Leenders, pers. comm.). However, the amount of sediment released is not exceptionally high. Assuming that adjustments last for a maximum period of two years after rehabilitation and that degradation rates are equally high in all parts of the rehabilitated reaches, the total amount of material potentially released from the entire rehabilitation reach varies from 273 m^3 in the Tongelreep to 120 m^3 in the Keersop. These amounts may be trapped, to prevent flooding if necessary, in sand traps of a size commonly used in the Netherlands. These data present a worst case scenario, as a small part of the sediment produced during the adjustment period is deposited within the rehabilitated reach itself and not moved to downstream reaches.

Role of design variables

The different adjustments of the Tongelreep, Keersop and Aa may be related to the various design variables, such as the width and depth, the shape of the cross sections, the stream planform and the by-pass (Table 4.1; Fig. 4.2). Obviously, the dimensions of the Aa were overestimated in the design. Data on mean flow velocity and specific stream power during the maximum discharge (Table 4.2) indicate that forces in general remained well below the critical values for entrainment of sand-sized bed material, resulting in aggradation. Also, the gentle slopes of the Aa prevented any kind of bank failure. The different cross-section types applied to bends in the Tongelreep and Keersop did not result in a very different flow pattern, nor in different rates of bank undercutting. Besides, the V-shaped channel bed of the Tongelreep was covered by a horizontal layer of rippled sands, so that the cross section of bends soon resembled the trapezoidal one in the Keersop. In contrast, planform had a major influence: channel migration rates in tight bends were smaller compared with the gently curved bends (Fig. 4.11). In general, maximum migration rates are observed in bends with a radius of bend curvature to channel width ratio of 2 to 3 (Nanson and Hickin, 1981; Hooke, 1997). In tighter bends, migration rates decrease rapidly with decreasing ratio values because of the different flow pattern, which generates large eddies. The data on the Tongelreep and Keersop support the few data concerning very tight bends in natural rivers. The by-pass along the Tongelreep did not result in different developments in bend 1 and bend 2, as all differences between those bends were observed well before the by-pass was in function for the first time during the summer thunderstorm in August 1996.

Bed and bank material characteristics were also observed to have a significant effect. The differences in undercutting (Fig. 4.5), pool formation (Fig. 4.7) and channel migration (Fig. 4.11) between bend 1 and 2 in the Tongelreep are believed to be the result of the presence of a loam layer underlying the channel bed, which hampers scour in bend 2. Lower values of bank retreat may be related to this retarded scour, but more likely to the thicker loam layer on top of the banks of bend 2. In bend 1, the banks were dominated by well sorted, fine sands, which are easily eroded and thus induced a collapse of the overlying thinner loam layer. Similarly, in the Keersop, exposed peat layers hampered bed scour and densely rooted peat in banks prevented bank failure.

Morphological and ecological diversity

As the meander rehabilitation was primarily aimed at designing channels that possess a large heterogeneity in flow characteristics, bedforms and bed materials, assessing the morphological diversity is an important means to evaluate the success of this measure. The morphological diversity of natural sand-bed streams encompasses features such as (1) channel cross sections showing symmetry at inflexion points and asymmetry at bends, (2) well developed point bars and pools, (3) ripples and small bars, depending on local hydraulic conditions, and (4) areas of gravel where the flow has stripped away the sand (e.g. Thorne et al., 1983). While the former straightened channels of the Tongelreep and Keersop were almost entirely characterised by rippled sands, diversity of bedforms and associated bedform materials strongly increased within a few months of re-meandering (Fig. 4.8 and Fig. 4.9). In the Tongelreep, however, the area of rippled sands was still largely fed by the continuing high sediment production. The most complete sequences of bedforms were observed in the Keersop. Their formation was not only induced by the decrease in sediment production, but also by the flow pattern in the tightly curved bend and the establishment of aquatic macrophytes. The Keersop, therefore, indicates the potential success of meander rehabilitation. Obviously, the morphology of the Aa is far from natural as almost none of the features mentioned was observed.

Bedforms are the result of the interaction of water flow and channel substrate and provide habitats for aquatic organisms. The recovery of the habitat function of a stream can, therefore, be evaluated in terms of bedform environments (Kershner and Snider, 1992). Features observed, such as the pools, erosional channels, gravel lags, chutes, sand bars and deposits of particulate organic matter are important to sand-bed lowland streams communities (Tolkamp, 1980). However, a comparison with data on the instream macrofauna community (Table 4.5; from Koomen et al., 1998) reveals that the ecological response is delayed. Although rich in species, the Tongelreep macroinvertebrate community still hosts a low number of species characteristic of healthy streams. Only species are present which tolerate pollution to some degree, since the water in the Tongelreep is of poor quality (NO_3^-: 7.53 mg l^{-1}; NH_4^+: 2.18 mg l^{-1}; PO_4^{3-}: 0.35 mg l^{-1}; from Mesters, 1997). It also appears that both the total number of species and the number of characteristic species declined after completion of the rehabilitation project. In the Keersop, however, the total number of species and the number of characteristic species increased slightly in number and was noticable from the first sampling. Obviously, the new meandering reach has been invaded quickly by species already present in the stream system, which is known to be quite a healthy one. Among the new inhabitants were species which require eroding habitats and some which require a stable depositional environment. The Aa also shows a slight increase in numbers of both types of species mentioned above, despite of the fact that the reach of the Aa under study is ecologically a rather isolated stream. These findings are consistent with those of Friberg et al. (1998) and Biggs et al. (1998), who also reported a rapid colonisation of new meandering reaches after an initial decrease, while Biggs et al. (1998) observed that species richness remained slightly below the pre-rehabilitation values. A few years of monitoring may be too short to register full recovery. Besides, a limited length of a rehabilitated reach within an entirely channelised stream system may hamper full ecological recovery, despite a substantial improvement in the physical conditions.

Table 4.5.
Comparison of macroinvertebrate species richness before (1993) and after rehabilitation (1994 and 1995) (from Koomen et al., 1998)

RIVER	YEAR	SPECIES (n)	SPECIES CHARACTERISTIC OF HEALTHY STREAMS (n)	DECLINING SPECIES (n)	THREATHENED SPECIES (n)
Tongelreep	1993	78	13	6	0
	1995	47	10	3	0
Keersop	1993	119	37	13	4
	1994	128	40	17	2
	1995	122	38	21	1
Aa	1993	81	0	0	0
	1995	88	4	1	0

Benefits of post-project appraisal

The need to evaluate stream rehabilitation projects has been stressed by Brookes (1995) and Kondolf and Micheli (1995). The results of the present study clearly demonstrate that lessons can be learned from geomorphological post-project appraisal, lessons can be learned which are important for arriving at cost-effective strategies in water management. (1) The artificial re-creation of meanders is a promising technique for rehabilitating channelised streams in lowland environments in which meandering of flow is unlikely to be initiated by natural physical processes alone; it enhances heterogeneity of flow, bedforms and bed materials in a short period of time. (2) Rehabilitated streams require only a narrow riparian zone along the meandering channel to accommodate the lateral migration of channels, since rates of meandering are generally low; the collapse of unvegetated banks is mainly restricted to the concave banks. (3) The increase in sediment production during the initial years following rehabilitation appears to be limited to major discharge events, and the impact on sediment yields can be accommodated by the installation of a sand trap of the usual size, which needs no further maintenance. (4) The design of new channels should take account of the influence of bank materials susceptible to entrainment and bank failure because these have a large impact on the length of the response period. (5) An irregularly meandering channel with some tightly curved bends is to be preferred since this results in a larger diversity of bedforms and probably a more enhanced habitat function than a very regular low sinuosity stream. (6) The excavation of streams needs not to be designed and executed in detail because the flow of water within the newly meandering channel is capable of creating various ecologically important bedform environments.

Attempts at post-project evaluation have often used only biological criteria (Kondolf, 1995). Surveys and evaluations of macroinvertebrate and fish communities are widely used in water management. The results of this study, however, also indicate that a geomorphological assessment can be valuable for other than physical reasons too. (1) Such an assessment reveals the dynamics of physical habitats, which are important aspects in an ecological evaluation since habitat suitability not only depends on the present flow and bed material characteristics, but also on the history of erosion and deposition (Tolkamp, 1980). (2) When additional factors such as pollution, isolation or disease temporarily hamper the development of the instream fauna communities, a geomorphological assessment still provides the information needed to evaluate the physical results of stream rehabilitation measures and the future potential for ecological recovery. Although geomorphological targets in general are poorly defined and evaluation criteria have not been established yet (Sear et al., 1998), incorporation of geomorphological aspects in design and post-project appraisals therefore should be advocated.

CONCLUSIONS

In the first few years following meander rehabilitation, a relatively large morphological activity was observed in the Tongelreep and the Keersop. The first peak discharges triggered an initial phase of erosion, resulting in high sediment yields due to local bed scour and undercutting of banks. The first bankfull flow, however, was the major sediment production event, with gross sediment production rates up to approximately 0.3 m yr^{-1}. During this event, scouring of gravel lags, formation of pools and failure of banks reached maximum intensity for the first time. In the periods between peak flows, sediment production remained slightly elevated due to local reworking of deposited material. After the bankfull event, the rates of sediment production gradually declined, but during the two-year monitoring period the balance between sediment input and output was observed to be restored in the Keersop only. In general, maximum channel migration rates observed were low, which is typical for streams in a lowland setting.

The influence of design variables on the streams' adjustments to rehabilitation varied considerably. Oversized cross-sectional dimensions led to a very low dynamic environment in the Aa and resulted in the deposition of a clay layer. The application of various cross-section types and the excavation of a by-pass channel did not result in differences among the streams. In contrast, planform had a major influence. In a similar process to natural rivers, the rates of channel migration decreased with increasing bend tightness. Rates of bank failure and the evolution of a new bedform configuration were shown to depend largely on the lithology of both bank material and bed substrate. Clay loams and densely rooted peat soils provided stability to banks, while thin clay loam layers underlain by well sorted sands were associated with higher rates of bank collapse. Clay loams and peat layers also hamper the development of bedforms such as pools and erosional channels.

The bedforms in the channel beds in the former straightened streams were almost entirely rippled sands. A few months after re-meandering, though, a much greater diversity of bedforms had appeared. The most complete sequence of bedforms, similar to that of natural sand-bed rivers, was observed in the Keersop not only because sediment production has declined but also because of the differences in bend tightness applied in the design. The increase in bedform diversity demonstrates the success of meander rehabilitation as a measure applied in lowland streams in which flow is unlikely to be initiated by natural processes alone. The increase in morphological diversity is expected to enhance the stream habitat function, although an increase in species richness has not yet been demonstrated, probably because the two year monitoring period is too short.

ACKNOWLEDGEMENTS

This research was financed by the Province of Noord-Brabant and by the Netherlands Ministery of Agriculture, Nature Management and Fisheries. We gratefully acknowledge the cooperation of De Dommel and De Aa water boards, who collected and provided the data on discharge and cross-sectional dimensions. Valuable comments on a draft of this paper were given by Janrik van den Berg, Bert Higler, Jan Klijn, Ward Koster and Colin Thorne.

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5 The formation of natural levees as a disturbance process significant to the conservation of riverine pastures

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Accepted by Landscape Ecology

ABSTRACT

Disturbances and patch dynamics are inherent to many ecosystems of the world, especially in the riparian zone. This paper describes the influence of natural levee overbank deposition on riverine grasslands along the meandering River Dinkel (the Netherlands). Here, the rare vegetation type *Diantho-Armerietum*, characterised by *Dianthus deltoides, Thymus pulegioides, Pimpinella saxifraga* and *Galium verum*, has been identified as important to nature conservation. *Diantho-Armerietum* shows a strong preference for dry, nutrient-poor, sandy and relatively young soils, with an elevation approximately 30–50 cm above bankfull discharge level, corresponding to a flooding frequency of 2 to 3 times per year. The lower zones are strongly influenced by nutrient-rich water, whereas the higher zones are vulnerable to soil acidification. In the intermediate zone, soil development may be reset due to the supply of calcium, adsorbed to recently deposited levee sands. Since deposition rates will decrease with increasing levee heights, new levees are regularly needed to stop the decline of this floriferous vegetation type. The formation of new natural levees is favoured by the occurrence of meander cutoffs, causing a cyclic succession of landforms along the river. Therefore a conservation strategy for this vegetation type needs to aim at the rehabilitation of the natural levee disturbance process, in conjunction with encouraging the meandering of the river.

KEYWORDS
Disturbance; Meandering; Natural levee; Overbank deposition; Riverine grassland, River rehabilitation, River Dinkel, the Netherlands

INTRODUCTION

Disturbance and patch dynamics have become important research topics in landscape ecology (Picket and White, 1985; Turner, 1987). It is now well acknowledged that disturbances are inherent to many ecosystems of the world. Disturbances are distinct, rapid events that disrupt communities or the availability of resources, thus creating open spaces where juvenile stages can start the succession of life communities all over again. Disturbances vary from rare catastrophes to habitually occurring 'extreme events'. Species characteristic of dynamic ecosystems may even depend on the latter type, in case their communities are adapted to specific disturbance regimes. Disturbances encompass a variety of processes ranging from purely physical ones such as fires, gales, floods, landslides and droughts, to biotically induced ones such as beaver dams, animal burrows and insect outbreaks.

Parallel to a growing scientific insight, the concepts of disturbance and patch dynamics are gradually being incorporated into the management of natural resources (Finck et al., 1998; Peck, 1998). It is realised that ecosystems in which change is inherent naturally require a dynamic approach for sustaining biodiversity. One of the aspects of this approach is determining the variability ranges for important ecosystem attributes instead of selecting a single and constant baseline condition as a management goal. Another is the use of man-made disturbances, e.g. controlled burning, as tools for landscape management, where the natural equivalent is not to be expected to take place readily.

Riparian zones belong to the most dynamic components of the landscape, where frequent disturbances create complex mosaics of landforms and biological communities (Bravard et al., 1986; Junk et al., 1989). Disturbances are caused mainly by erosion, sedimentation and flooding during high discharge events. Within river systems, the effects of flood pulse related disturbances decrease in a downstream direction, due to an increase in predictability. The effects also, in general, decrease in magnitude away from the river channel, although prolonged flooding may be more influential in remote floodplain areas. The research, emphasis has been on the in-channel geomorphological disturbances and on the effects of flooding on riparian wetlands. Well known examples are the studies on the effects of gravel bar dynamics on beetle and ant communities (Plachter, 1998), on the effects of bar formation and meander migration on riparian forest succession (Johnson, et al., 1976; Nanson and Beach, 1977) and on the effects of flooding and sedimentation on aquatic vegetation in oxbow lakes and abandoned braided channels (Brock et al., 1987; Bornette et al., 1994).

Relatively unknown, however, is the role of overbank deposition on natural levees as a disturbance process. This may be due to the fact that the process of sedimentation itself is not yet very well documented (Brierley et al., 1997; Cazanacli and Smith, 1998). Natural levees are elongate ridges on either side of the river channel, formed when overbank flow occurs. Sediment is deposited here, when flow enters the shallower floodplain and loses much of its velocity and transport capacity. Natural levee deposits are coarser in texture compared to the overbank sediments in distal parts of the floodplain, which are mainly deposited by settling of fine material in tranquil water. Natural levee overbank deposition is characteristic of many meandering rivers occurring in rural landscapes, and therefore is an important process in the management of semi-natural riverine grasslands. In this paper it will be demonstrated that overbank deposition on natural levees along a small, high sinuosity sand-bed river has a major influence on soil development and the species composition of the grassland vegetation. It will also be argued that the management of this vegetation type requires, in addition to the present conservation strategy focussing on restricted manuring an fertilizer use, an approach aiming at the rehabilitation of this natural levee disturbance process and the associated meandering of the river, to ensure long term sustainability.

MATERIALS AND METHODS

Study area

The River Dinkel is a small meandering sand-bed river running along the Dutch-German state border and is a tributary of the River Vecht (Fig. 5.1). Its total drainage basin measures 643 km^2, ranging from an elevation of 110 to 15 m above mean sea level. The area has an undulating topography, underlain mainly by Cretaceous limestones, Tertiary clays and Pleistocene tills. In the valleys these are covered by periglacial sands and fine gravels locally associated with sandy aeolian deposits. The study focused on the Dutch part of the Dinkel valley where, over a distance of some 17.5 km, the river is not channelised or diverted. Being part of the transport zone of the river (cf. Schumm, 1988), fluvial sediments have been stored here during the Holocene in a floodplain 250 to 500 m wide and flanked by valley bluffs. The Dinkel valley is mainly used for dairy farming, while approximately 10% of the area is a nature reserve. Locally, up to a total length of 2.3 km, farmers have been reinforcing banks (with bricks) in order to prevent bank retreat (pers. comm. M. Zonderwijk, Waterboard Regge and Dinkel).

In the period 1961–1990, mean annual precipitation was 750–800 mm, and mean annual evapotranspiration approximately 525 mm (Meinardi et al., 1998). Evapotranspiration exceeds precipitation in the period April–August. As a result the discharge hydrograph generally shows large volumes of runoff occurring in winter and base flow discharge in July and August. Bankfull discharge in the study reach is approximately 15 m^3 s^{-1} (pers. comm. M. Zonderwijk), with the exception of the most downstream section where discharges do not exceed 13 m^3 s^{-1} since the construction of a by-pass channel in 1965. Due to the combined effects of the undulating topography and impermeable subsoil, the discharge events are characterised by relatively high water levels and short inundation periods. Data from the only gauge in the study area (Fig. 5.1) indicate that the bankfull discharge level was exceeded 4.9 times a year on average, during the period 1969-1993. Because of agricultural run-off and waste water from municipalities upstream from the study area, the surface water is eutrophic with relatively high nitrate ($N\text{-}NO_3^-$: 6.8 mg l^{-1}; $N\text{-}NH_4^+$: 0.6 mg l^{-1}) and phosphate (P_{tot}: 0.7 mg l^{-1}) concentrations (Verdonschot et al., 1993).

One of the most valued and characteristic vegetation types of the Dinkel valley

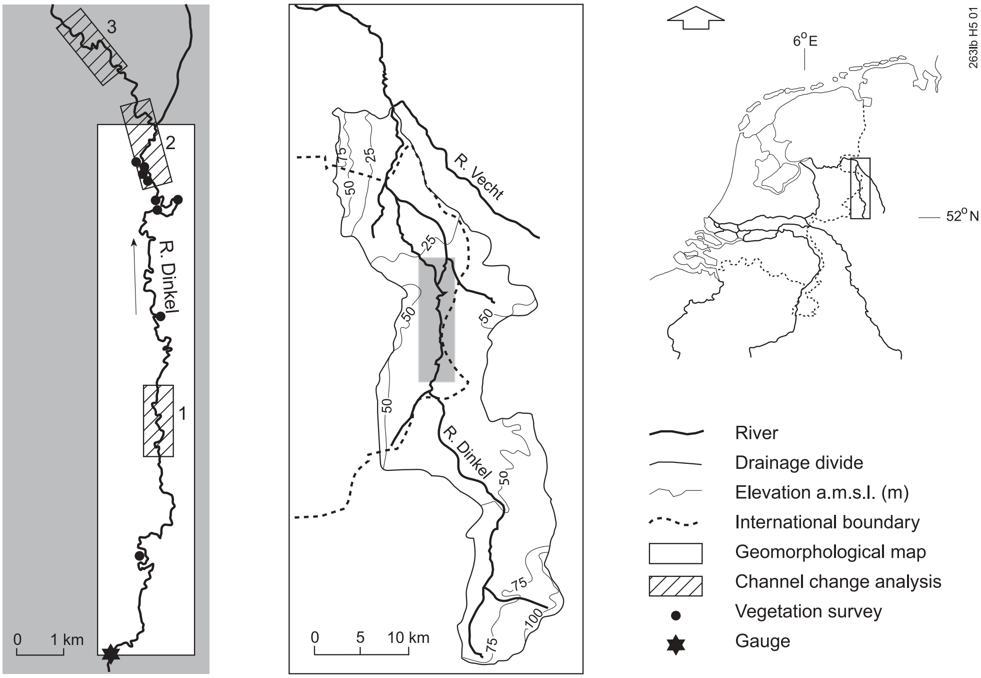

Fig. 5.1.
Locations of the River Dinkel and the study areas

is a type of grassland in which maiden pink (*Dianthus deltoides*) occurs. These floriferous grasslands are exceptionally rich in colour with, besides *Dianthus*, species such as larger wilde thyme *(Thymus pulegioides*), lesser burnet saxifrage (*Pimpinella saxifraga*) and Our Lady's bedstraw (*Galium verum*). The community type is often referred to as 'Dinkel pastures'. In the Netherlands it is classified as *Festuco-Thymetum serpilli* (alliance: *Plantagini Festucion*; Schaminée et al., 1996). In the adjacent part of Germany, very similar pastures were described as *Diantho-Armerietum* (alliance: *Sedo-Cerastion*; Krausch, 1968). Following Bos and Hagman (1981), the latter denomination is preferred here. The community type can be regarded as remnants of an old agricultural landscape in the eastern part of the Netherlands, named *Hudelandschaften*, i.e. pasture landscapes, in the adjoining area of Germany (Burrigter et al., 1980, Pott and Hüppe, 1991). There, river valleys were used as common pastures for extensive livestock grazing which resulted in a variegated landscape characterised by remnants of grazing woods, groups of bushes, individual trees and open grazing land.

Vegetation survey

Site factors, possibly related to the occurrence of *Diantho-Armerietum* were studied at nine representative sites (maximum 100 m^2 in size) along the banks of the River Dinkel. Sites were chosen which covered both the variety in overbank deposition rates and in intensity of agricultural use (i.e. manuring) as much as possible. Landforms and the associated soils, as well as the vegetation, were mapped in detail on scale 1:200. Levelling provided information on the topography of the sites, which was expressed in terms of elevation above the bankfull discharge level, by means of extrapolating the gauge data along the water surface slope. The vegetation survey implied mapping community types and then, separately, the four species mentioned above.

The geographical information system ARC/INFO (ESRI, Redlands, CA) was used for data processing. The occurrence of community types and species was related to the various site factors by means of an overlay procedure of vegetation maps on the one hand and maps on elevation above bankfull water level, thickness of recent overbank deposits, subsoil lithology, texture of overbank deposits, topsoil organic matter content, groundwater-table class, soil type and agricultural pressure on the other. Relationships were elaborated using frequency diagrams. The procedure was derived from Hommel et al. (1990).

Geomorphological survey

The occurrence and evolution of the natural levee environment along the River Dinkel was studied by means of mapping the geomorphology of the Dinkel valley at a scale of 1:10,000, as well as the meandering of the River Dinkel channel. The geomorphological map was compiled using existing 1:50,000 geological, geomorphological and soil maps, as well as a 1:10,000 contour map and a preliminary geomorphological air photo-interpretation map (Gonggrijp, 1976). The legend was based upon commonly distinguished landforms and deposits of sand-bed alluvial rivers (e.g. Leopold et al., 1964; Reineck and Singh, 1980).

The meandering of the River Dinkel channel was studied using historical editions of topographical maps at a scale of 1:25,000. Maps used in this study were surveyed in 1846–1848, 1901–1902, 1933 and 1987. The analysis was performed in three sections of the river valley (Fig. 5.1); other parts of the river valley were excluded because maps were surveyed in other periods, obvious human influence or because of different geological setting. Since the scale of 1:25,000 is not very accurate for this purpose the position of the former channel was checked, whenever possible, with the position of abandoned channels having the same planform as depicted on aerial photographs surveyed in 1951 (scale 1:18,000). The historical changes have been expressed in terms of migration rates (i.e. the mean distance covered yearly by the shifting river channel; areas related to cutoffs were omitted) and in terms of sinuosity. Analysis of the historical changes helped in the genetic interpretation of the various landforms depicted on the geomorphological map.

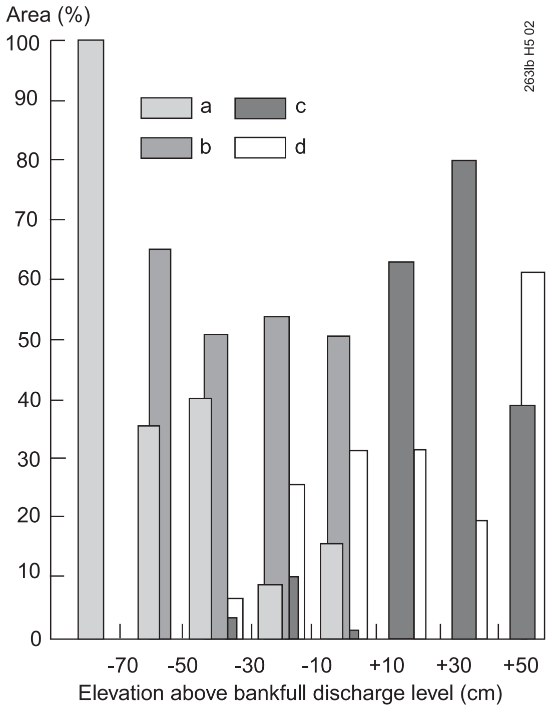

Fig. 5.2.
Vegetation zonation along the River Dinkel (a: tall, productive vegetation; b: moist pastures; c: Dinkel pastures; d: manured agricultural pastures)

RESULTS

Vegetation zonation and site factors

Four vegetation types have been mapped in the nine representative sites along the River Dinkel. On the lowermost terrain, approximately 70 cm below bankfull discharge level only tall, highly productive vegetation (*Galio-Aliarion*) was found, including stinging nettle (*Urtica dioica*), creeping thistle (*Cirsium arvense*) and common orache (*Atriplex patula*). On higher terrain, until approximately 10 cm above bankfull discharge level, moist pastures (*Lolio-Potentillion*) with fiorin grass (*Agrostis stolonifera*), creeping buttercup (*Ranunculus repens*) and silverweed (*Potentilla anserina*) were mapped. Above the latter level dry nutrient-poor pastures occur, the Dinkel pastures, dominated by creeping fescue (*Festuca rubra*) and with maiden pink (*Dianthus deltoides*). These three vegetation types therefore clearly show a zonation along a topographical gradient (Fig. 5.2). On many places, however, this zonation is no longer present, because a fourth vegetation type (*Plantaginetea majoris / Molinio-Arrhenatheretea*) now dominates the site in response to heavy manuring and fertilizer use. These agricultural pastures were mapped with rye-grass (*Lolium perenne*), cough-grass (*Elymus repens*) and chickweed (*Stellaria media*) and occur at higher levels.

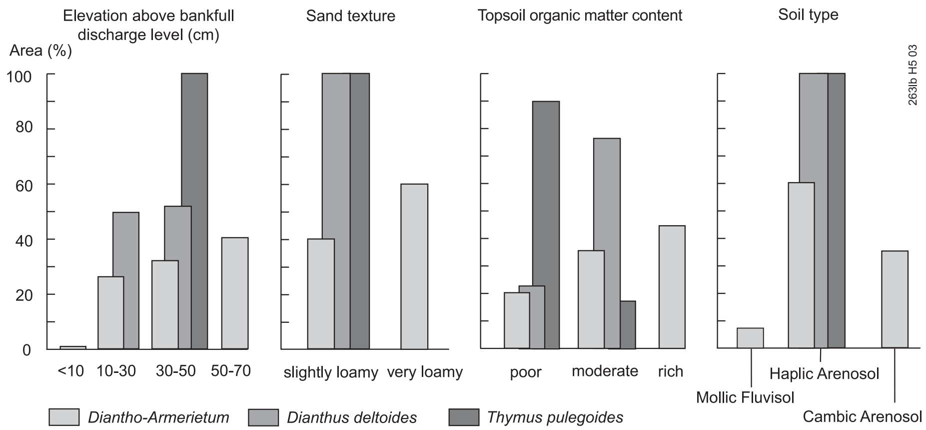

Fig. 5.3.
The occurrence of Dinkel pastures and maiden pink in relation to site factors

The results of the analysis of site factors relevant to the four species characteristic of Dinkel pastures are summarized in Fig. 5.3. More details are published in Hommel et al. (1994). The frequency diagrams of *Dianthus deltoides* are comparable to the other three characteristic species. However, *Thymus pulegioides* and *Pimpinella saxifraga* occur in a smaller range than *Dianthus*, while *Galium verum* is less selective. It was found that typical Dinkel pastures (i.e. those including *Dianthus deltoides*, *Thymus pulegioides* and *Pimpinella saxifraga*) have a strong preference for sites 30 cm above the bankfull water level, a relatively deep ground water level, and soils characterised by a thick layer of non-loamy sand and the absence of clay in the subsoil. These characteristics are typical for overbank deposits in a natural levee setting. Furthermore, the Dinkel pastures, and especially maiden pink, show a preference for initial sandy soils (Haplic Arenosols; cf. Food and Agricultural Organisation, 1989), and a low organic matter content of the top-soil, but avoid soils with a slightly developed colour-B soil horizon (Cambic Arenosols). This suggests that the soils on which Dinkel pastures occur are relatively young, due to active deposition of sediments. Finally, it is evident that the three most selective species do not occur on sites 50 cm or more above bankfull discharge level, while all species avoid manured grasslands.

Floodplain geomorphology

A fragment of the geomorphological map of the Dinkel valley is given in Fig. 5.4; the entire map is published in Hommel et al. (1994). Characteristics of the landforms distinguished are described in Table 5.1. The landforms of the Dinkel floodplain show great resemblance to those described in classical models of meandering rivers (e.g. Miall, 1996), thus illustrating the fluvial processes at work

Table 5.1.
Characteristic of fluvial landforms within the River Dinkel valley

LANDFORM	MORPHOLOGY	DEPOSITS	GENESIS	ELEVATION ABOVE BANKFULL DISCHARGE LEVEL (cm)
Scroll bars and swales	Elongate depressions in between subsequent point-bar scrolls	Channel deposits: coarse sand; thin channel fill deposits in swales: loam	Migration of river bend and associated point-bar formation	± - 100
Natural levee	Elongate, narrow ridge along the river channel	Overbank deposits: sand	Deposition of bedload due to overtopping of banks	≥ + 30
Floodplain flat	Flat valley bottom	Overbank deposits: loam	Settling of fines during waning of flow events	- 100 to + 30
Floodplain low	Undulating low terrain with abandoned channels	Channel deposits covered by thin layer of overbank deposits: coarse sand covered by loam	Settling of fines during waning of flow events, after meander cutoff	± - 100
Oxbow lake	Abandoned, shallow channel	Channel-fill deposits: sand, loam and peat	Overbank deposition and settling of fines after cutoff	≤ - 100
Fluvial terrace	Undulating to flat terrain along the valley margins	Old fluvial deposits: loam	Variable	≥ + 30

during high discharge events. The highly sinuous river channel, the scroll bars and swales in areas enclosed by river bends, and the many oxbow lakes indicate the River Dinkel has been an actively migrating river in which point-bar formation and meander cuttoffs frequently occurred. Natural levees and partly or fully infilled oxbow lakes indicate that apart from these in-channel processes, overbank deposition of both levee sands and floodplain fines have been influential processes in the floodplain environment.

The geomorphological map reveals that conspicuous natural levees have not been formed everywhere in the Dinkel valley. Instead, scroll-bar and swale areas and floodplain lows alternate with relatively high and elongate levees along the river channel. Some exceptionally large scroll-bar and swale sequences occur, indicating intensive lateral erosion of the outer bank in bends, e.g. the Groene Staart area (Fig. 5.4). Without exception, these areas are all opposite to banks formed in fluvio-periglacial and aeolian sands, which fringe the Dinkel river valley. Obviously, the relatively high bluffs formed in these sands are more vulnerable to bank collapse than the banks formed in the Holocene alluvial sediments. Referring to its low elevation and many abandoned channels the floodplain low is interpreted an old scroll-bar and swale area, which was abandoned by the river after a major meander cutoff.

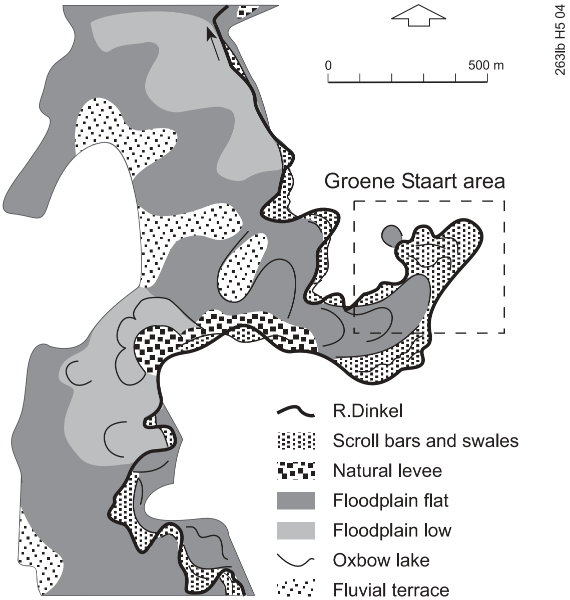

Fig. 5.4.
Fragment of the geomorphological map of the Dinkel valley

Historical migration rates

The data on migration rates and sinuosity confirm that the River Dinkel has been actively meandering throughout the historical period investigated (Fig. 5.5): migration rates vary from 0.11 to 0.40 m per year and sinuosity has been changing in all three the periods investigated, varying from 1.07 to 1.64. Maximum migration rates were measured opposite the above mentioned Groene Staart area where the river channel migrated approximately 170 m in 139 years (1.22 m per year).

The changes registered also show migration rates have been varying in time. The migration rates during the period 1933–1988 are almost as high as those during the period 1848-1901. During the intervening period 1901–1933, however, the migration activity of the river was two to three times as high. The sinuosity measured in 1988 is not equalled in any previous record and the measurements of 1848, 1901 and 1933 show a less sinuous river course. Following a period with decreasing values, sinuosity has been increasing from 1901 onwards.

DISCUSSION

Disturbance model

Dinkel pastures with *Dianthus deltoides*, and other characteristic species occur on natural levees, maintained by active deposition of overbank sediments. Although

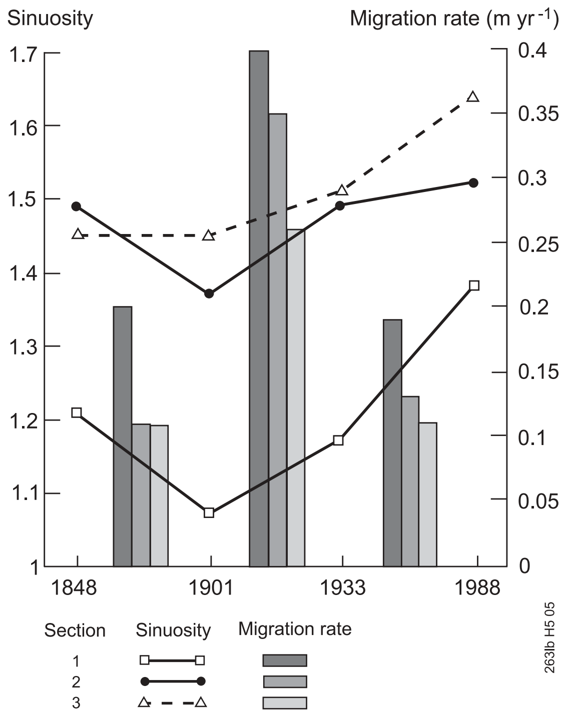

Fig. 5.5.
Changing migration rates and sinuosity of the Dinkel river channel during the period 1848–1988

the *Diantho-Armerietum* occurs within a zone of 10 to 70 cm above bankfull discharge level, the occurence of the most selective characteristic species (*Dianthus deltoides, Thymus pulegioides* and *Pimpinella saxifraga*) is restricted to the 30 to 50 cm level. From a comparison of species and soil characteristics above and below the 50 cm level; it can be hypothesised that the upper limit is related to interactions of depositional and soil forming processes (Fig. 5.6). After deposition of the overbank sediments, soil development processes will start to gradually change the soil properties. Organic matter accumulates in the top-soil and eventually will be transported through the soil, a process, via the development of a cambic horizon, ultimately resulting in a Podzol. The development of a humic top soil is associated with a natural acidification which, in the Netherlands, may be accelerated by acid deposition. In similar settings with *Diantho-Armerietum* along the River Vecht pH values of 4.8 to 5.4 (Rulkens, 1983; Hommel et al., unpubl. data) have been measured. This closely corresponds to the lower limit of the pH range (4.5 to 5.5) which allows effective acid buffering by calcium. Both the water and recently deposited sediments of the River Dinkel can supply calcium. The close correspondence to the elevation above bankfull discharge level indicates that flooding with calcium rich water is a very likely process capable of counteracting further acidification below the level of 50 cm. Due to the short duration of flooding events, however, only calcium adsorbed to the sediment particles is assumed to be capable of buffering the acidification process of natural levee soils. Thus, periodical

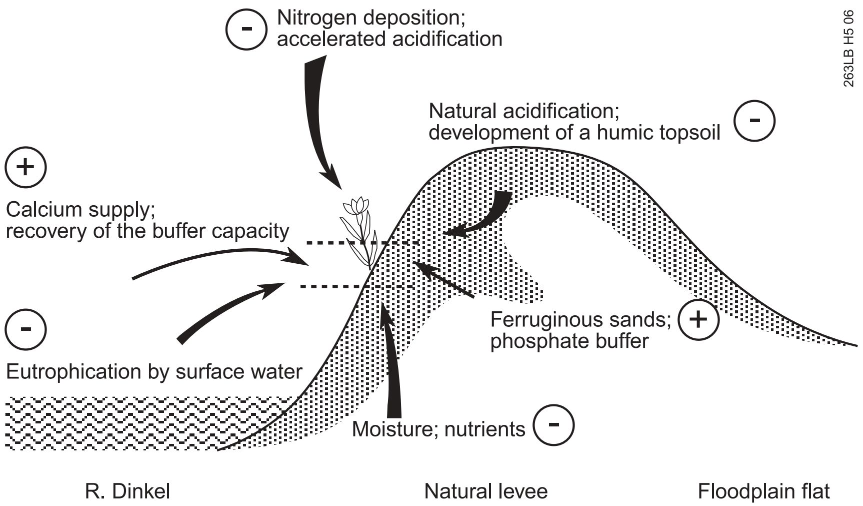

Fig. 5.6.
Conceptual model of the various factors which either favour (+) or impede (–) Dinkel pastures with maiden pink

overbank deposition may be considered a disturbance process, resetting site conditions and vegetation succession of Dinkel pastures on natural levees.

The lower limit of occurrence of typical Dinkel pastures is related to flooding in a similar way. The lower zones (< 30 cm) are less suitable for the *Diantho-Armerietum* because of too frequent flooding by nutrient-rich water which alters the nutrient concentrations in the soil. Increases in phosphates may be buffered by iron released by the ferruginous Dinkel sediments, but uptake of phosphates by plant roots will only occur during lasting anaerobic circumstances during floods and inundations of a long duration are very rare in the River Dinkel valley natural levee environment. Hence, it is concluded that not only to rare, but also too frequent flooding would lead to the decline of the Dinkel pastures. Where the 30 and 50 cm levels correspond to flooding frequencies of approximately 2 to 3 times a year (Table 5.2), this frequency is required for sustainability of the typical Dinkel pastures.

Landform succession

The landforms in the River Dinkel valley have been formed mainly by channel migration, meander cutoffs and overbank deposition, processes which have been active at least throughout the last 150 years. However, the landform pattern as well as the migration rates indicate that these processes have varied both in space and time. Probably, the occurrence of meander cutoffs has been triggering the variation

Table 5.2.
Average annual flooding frequency in terms of water levels significant to the Dinkel pastures

ELEVATION ABOVE BANKFULL DISCHARGE LEVEL (cm)	1969–1982	1983–1993	1969–1993
+ 10	5.0	3.0	4.1
+ 30	3.4	1.9	2.7
+ 50	1.9	1.5	1.7

in space. Cutoffs are known to have a pronounced effect on both the upstream and downstream parts of the river (Parker and Andres, 1976). Immediately after the cutoff, the new route of the channel will be shorter, which implies a sudden increase in water gradient and stream power. This will cause channel degradation, progressing in upstream direction as a nickpoint, followed by bank collapse and ultimately by the formation of new point bars merging into a new scroll-bar and swale area somewhere upstream of the cutoff (Fig. 5.7). The local excess of load will be transported as far as the channel has an increased slope. Once the original channel slope will be encountered downstream of the cutoff, the sediment will be deposited, resulting in an aggrading channel and in new natural levees. This mechanism may explain the specific downstream sequence of scroll-bar and swale area–floodplain low–natural levees, found in some parts of the Dinkel valley (Fig. 5.4). Hence, it is concluded that in the long term locations with intense overbank deposition, and thus the potential sites for *Diantho-Armerietum*, will continuously change position once new cutoffs are generated by the meander migration.

Any discussion on the causes of changing migration rates and sinuosity remains highly speculative, because no data are available on changes in discharge and sediment budgets. However, the changes in time seem to be related to changes in land use in the drainage basin. The three river sections investigated show small but consistent differences in changing migration rates and sinuosity, which indicates that regional, as opposed to local factors are a more likely cause of the registered changes. Moreover, the relatively high migration rates during the period 1901–1933 coincide with a period of intensified reclamation of the remaining heathlands in this region, of which the major part took place during the second half of this period. In general, reclamation and drainage of land is associated with temporarily rises in sediment load and discharge, to which rivers may adapt. Similarly, the oldest Holocene river deposits in this area, dated 3000–500 B.C., have been attributed to the earliest settlement of man in this area (Van der Hammen and Bakker, 1971).

Rehabilitation strategies

The conservation of the floriferous Dinkel pastures with *Dianthus deltoides* is

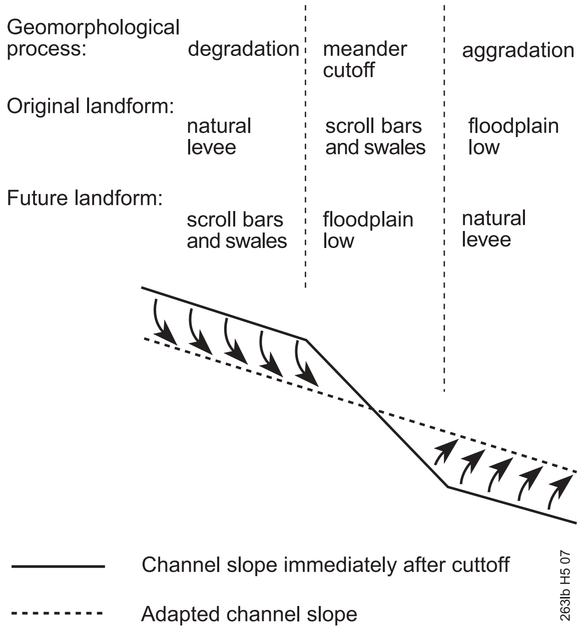

Fig. 5.7.
Conceptual model of landform succession due to meander cutoffs

incorporated in regional nature conservation policies (Provincie Overijssel, 1993). However, only small nature reserves have been appointed to date, to be maintained mainly by a specific type of management, based on traditional agricultural land use. Restrictions to manuring and fertilizer use, however, cannot prevent the soil forming process taking place, eventually leading to the loss of the last Dinkel pastures. Like floodplain aggradation (e.g. Nanson and Beach, 1977), natural levee deposition rates have been described to decrease with levee age (Makaske, 1998), presumably because higher levees are less frequently flooded. This implies that eventually, the soil acidification process will no longer be buffered. Burrowing activities of rabbits and ants may slow down the process, but in the end the characteristic plant species will disappear within an estimated period of years to decades, depending on the level of calcium supply during flood events. Accordingly, as a complementary strategy, it is argued here that it is necessary to rehabilitate the fluvial processes, which may lead to new sites suitable for *Diantho-Armerietum*. Such a strategy also fits in the restoration of the *Hudelandschaften* since the processes addressed have been part of the river valleys over historical time.

As part of this strategy, two consecutive scenarios can be envisaged. The first scenario aims at rehabilitating the natural levee disturbance processes, in order to increase the area suitable for the establishment of the species characteristic of *Diantho-Armerietum*. The most suitable locations for deposition of thick pockets of sandy overbank sediments are the present natural levees; prolonged sedimentation will reduce the distal slope of the levee, thus increasing its width

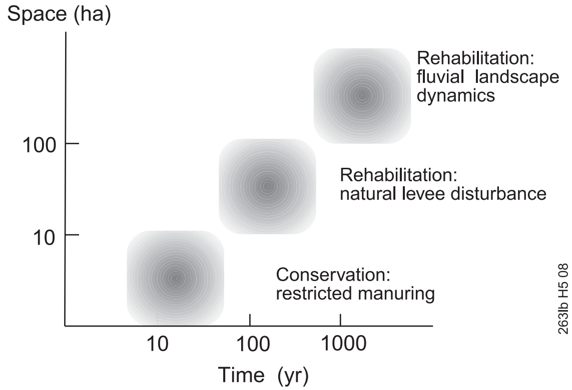

Fig. 5.8.
The spatio-temporal domains of processes addressed in the present nature conservation and complementary disturbance strategies

(Cazanacli and Smith, 1998). An increase in overbank deposition requires the removal of local bank protection structures immediately upstream of this river section, namely where scroll bars and swales indicate that failure of opposite banks is likely to occur. This scenario does not imply dramatic changes to agricultural land use. Manuring and fertilizer use must be avoided on the potential sites for the Dinkel pastures, but still can be applied to pasture in the scroll-bar and swale areas. Clearly, this scenario addresses processes operating on a larger spatio-temporal domain, its extent being based on the area of natural levees and length of river sections bordered by scroll bars and swales (Fig. 5.8).

The second scenario aims at rehabilitating fluvial landscape dynamics, in order to enable the formation of new natural levees once the older levees have reached their maximum height. Hence, the cyclical succession of landforms caused by meander cutoffs would be used as a management tool. This scenario addresses processes operating on a much larger spatio-temporal domain. Enabling the full landform sequence of scroll-bar and swale area, floodplain low and natural levee to continuously migrate in upstream direction, a nature reserve should encompass two of such sequences at the least. Moreover, the reserve should comprise the full width of the river valley, enabling the river to encounter the valley bluffs, so that sediment load may reach maximum values. Based upon the historical migration activity, it is estimated that a complete cycle of landform succession will require several centuries.

Rehabilitating the geomorphological processes in the Dinkel valley can also be considered a flood management tool. Flooding hampers agriculture, and it has been assumed recently that problems will increase owing to the urbanisation of the drainage basin. Measures are being considered to reduce the flooding frequency considerably, such as the construction of retention basins. Obviously, this would not favour the Dinkel pastures, which require flood events of short duration and flooding frequency of two to three times per year. Because it has been demonstrated in this paper that floods are inherent to the Dinkel river system since the earliest settlement of man and that the increasing urbanisation during the last decades did not result in higher flooding frequencies it is advocated that a 'working with nature' approach should be adopted. As in other dynamic river systems with sufficient stream power and sediment load (Kondolf, 2000), artificial measures are not needed when the fluvial landscape dynamics are fully rehabilitated. The River Dinkel then is likely to adapt to increasing discharges by means of naturally enlarging the dimensions of its channel, thus maintaining equilibrium flow velocities and frequencies of floodplain flooding.

CONCLUSIONS

The formation of natural levees along the sand-bed meandering River Dinkel is an example of an intermediate disturbance process significant to the occurrence of *Diantho-Armerietum* on natural levees. Deposition of overbank sediments is argued to provide calcium which counteracts the natural soil acidification in natural levee sediments. Resetting soil site conditions requires a flooding frequency of approximately 2 to 3 times per year.

The formation of new natural levees is favoured by the occurrence of meander cutoffs, causing a succession of landforms along the river. Since the Dinkel has been actively meandering throughout the last 150 years at least, frequent flooding events and the associated alluvial deposition are to be considered inherent to the river system and to be characteristic to the *Hudelandschaften*, i.e. pastures landscapes, in this part of Europe.

Where overbank deposition rates decrease when levee heights increase, conservation of present Dinkel pastures by means of agricultural measures, such as restricted manuring and fertilizer use alone, cannot stop its decline. In addition, a strategy is required aiming at the rehabilitation of the natural levee disturbance process and the meandering of the Dinkel. This requires commitment to processes operating at larger spatio-temporal domains.

ACKNOWLEDGEMENTS

This study was commissioned by the Waterboard Regge and Dinkel and benefited from stimulating discussions with Maarten Zonderwijk and Gertie Schmidt. Han van Dobben, Marcel Horsthuis, Gilbert Maas, Margriet Vocks and Joop Vrielink assisted in collecting field data. Valuable comments on a draft of this paper were given by Bert Harms, Jan Klijn, Ward Koster and Jef Vandenberghe.

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Variability in meandering of a lowland river controlled by bank composition

6

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Submitted to Earth Surface Processes and landforms

ABSTRACT

The morphodynamics of the lower River Vecht in the Netherlands and the influence of geomorphological setting and bank composition on meander migration was studied by means of reconstructing the pre-channelisation landform configuration on a scale of 1:25,000, using historical maps from 1720, 1850 and 1890 and other data. A downstream sequence of reaches was observed, each with a typical fluvial style and channel migration rate: (A) a narrow meander belt and a highly sinuous channel with intermediate migration rate, in the middle of an extensive floodbasin, (B) a wide meander belt and high rates of lateral channel migration, especially where large meanders impinged upon valley bluffs, as part of an incised setting, (C) a low sinuosity, embanked channel with low rates of downstream migration confined by dikes, occurring in an inland delta with sandy sediments. Local variation was observed within reach B. Different migration rates were caused by the spatial variability of bank resistance as reflected by the width–depth ratio of the channel and the silt–clay ratios of deposits. River banks are: (1) very erodible when composed of channel deposits, aeolian dune deposits or when coarse fluvio-periglacial deposits occur at their base, (2) erodible when dominated by overbank deposits or aeolian sand sheet deposits, (3) resistant when a plaggen layer is exposed, and (4) very resistant when dominated by floodbasin deposits. These implications of meander variability have been used to select locations suitable for a meander rehabilitation experiment.

KEYWORDS
Channel migration, Floodplain geomorphology, Fluvial sediments, River rehabilitation, River Vecht, the Netherlands

INTRODUCTION

Rehabilitating fluvial processes in channelised river systems has become an important theme in water management during the 1990s (Van de Kraats, 1994; Brookes and Shields, 1996; Hansen et al., 1998). One of the processes involved is meandering (e.g. Glitz, 1983; Brookes, 1987; Vivash et al., 1998). Meandering is considered important for (1) the renewal of habitats for in-stream fauna and riparian vegetation, (2) a relatively longer retention time for water in the fluvial system, and (3) increased recreational amenity of the fluvial landscape. Rehabilitation of the meandering process in straightened channels was initially restricted to small streams in Europe and Northern America. Increasingly, however, the possibilities in medium-sized rivers are being explored (e.g. Rasmussen, 1999). In many river systems re-meandering is not easy to implement because they contain weirs that have a function in the water management of the surrounding agricultural lands, and the built-up area and infrastructure have expanded since channelisation. In rehabilitation planning, therefore, one has to assess how the future effects of meandering will vary along the river to determine where measures will be feasible and most cost-effective.

Single-thread meandering rivers are generally associated with intermediate values of stream power and intermediate textured floodplain sediments (Leopold and Wolman, 1957; Knighton, 1984; Nanson and Croke, 1992; Van den Berg, 1995). Terrain and sedimentary variability are mentioned as primary controls on the downstream changes in long-term rates of lateral channel migration of meandering rivers. Point-bar accretion has been shown to decrease dramatically in the lower reaches of the Mississippi River as the river scoured into coarse alluvial sands, Pleistocene clays and prodelta clays successively (Kolb, 1963). A sequence of truly free, confined free, restricted and fixed meanders was observed to be strongly influenced by the distribution of thick, fine-grained cohesive floodplain deposits along the River Teshio (Ikeda, 1989). In certain reaches, crossings with older meander belts increased lateral change of the distributaries of the Rhine-Meuse deltaic area (Berendsen, 1982). The occurrence of clay plugs in sandy alluvial sediments of the Mississippi River has been shown to hamper channel migration rates (Hudson and Kesel, 2000).

However, it has long been agreed that the resistance of river bank materials is under exposed in the study of channel patterns (e.g. Knighton, 1984; Bull, 1991; Parker, 1998), so that more field evidence is required to obtain a predictor of lateral channel migration. In this paper a case study is presented on the lower River Vecht in the eastern part of the Netherlands (Fig. 6.1), which was relatively free from major human disturbance previous to channelisation in the early 1890s. The floodplain geomorphology, historical maps and 19th century engineering data provide an opportunity to investigate the spatial variability of channel pattern change and its relationship with geomorphological setting and bank composition. The aim of this study is (1) to document the relationship between geomorphological setting and fluvial styles, (2) to determine the influence of bank composition on channel migration rates, and (3) to advocate the use of this type of geomorphological-sedimentological information in the selection of areas suitable for meander rehabilitation.

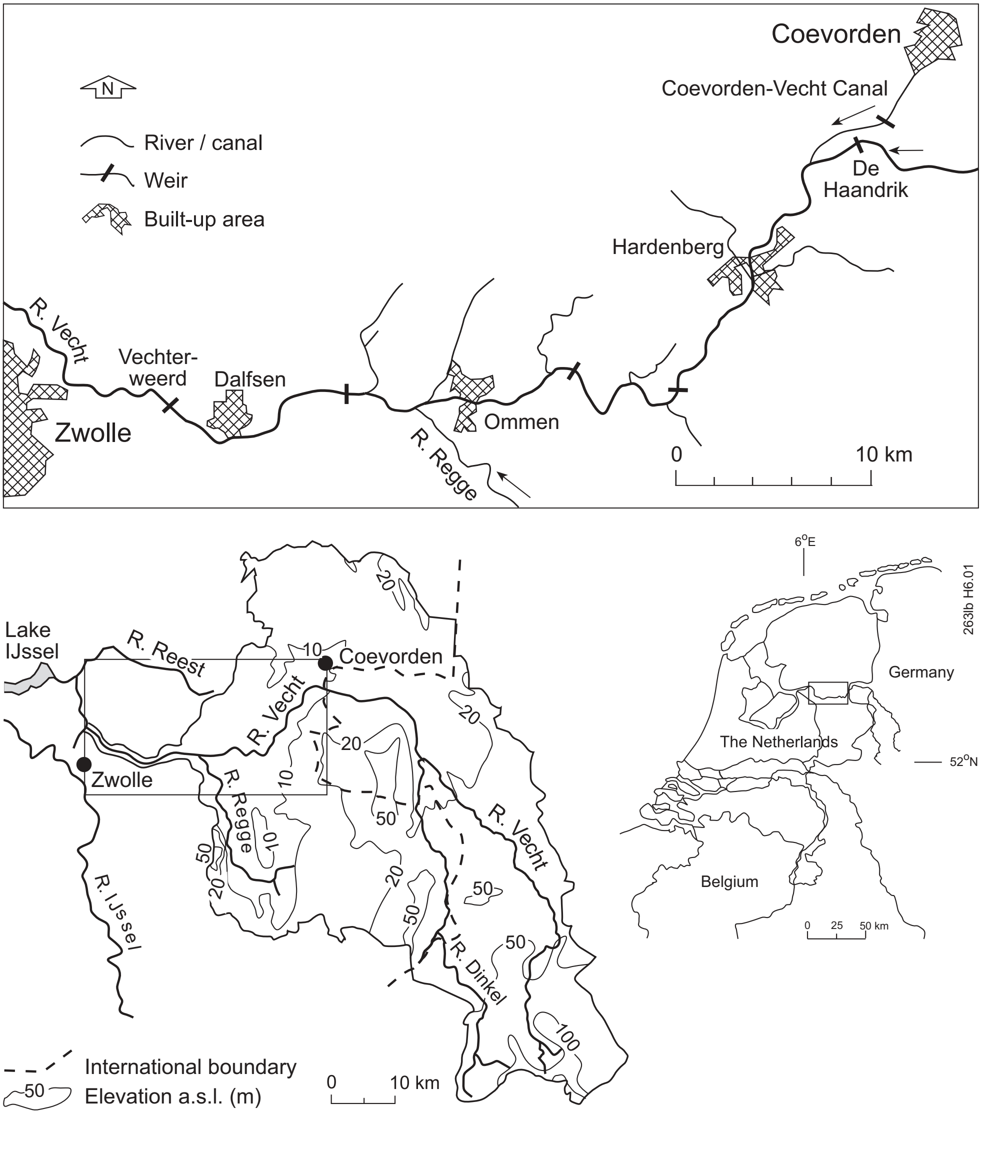


Fig. 6.1.
Location of the River Vecht and study area

MATERIALS AND METHODS

The study area

The River Vecht is a 167 km long river which drains an area of 3785 km2 (Fig. 6.1). Its source is in the hills of Lower Saxony, Germany, at approximately 110 m above sea level. The river debouches into Lake IJssel in the Netherlands. The eastern part of the drainage basin has an undulating topography formed in Cretaceous limestones, Tertiary clays and Pleistocene tills. The western part consists of flat lowlands underlain by Weichselian fluvio-periglacial sands, locally covered by aeolian sands of the Weichselian (coversands) or the Holocene. Near its mouth the river encounters a Holocene environment with fluvial clays and coastal peat. The mean annual precipitation varies from 700 to 825 mm, and evapotranspiration is approximately 525 mm (Meinardi et al., 1998). The discharge regime is characterised by a relatively quick response during periods of high precipitation in winter, but a near absence of flow during the summer period. Peak discharges occurring once in two years, approximating bankfull discharge, are 182 m^3 s-1 near the Dutch-German border at present.

Downstream of Dalfsen, dikes have been constructed along the river since the 14th century. The Dutch part of river was channelised during the periods 1896–1914 and 1932–1957, followed by the German part during the period 1952–1960. In the Netherlands, 69 meanders were cut off, reducing the original length of the lower River Vecht from 90 to 60 km. To prevent degradation of the channel and an associated lowering of groundwater levels in the surrounding region, and to serve navigation in canals connected to the river near De Haandrik, 7 weirs were constructed, of which 6 remain today. In addition, revetments were installed all along the river banks. Parts of the floodplain have been levelled for agricultural purposes, but much of the original floodplain topography still exists.

Downstream changes in discharge and slope, which determine stream power, and bank composition may have influenced lateral channel migration of the pre-channelisation River Vecht. Within the study area, however, the 0.00014 valley slope of the entire lowland River Vecht was rather uniform (Fig. 6.2A), as indicated by 1848 stage data (Staring and Stieltjes, 1848). The discharge of the River Vecht increases mainly due to confluences with the Coevorden-Vecht Canal (named Coevordense Vecht before channelisation) and the River Regge (Fig. 6.2B). These observations justify the assumption that spatial differences in fluvial style and lateral channel migration that do not coincide with these two points of confluence are likely to be caused by differences in bank composition.

Geomorphological survey

The pre-channelisation geomorphology of the study area (before 1890) was reconstructed and mapped on a scale of 1:25,000. Mapping was based on information provided by available maps on geomorphology, soils and topography, and on aerial

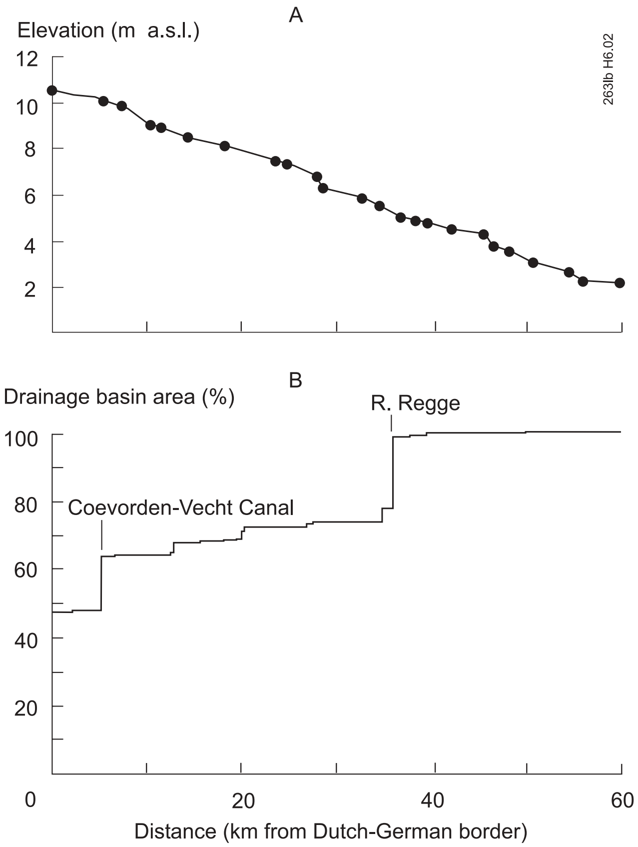


Fig. 6.2. Changes in
(A) valley slope and
(B) discharge along the lower River Vecht

photographs from the period 1944–1951. The classification of morphological units of fluvial origin was based on commonly distinguished landforms and deposits of sand-bed alluvial rivers (e.g. Leopold et al., 1964; Reineck and Singh, 1980). Areas with a plaggen layer were mapped as open field. Plaggen soils are the result of many centuries of manuring and are widespread in the Vecht drainage basin on various types of arable land, especially those at relatively high elevation (Pape, 1970). The plaggen layer may be as thick as 1 m. During the mapping procedure a field check was done to verify and correct the interpretation of information. The maps were digitised using the software package ARC/INFO (ESRI, Redlands, CA) enabling a quantitative analysis of areas.

To analyse sedimentological characteristics, three cross sections were constructed across the floodplain to a depth of a few metres below the surface. Locations have been selected that are representative of different types of meandering, as revealed by the analysis of the geomorphological map.

Fig. 6.3.
Fragments of the historical maps used in this study (for location see Fig. 6.4)

Channel migration data

Channel migration was investigated by stydying historical maps. Four maps were selected that satisfy criteria concerning topographic, geometric and chronometric accuracy (Hooke and Redmond, 1989; Middelkoop, 1997) and cover large areas (Fig. 6.3). The oldest map dates from 1720. It shows the river between the Dutch-German border and Ommen in the Netherlands, on a scale of 1:19,200. Another map from this period shows the design of a military line of defence along the river from De Haandrik to Vechterweerd, on a scale of 1:7200. As both these maps were made by the same cartographer, P. de la Rive, and depict the river in a similar way, the information on the second map is assumed to date from 1720 too. More recent maps used were the 19th century editions of the Topographical map on a scale of 1:50,000, surveyed in 1850 and 1890. A comparison of the width of the river, measured as the channel area to channel length ratio, shows that the accuracy of the maps differ (Table 6.1). The 1720 map is least accurate. Therefore, the river channel depicted on each map was transformed into a geometrical correct representation by comparing it with the 1890 and recent topographical maps, before digitising the information.

Channel pattern characteristics were derived from the 1890 map, the most accurate map. Meander wavelength was measured as the distance between inflection points. The reconstruction of channel migration was obtained by digital overlaying. Lateral erosion and accretion of river reaches was measured as the area between two successive positions of the river bank per unit length of river. Average channel migration rates were derived from the data on lateral erosion, because eroding

Table 6.1.
Comparison of values of the mean width of the river channel in historical time as shown by maps and measured by Staring and Stieltjes (1848)

RIVER REACH	WIDTH (m)			
	Historical maps			Measurements
	1720	1850	1890	1848
A	105.2	60.3	87.8	30.1
B1	117.7	76.3	65.7	22.3
B2	140.0	81.4	70.1	42.8
B3	108.4	83.2	81.7	49.0
B4	91.8	88.2	82.1	56.4
C	73.2	64.5	74.2	93.1
River	107.0	74.2	77.7	55.8

banks are generally steeper than accreting banks so that their position on the historical maps is probably indicated with more precision. Maximum bend migration was measured as the distance of migration of concave banks at the apex of the bend.

RESULTS

River reaches and fluvial styles

The characteristics of the landforms along the River Vecht are listed in Table 6.2. The associated lithofacies are grouped into lithogenetic units, which can be considered architectural elements (cf. Miall, 1985). Table 6.3 presents a lithostratigraphical classification of the architectural elements, with brief lithological descriptions. Three reaches are distinguished, each with a typical fluvial style induced by differences in geomorphological setting (Fig. 6.4). Four subreaches were distinguished within reach B, which was morphologically and sedimentologically not as homogeneous as reaches A and C.

Reach A, from the Dutch-German border to Hardenberg, is characterised by a relatively narrow Holocene meander belt in the middle of an extensive floodbasin (Fig. 6.5A; Table 6.4). The meander belt is mainly composed of natural levees, although in some parts these are absent. Scroll-bar and swale topography is scarce, and so are abandoned channels. The bend dimensions of the abandoned channels are relatively small, similar to the river meanders in 1890. In the proximal part of the floodbasin a layer of fluvial clays occurs, which is approximately 1 m thick. The floodbasin clays were deposited on the Weichselian Late Pleniglacial palaeo-floodplain of the Vecht (Fig. 6.4A), which occupied the entire area between the present Vecht and Reest rivers (Huisink, 1998). Topographically high areas of the palaeo-valley occur as outcrops in the Holocene floodbasin, and are capped by a plaggen layer. All these features point to a tranquil depositional setting.

In reach B, from Hardenberg to Dalfsen, the meander belt is wider, but found

Table 6.2.
Geomorphological and sedimentological characteristics of landforms

LANDFORM	MORPHOLOGY	ARCHITECTURAL ELEMENTS	GENESIS
HOLOCENE FLUVIAL LANDSCAPE			
River channel	Sinuous channel	Channel deposits	Scour and bank collapse during bankfull; formation of point bars and aggradation during waning of flow
Abandoned channel (1)	Abandoned, sinuous channel	Overbank deposits or flood-plain deposits on channel- fill deposits on channel deposits	Overbank deposition and settling of fines after cutoff
Scroll bars and swales (2)	Pattern of small, crescentic ridges and elongate depressions in between	Overbank deposits on channel deposits	Migration of river bend and associated point-bar and scroll-bar formation
Natural levee (3)	Elongate, narrow ridge along the river channel	Overbank deposits on channel deposits	Deposition of bedload and suspended load due to overtopping of banks
Aeolian dunes (4)	Chaotic dune morphology	Aeolian deposits on overbank deposits or channel deposits	Deflation of fluvial sands by wind
Floodplain flat (5)	Flat valley bottom	Overbank deposits on channel deposits or fluvio-periglacial deposits	Settling of suspended load during waning of flood events
Floodbasin (6)	Undulating low terrain with abandoned channels	Floodbasin deposits on fluvio-periglacial deposits	Settling of suspended load during waning of flood events and peat formation
Dike breach pond (8)	Small depression	Channel-fill deposits	Scour caused by dike breach
WEICHSELIAN PERIGLACIAL AND HOLOCENE AEOLIAN LANDSCAPES			
Coversand undulations / River terrace (9)	Undulating to flat terrain	Aeolian deposits on fluvio-periglacial deposits / fluvio-periglacial deposits	Fluvial deposition in a braided river system and deflation of deposits by wind
Open field with plaggen soil (10)	Smooth and shallow undulation	Plaggen layer on aeolian dune or sand sheet deposits on/or fluvio-periglacial deposits	Manuring and subsequent formation of plaggen soils
Aeolian dunes (11)	Chaotic dune morphology	Aeolian dune deposits on aeolian sand sheet deposits	Deflation of coversands by wind

within a valley setting (Fig. 6.5B). The most striking features are the many oxbow lakes enclosing relatively large areas with scroll-bar and swale topography, on top of which aeolian dunes occur frequently. Natural levees are also prominent. In contrast, floodplain flats and floodbasins constitute no more than half of the valley bottom. The width of the channel belt increases the further downstream it is, while the thickness of overbank deposits and the extent of the floodbasin clays decrease (Fig. 6.6). The overbank deposits of floodplain flats and floodbasin clays are partly underlain by Weichselian Late Glacial fluvio-periglacial deposits (Fig. 6.6). At such locations the

Table 6.3.

Lithology and lithostratigraphical classification of architectural elements

LITHOSTRATIGRAPHICAL UNIT[1]	ARCHITECTURAL ELEMENT	LITHOLOGY
Kootwijk formation (Holocene aeolian deposits)	Aeolian dune deposits (D)	Fine sand
Singraven Formation (Holocene fluvial deposits)	Floodbasin deposits (B)	Clay, silty clay
	Overbank deposits (O)	Fine sand and loamy sand; including iron concretions
	Channel-fill deposits (F)	Humic clay and clayey peat
	Channel deposits (C)	Coarse and fine sand; occasionally with loamy layers; fining upwards
Twenthe Formation (Weichselian periglacial deposits)	Aeolian dune deposits (A)	Fine sand
	Aeolian sand sheet deposits (S)	Loamy sand
	Fluvio-periglacial (terrace) deposits (T)	Fine sand
	Fluvio-periglacial (palaeo-valley) deposits (P)	Coarse and fine sand

[1] *cf. Doppert et al. (1975)*

Table 6.4.

Occurrence of fluvial landforms in river reaches and the lower River Vecht around 1890

RIVER REACH[1]	LANDFORM							
	Abandoned channel (% area)	Scroll bars and swales (% area)	Natural levee (% area)	Aeolian dunes (% area)	Flood-plain flat (% area)	Flood-basin (% area)	Estuarine basin (% area)	Dike breach pond (% area)
A	1.4	1.2	7.1	0.1	33.6	56.7	0.0	0.0
B1	9.1	6.0	20.0	1.4	0.0	63.4	0.0	0.0
B2	7.4	13.4	21.7	6.6	13.3	37.7	0.0	0.0
B3	6.1	14.4	18.6	9.1	27.8	24.1	0.0	0.0
B4	6.3	17.5	21.4	4.9	39.2	10.6	0.0	0.0
C	8.4	15.9	21.6	0.0	26.9	4.9	21.1	1.1
R. Vecht	6.5	11.4	18.4	3.7	23.5	32.9	3.5	0.2

[1] *total area: A, 1399 ha; B1, 394 ha; B2, 595 ha; B3, 859 ha; B4, 846 ha; C, 565 ha; R. Vecht, 4658 ha.*

overbank deposits are rich in iron. Late Glacial fluvial terraces as well as the isolated terrace outcrops found in subreach B3 are often capped by a plaggen layer. The river valley is bordered by conspicuous bluffs, separating its Holocene alluvial deposits from the adjacent Weichselian sandy fluvio-periglacial and aeolian deposits. Many open fields with a plaggen layer occur along the river valley. Some large meanders that penetrate deeply into the aeolian dune areas adjacent to valley bluffs are typical of subreach B2. The river abandoned its former palaeo-valley and shifted to its present valley with the onset of a warmer climate in the Weichselian Late Glacial (Huisink, 1998). River reach B is interpreted as a dynamic depositional setting.

In reach C, from Dalfsen to Vechterweerd, historical channel deposits are found

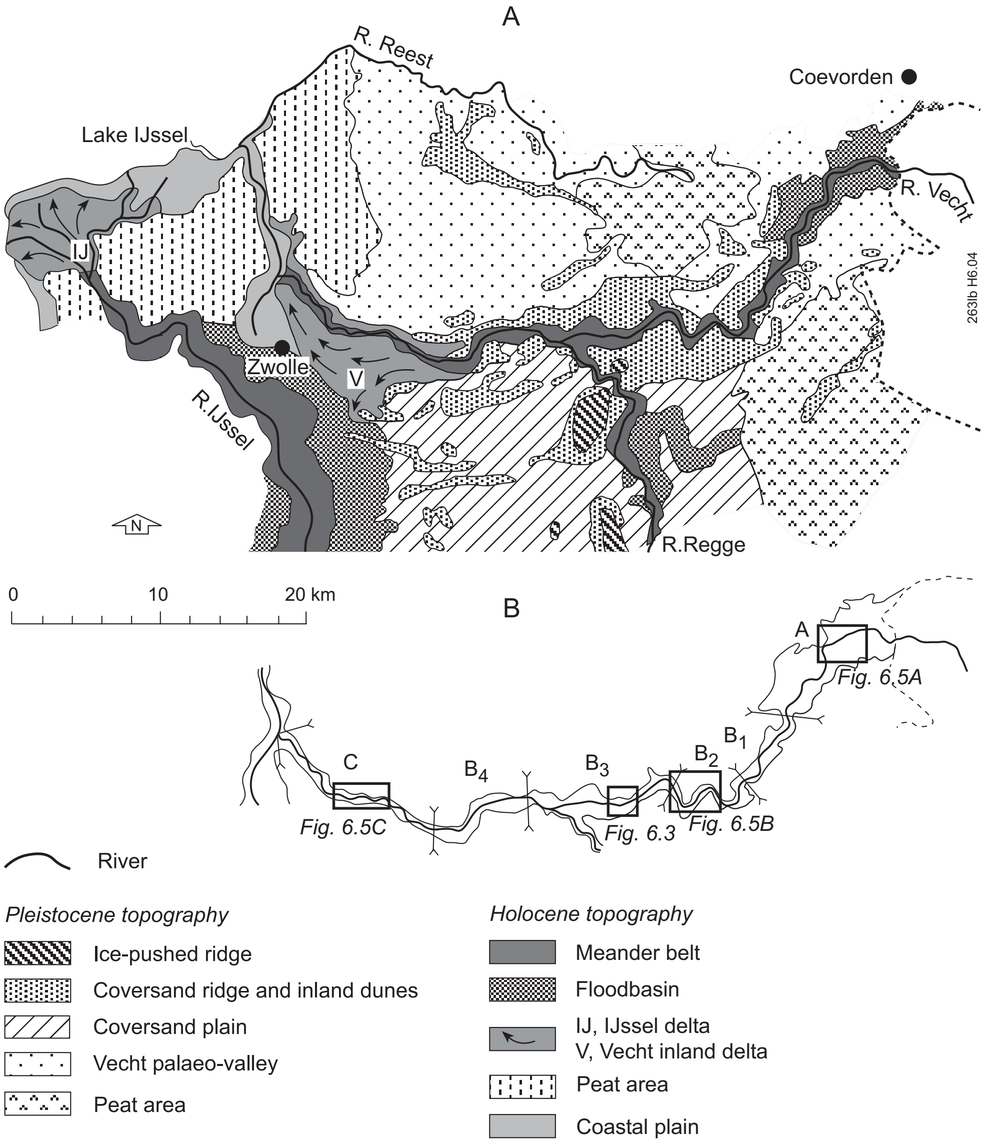


Fig. 6.4.

Maps of (A) the geomorphological setting of the lower River Vecht (based on Ente et al., 1965) and (B) the river reaches distinguished

between the dikes. The sinuosity of the 1890 river channel was much lower compared with the other reaches (Fig. 6.5C). Also, a different landform configuration is observed. Natural levees occur along the upstream part of convex channel banks, while scroll bars and swales occur adjacent to the downstream part. The downstream parts of scroll bars are bent convex to the river in planform. Oxbow lakes are rare, but sloughs are characteristically connected to the river channel near the bend apex of concave banks. These features are generally related to confined rivers (Howard, 1992), in which downstream channel migration is common instead of lateral migration. Accretion was probably of the concave bank bench type (Page and Nanson, 1982) and loamy sands dominate the deposits in this reach. Reach C was embanked because it is relatively high due to its position in an alluvial fan-like inland delta (Fig. 6.4A). This delta has been formed where the Vecht river system meets the Holocene fluvial and marine environments of the River IJssel and Lake IJssel.

Lateral erosion and accretion

The channel pattern of the River Vecht did not change dramatically in historical time: the 1720 channel pattern remained more or less unchanged until 1890 (Fig. 6.3). During the period 1720–1890, 6 meanders were cut off, four of which were situated in reach A, one in reach B and one in reach C.

Data on lateral erosion and accretion are presented in Table 6.5 and Table 6.6. Data obtained from the area with scroll bars and swales indicates the renewal of floodplain lands due to lateral accretion, but only gives a rough approximation of lateral accretion rates, as part of this topography was found subdued by younger overbank deposits and

Table 6.5.
Lateral accretion and erosion in river reaches

RIVER REACH[1]	**ACCRETION**			**EROSION**	
	Scroll-bar and swale area (ha/km)	**Channel migration (ha/km)**		**Channel migration (ha/km)**	
		1720–1850	**1850–1890**	**1720–1850**	**1850–1890**
A	1.20	9.84	4.19	5.43	2.61
B1	3.87	9.26	3.87	5.13	2.78
B2	8.74	13.18	4.22	7.96	3.09
B3	13.00	7.97	3.67	5.46	3.52
B4	18.27	10.82	4.67	10.45	4.06
C	5.91	2.19[1]	0.66	1.79	1.63
R. Vecht	7.95	8.31	3.49	5.54	2.79

[1] *length of river reach, measured along valley axis:* A, *12.3 km;* B1, *6.1 km;* B2, *9.1 km;* B3, *9.5 km;* B4, *8.1 km;* C, *15.2 km.*

Table 6.6.
Average channel migration rates in historical time

PERIOD	**LATERAL EROSION**		
	Area (ha)	**M ($m\ yr^{-1}$)**	**M/w (yr^{-1})**
1720–1850	334	0.46	0.0082
1850–1890	168	0.55	0.0099

M, migration rate; M/w relative migration rate; w, channel width

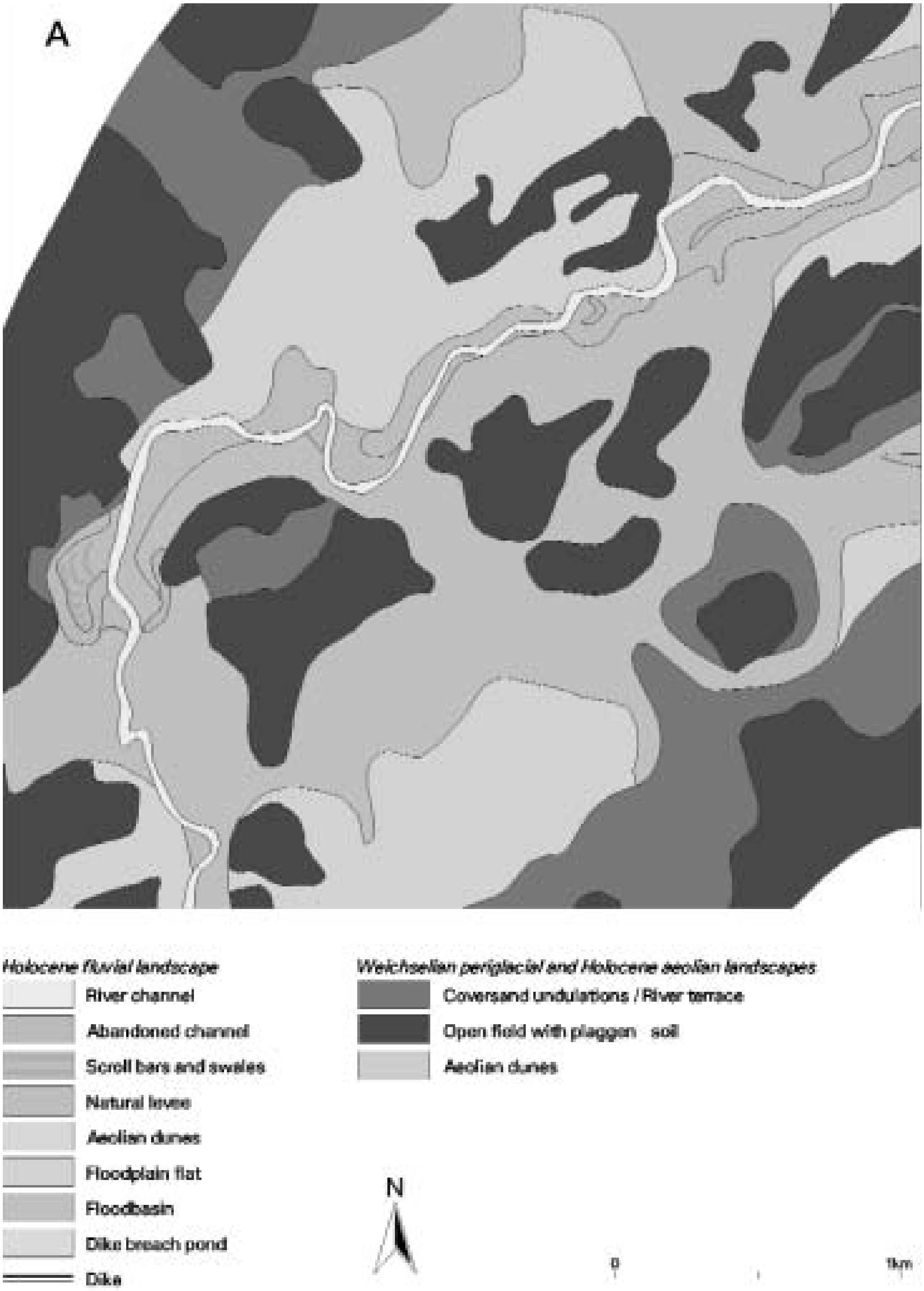
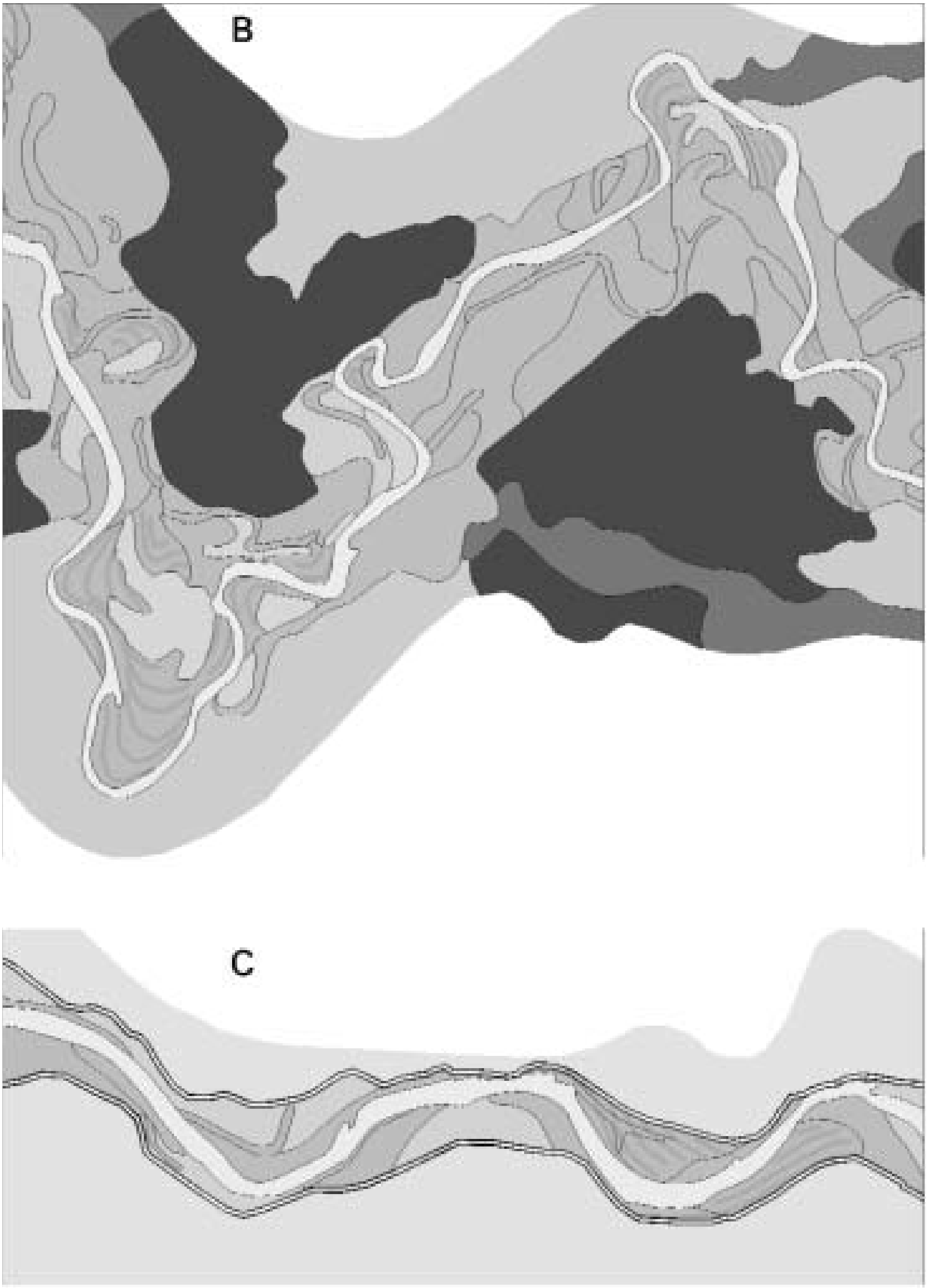


Fig. 6.5.

Characteristic alluvial landform configurations in the three river reaches (for location see Fig. 6.4)


B
C

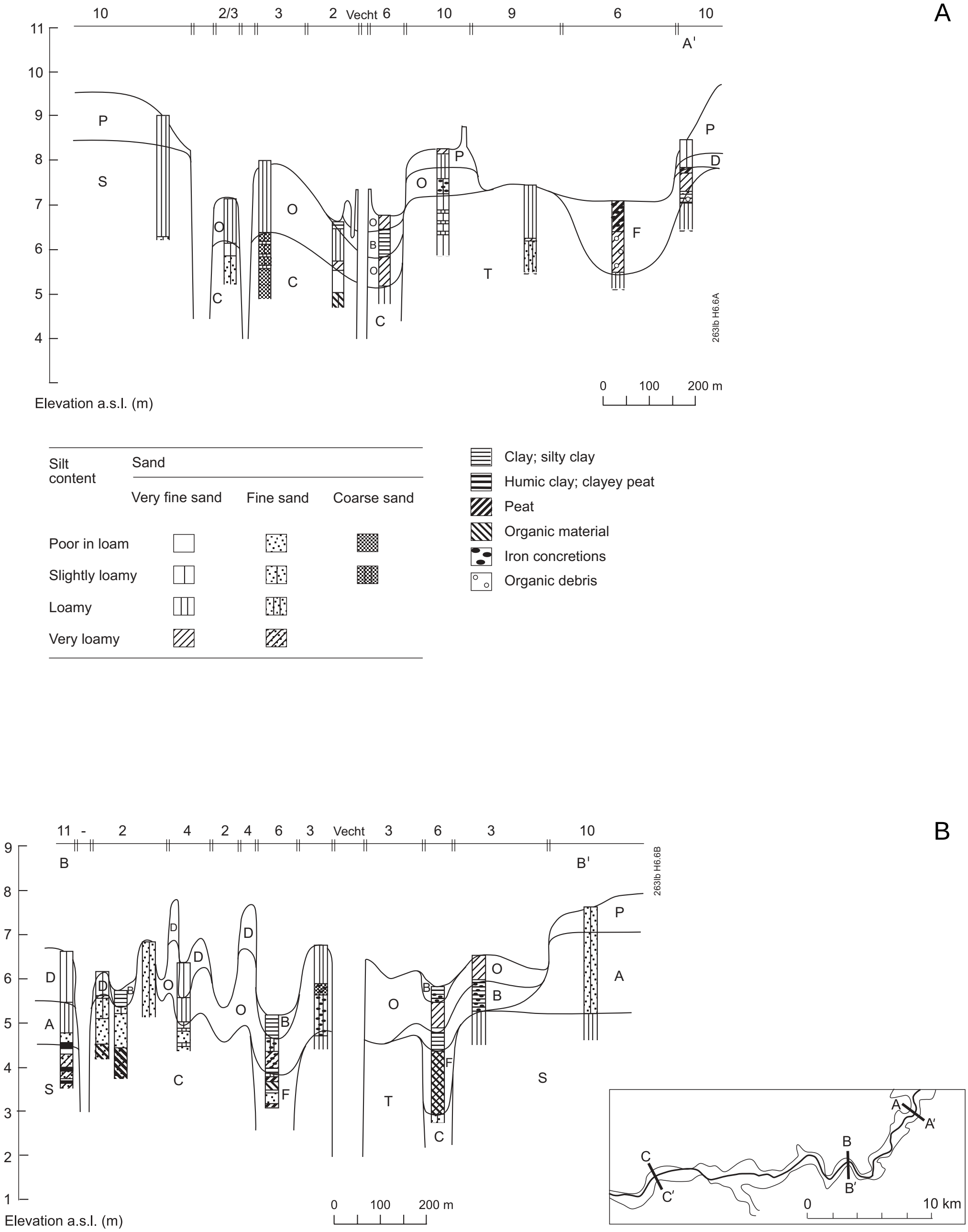
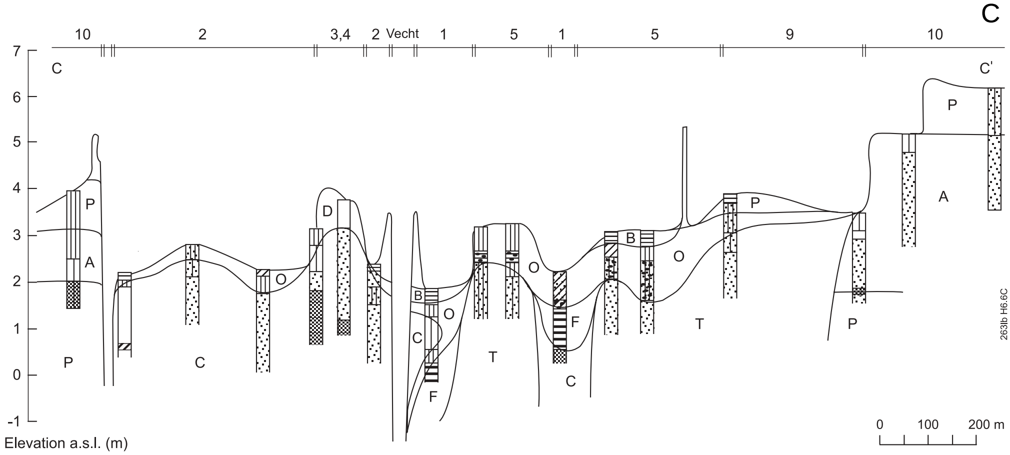


Fig. 6.6.
Cross sections showing alluvial valley topography, borehole sediment characteristics and lithological units of reach B (numbers 0–11 refer to landforms given in Table 6.2; letters D, B, O, F, C, A, S, and W refer to architectural elements mentioned in Table 6.3; P = plaggen layer)



was mapped as natural levee, floodplain flat or floodbasin. Data obtained from the historical maps also can only approximate channel migration rates, as maps are not fully reliable. Differences in the width of the river depicted on the maps from 1720, 1850 and 1890, for instance, causes differences between measured erosion and accretion.

Nevertheless, the data show a consistent pattern, which largely reflects the differences between the reaches A, B and C. Channel migration in reach A and subreach B1 was small compared with that of reach B. This is attributed to the influence of resistant clayey floodbasin deposits which decreases further downstream. Within reach B, lateral erosion and accretion was largest in the subreaches B2 and B4. In these subreaches, the river flows in sandy channel deposits and often impinges on valley bluffs composed of sandy aeolian or fluvio-periglacial sediments (Fig. 6.6B and Fig. 6.6C). These types of bank materials are easily entrained by the flow of water. Migration in reaches A and B occurred mainly in a lateral direction. In reach C, historical migration appeared to be much smaller than the area of scroll bars and swales suggests. This points to an initially dynamic river reach, in which the downstream migration of the channel eventually became hampered by the presence of dikes.

The meander wavelength of the 1890 channel in river reaches is given in Fig. 6.7. The data reflect the differences in lateral erosion and accretion. The small wavelength in subreach B1 is very similar to that in reach A. Meander wavelength in reach C is clearly different from that in reaches A and B. Within reach B, the ranges of values of wavelength are large in subreach B3, but are exceptionally small in subreach B4. This is related to the amount of erosion-resistant bank materials encountered by the river. The river was much more confined by Late Glacial terrace outcrops capped by overbank deposits rich in iron and by plaggen layers in subreach B3. In contrast, the river was able to meander freely and to develop a regular meander pattern in its wide belt of channel deposits in subreach B4.

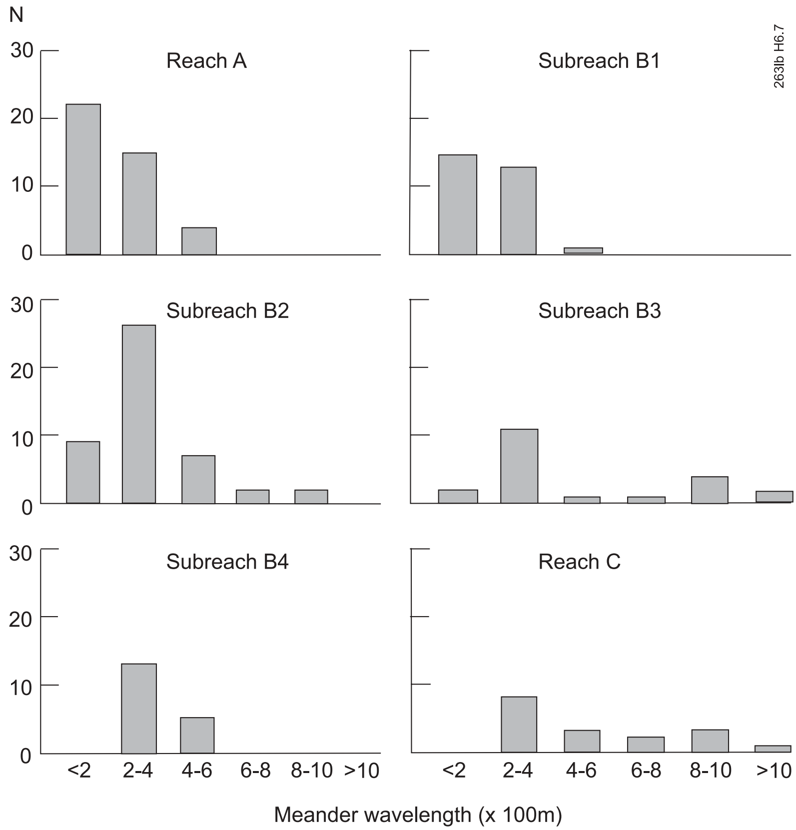


Fig. 6.7.
Downstream changes in meander wavelength

Meander bend migration

Maximum rates of bank retreat in bends were observed in reach B. Maximum bend migration observed during the period 1720–1890 amounted to 500 m, which is a migration rate of 2.94 m per year. An imaginary example of such a rapidly migrating bend is given in Fig. 6.8A. It depicts schematically the evolution of the large meander bends in subreach B2. Bends of this type developed at locations where the river impinged upon valley bluffs composed of Holocene aeolian dune sands on top of Weichselian aeolian dune sands (Fig. 6.5B and Fig. 6.6B). The associated increase in the length of the river channel was accommodated by the development of new bends within the meander, restoring its original sinuosity. Other rapidly migrating bends impinged upon valley bluffs of which the lower part was composed of relatively coarse fluvio-periglacial sands, underlying aeolian sands or even plaggen layers (Fig. 6.6C). These erodible sands were observed in subreach B4 only.

A typical example of a bend with resistant bank sediments is depicted in Fig. 6.8B. Bends of this type occurred in the reaches A and B, where the river impinged upon

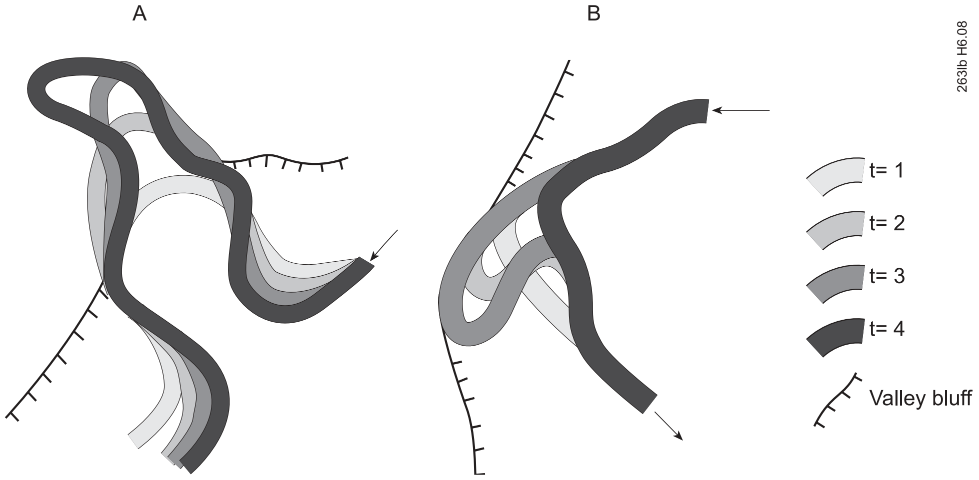


Fig. 6.8.
Styles of meander evolution influenced by banks composition: (A) banks dominated by very erodible aeolian sands and (B) banks with resistant plaggen layers on top

terrain with a plaggen layer (Fig. 6.5 and Fig. 6.6A). Fields with plaggen soils were often surrounded by hedges. The binding forces of abundant organic matter and roots make these river banks where the plaggen layer is exposed stable and resistant to fluvial entrainment of material, hampering channel migration in a lateral direction. Where a river encounters such a terrain, it will often be diverted in downstream direction and the bend will be tightened, followed by a neck-cutoff somewhat upstream. Tight river bends are often associated with the formation of concave bank benches and an attack on the convex bank, leading to meander cutoff (Thorne, 1992).

DISCUSSION

Significance of bank materials

Classifications of channel pattern have been related to the width–depth ratio (Schumm, 1977; Fredsøe, 1978; Rosgen, 1994). Channels with more cohesive materials tend to be relatively narrow, deep and sinuous, and have smaller wavelengths (Schumm, 1968). They also tend to be more stable. Historical data on the channel width at high discharge and bankfull depth are provided by a study by Staring and Stieltjes (1848). Mean values of the width–depth ratio per river reach are compared with mean values of reach migration rates (Fig. 6.9). A strong relationship is observed within reaches A and B, with a high level of confidence, especially for the 1850–1890 data. The simultaneous increase in both parameters supports the idea that the influence of resistant floodbasin deposits gradually declines in a downstream direction. These downstream changes are related to the geomorphological setting. On its way

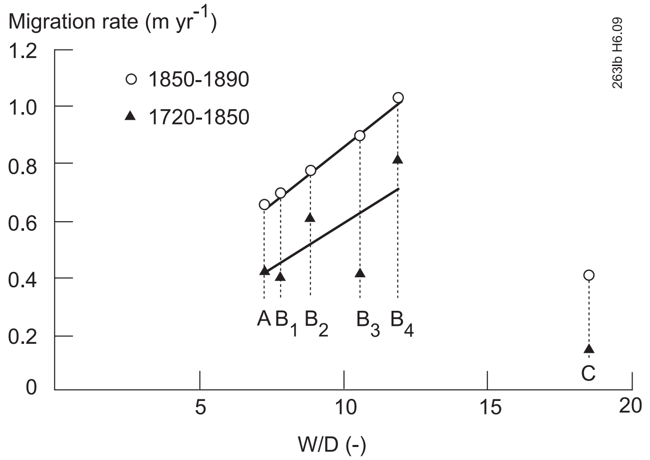


Fig. 6.9.
Relationship between mean channel migration rate and mean width–depth ratio values of river reaches

downstream, the migration rates of the river channel increased from reach A to reach B, because in reach B valley bluffs composed of sandy material provided sediment to the river. As a result, the extent of sandy channel belt sediments increased the further the river is downstream, which favoured the downstream increase in migration rates within reach B once again.

In reach C, the width–depth ratio values are much higher than those of reach B, but migration rates were much lower. Obviously, the relationships described above are not valid here. The high width–depth ratio values are mainly due to the large width of the river channel (Fig. 6.10). This supports the notion that the presence of dikes is the most likely cause of channel stability. Following embankment, channel migration must have been increasingly hampered by dikes, initially leading to downstream migration. As soon as the sinuosity of the channel became out of phase with the alignment of the dikes, migration must have stopped. Ikeda (1989) observed this was associated with a decrease in channel sinuosity and a widening of the channel. Widening increases the wetted perimeter and is a means to restore the channel's hydraulic roughness.

Classification of erodibility

To take account of the effect of bed and bank materials, Schumm (1968, 1977) related some of the channel properties to the percentage silt and clay in the sediments forming the perimeter of the channel. Sediments are more cohesive with increasing percentages of silt and clay so that these are considered to be an indication of bank stability. The silt and clay content of some of the deposits along the River Vecht can be derived from grain size distributions of soils, described at type localities of soils in this area (Staring Centrum, 1989; Kuijer and Rosing, 1994). Comparison of deposits is based on data on the C horizons at a depth of approximately 1 m (Fig. 6.11). The data on silt and clay content explain most of the observations on bank stability. Floodbasin deposits

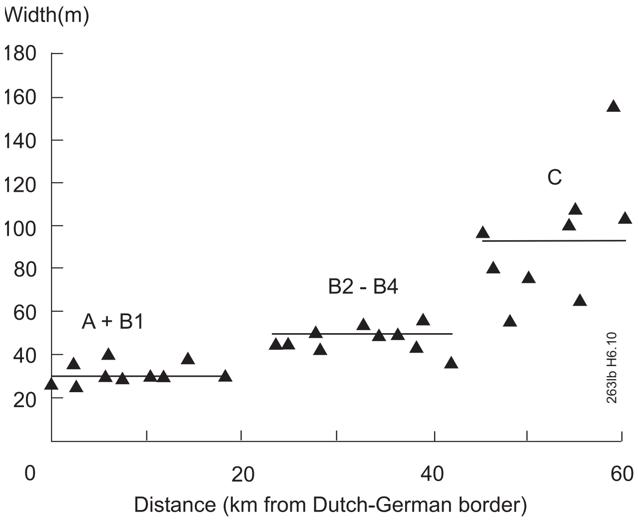


Fig. 6.10.
Channel width in river reaches

and loamy overbank deposits have high values of silt and clay (23–85%) and thus will be resistant to erosion. The silt and clay contents of these deposits decreases in the downstream direction, from 85% in reach A to 23% in reach C, suggesting a downstream decrease in cohesion. Overbank deposits overlying Weichselian fluvio-periglacial deposits in reach B, however, are rich in iron (Fig. 6.6) and this contributes to their resistance. Plaggen soils have intermediate values ranging from 11–15%, which seem to be relatively low as plaggen layers were assumed to be resistant to erosion. The cohesiveness of plaggen layers, however, is also related to the higher content of organic matter. Both the aeolian dune deposits (2–5%) and the channel deposits (4–11%) contain very small amounts of silt and clay and will be very erodible.

Historical evidence on channel migration and the bank material properties are used to set up a ranking in erodibility of river banks. Four classes of erodibility are proposed, related to bank composition. (1) Very erodible: banks dominated by non-cohesive sands characteristic of channel deposits and aeolian dune deposits. These are found in areas with scroll bars and swales, natural levees and aeolian dunes. Banks in which coarse fluvio-periglacial deposits occur at the base are also very erodible. This type of bank was observed in open fields at coversand ridges adjacent to the valley bluffs. (2) Erodible: banks dominated by loamy sands, sometimes rich in iron, with intermediate cohesion. These are typical of overbank deposits and aeolian sand sheet deposits, and are related to morphological units mapped as floodplain flats and coversand undulations / river terraces. (3) Resistant to erosion: banks with a cohesive plaggen layer on top of overbank deposits, fluvio-periglacial deposits or aeolian deposits. These are related to open fields. (4) Very resistant to erosion: banks dominated by very cohesive floodbasin deposits. Occasionally, floodbasin deposits are underlain by channel fill deposits, which have more or less the same properties. Separate clay plugs, however, were not observed to play a role (Thorne, 1992; Hudson and Kesel, 2000).

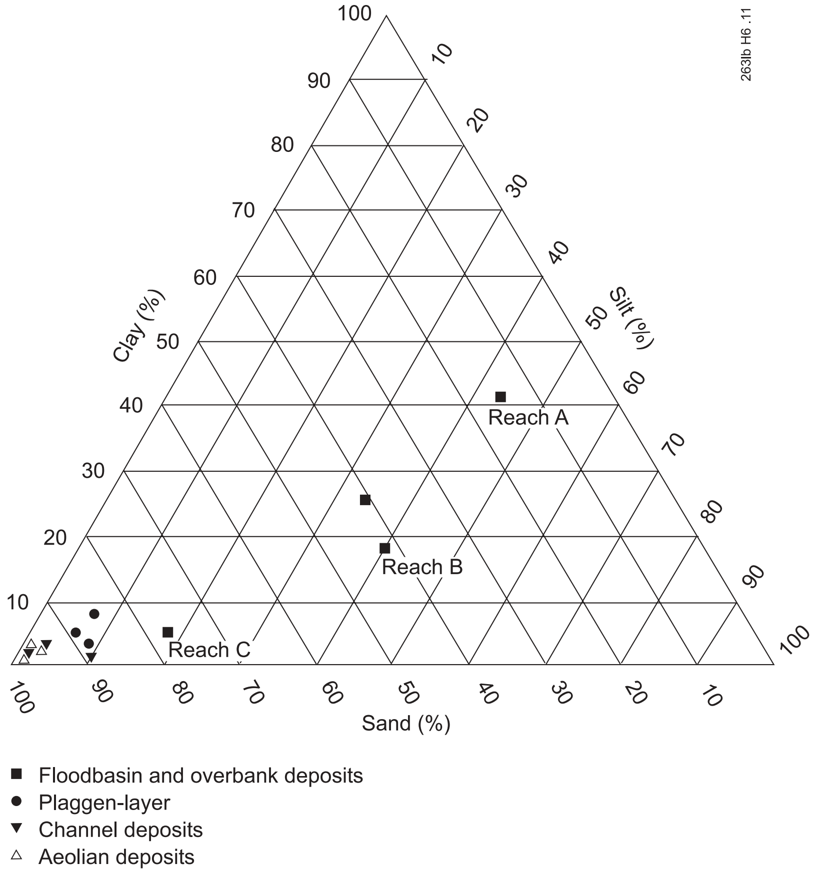


Fig. 6.11.
Textural composition of deposits along the River Vecht

Application in river rehabilitation

The River Vecht and its floodplain have been designated to be part of the National Ecological Network in the Netherlands (Ministerie van Landbouw, Natuurbeheer en Visserij, 1990; Provincie Overijssel, 1992). The Vecht valley is considered to be an important corridor for the migration of species between upland stream valleys and lowland marshes along Lake IJssel. As the river system lacks habitats crucial to characteristic riverine species at present, removal of revetments is one of the measures being considered to rehabilitate the meandering of the river. It is assumed that the meandering process will locally result in bank erosion and point-bar accretion, although weirs are present in the river. Weirs are open during periods of high discharges, which have been described to be the most effective channel forming events (Andrews, 1980; Richards, 1982). That the present, straightened river channel is still able to meander is indicated by data on specific stream power. Whereas the values of

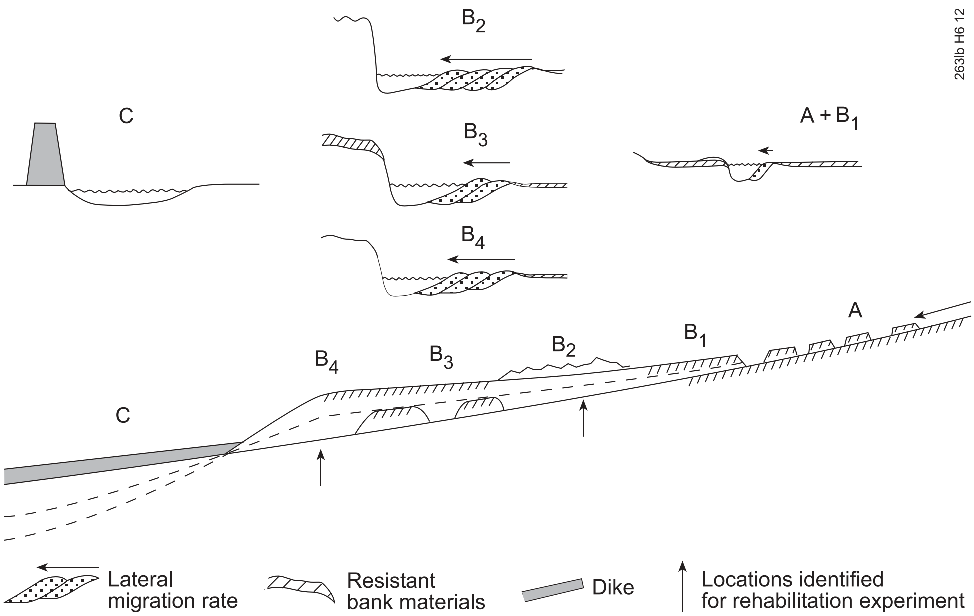


Fig. 6.12.
Model of the influence of geomorphological setting and bank composition on channel migration and the formation of lateral accretion deposits

specific stream power at bankfull discharge varied from 6.8 to 9.8 W m^{-2} in 1890, the present values range from 4.0 to 6.8 W m^{-2}, which is still comparable to those of other high sinuosity meandering rivers (Van den Berg, 1995).

Prior to full rehabilitation, an experiment will probably be conducted to examine the impacts of the removal of revetments. For this purpose, sites had to be identified where the process of meandering would have the largest effect. In the selection process, a model of meander variability was used, in which the implications described in this paper were summarised (Fig. 6.12). Large effects are neither expected in reaches A and B1, where banks composed of very resistant floodbasin clays hamper migration, nor in reach C, which is confined by dikes. Conspicuous channel migration and lateral accretion deposits are more likely to be expected in the reaches B2 to B4, due to their valley setting. Within these reaches the effects will be smallest where plaggen layers are exposed in channel banks, but will be largest if the river is allowed to impinge again on valley bluffs composed of aeolian dune deposits. This rationale lay behind the selection of three approximately 2 km long stretches in subreaches B2 and B4, as the most suitable parts of the river for a re-meandering experiment (Fig. 6.12). Alternatively, this model can be used to indicate the expected long-term effects if the meandering process is rehabilitated along the entire lower River Vecht.

CONCLUSIONS

Prior to channelisation, the lower River Vecht was an example of a river with a downstream succession of different reaches due to variation in geomorphological setting. This not only implied different fluvial styles, characterised by the fluvial landform configuration and the associated pattern of the meandering channel, but also differences in bank composition.

The spatial variability in bank composition led to differences in the long-term rates of lateral channel migration. This relationship was reflected by the width–depth ratio of the river channel and was largely explained by the silt-clay content of river bank deposits. Thus, the study yields new field evidence for optimising the understanding and prediction of the influence of bank materials on channel pattern.

These implications of meander variability can also be used to assess the effects of the rehabilitation of the meandering process. As long as a reliable predictor of meander migration and channel pattern is not available, this type of geomorphological-sedimentological information is recommended for use in rehabilitation planning.

ACKNOWLEDGEMENTS

This research was financed by the Department of Public Works and Water Management of the Netherlands Ministry of Transport, Public Works and Water Management. Writing of the paper was supported by the Ministry of Agriculture, Nature Management and Fisheries. Joep Dirkx collected historical maps and documents from various archives. Valuable comments on a draft of this paper were given by Jan Klijn, Ward Koster, Bart Makaske and Hans Middelkoop.

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7

Embanked river reaches in the River Rhine depositional zone – I. Historical geomorphology

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Submitted to Geomorphology

ABSTRACT

An understanding of the downstream changes in landform characteristics and associated processes is important for the rehabilitation of ecologically relevant channel-floodplain relationships in large, embanked rivers. In three sand-bed river reaches of the River Rhine depositional zone (the Netherlands), the pre-channelisation geomorphology was studied by means of analysing 16th–19th century historical maps. Landforms were mapped on a scale of 1 : 25,000 and the width–depth ratio, Shields parameter, flow velocity and the frequency of water level exceedance were calculated. Landforms were the result of island formation, point-bar formation and overbank deposition. However, the three river reaches showed consistent differences in configuration, development and hydrogeomorphological parameter values. Developments have been summarised in a conceptual model of landform succession and floodplain renewal. Width–depth ratio values may be regarded as a predictor of the initial phase of the succession, i.e. whether or not islands and secondary channels, (high or low) point bars and sloughs or, eventually, scroll bars and swales will be formed. Flow velocity over the floodplain during inundation has been proposed as a predictor of the evolution of sloughs and abandoned channels into floodplain flats. Four types of fluvial styles have been distinguished, of which three occurred in a continuum of river reaches typical of active distributaries. Central in this sequence is a confined, low-sinuosity, downstream migrating style, which is the result of embankment in this lowland fluvial environment. Upstream, a high-sinuosity, laterally migrating meandering style could persist after embankment, due to a thinner cover of Holocene flood basin deposits on erosive Pleistocene channel deposits. Downstream, a low-gradient, tidal island river style predominates, associated with a lack of bed-load transport capacity and stable banks in marine clays. A passively meandering style is the result of a decrease in transport capacity related to channel avulsion.

KEYWORDS
Floodplain, Fluvial landform, Fluvial style, Geomorphological map, Historical data, the Netherlands

INTRODUCTION

The rehabilitation of ecologically relevant relationships between the river channel and the adjacent floodplain is an important topic in modern, integrated water management (Petts and Amoros, 1996; Stanford et al., 1996). Awareness of this theme was raised after a long period during which most of the rivers in Europe and North America were channelised (Brookes, 1988), a process which has changed the riparian landscape structure dramatically (e.g. Roux et al., 1989; Marston et al., 1995). Reconnecting channel and floodplain is especially relevant in the downstream reaches of large rivers because the amount of stored alluvium is largest here (Church, 1992), as is the variability in floodplain topography. Characteristic landforms such as secondary channels, backwater sloughs, oxbow lakes, islands, point bars and natural levees constitute a patchwork of aquatic and terrestrial habitats, valuable to wild-life because of its relatively high biological productivity and its corridor function. The relationships between these various habitats and the habitat structure itself, are maintained by the pulsing water discharge (Junk et al., 1989). During flood events, all floodplain elements are connected to each other and to the river channel, providing possibilities for lateral exchange of sediments, nutrients and species. The flood pulse associated geomorphological change is a powerful mechanism for floodplain rejuvenation since erosion and deposition can reset processes such as floodplain aggradation and the vegetation succession.

The geomorphological characteristics of large alluvial rivers have been studied intensively, and a large number of fluvial styles has been described in various classification systems (e.g. Miall, 1996; Nanson and Croke, 1992). Which of these styles prevails depends on variables such as valley slope, water discharge, sediment load and the bed and bank sediments (Hey, 1978; Ferguson, 1987). Together, these determine the power to carry away and transport clastic material and the resistance to erosion. Usually, most of these variables change in the downstream direction, either gradually or abruptly. As a result, rivers have different reaches, each characterised by a specific river channel planform and associated floodplain geomorphology. Well-known examples of longitudinal changes in large river systems are those described for the River Rhine (Statzner and Kohmann, 1995) and the French Upper River Rhône (Bravard et al., 1986). More detailed studies refer to free flowing rivers such as the low-sinuosity sand-bed Platte River (Crowley, 1983) and the wandering gravel-bed Squamish River (Brierley and Hickin, 1991).

Detailed information on the downstream changes in embanked river systems, however, is not available to date. Insight into the various landform configurations and the associated causal processes of embanked rivers is highly relevant to river rehabilitation planning, for instance to decide where measures such as re-creating secondary channels, re-connecting oxbow lakes or lowering the floodplain surface (Van de Kamer et al., 1998) are appropriate or not. This paper addresses the embanked distributaries of the River Rhine depositional zone in the Netherlands. The aim of the study was to: (1) analyse the various landform configurations of distinct river reaches representative of the River Rhine distributary system, (2) describe the associated geomorphological processes and related hydrogeomorphological parameters, and (3) indicate the causal variables responsible for this river reach variability. Ideas and guidelines relevant to identifying and planning river rehabilitation targets are presented in Chapter 8.

MATERIALS AND METHODS

Physiographical setting

The depositional zone (cf. Schumm, 1977) of the Rhine river system is situated on the fringes of the North Sea basin. Fluvial aggradation in this deltaic area, located between the terrace crossing just east of Lobith and the North Sea (Fig 1.), has been caused mainly by a rise in sea-level during the Holocene (Van Dijk et al., 1991). Avulsion was the principle process in its development and resulted in a large number of both abandoned and active meander belts, interspaced by flood basins (Stouthamer, 2001). The contemporary distributaries of the River Rhine are the River Waal, the River Neder-Rijn and the River IJssel, which all became active in the first four centuries AD. (Törnqvist, 1994). All the distributaries are sand-bed rivers.

The River Rhine distributaries were embanked during the period 1050–1400. Since then, flooding has been restricted to the area between the dikes, which is approximately 1 to 2 km wide. Some meanders were artificially cut off and the positions of the river channels were finally fixed during the 18th and 19th centuries by means of groynes and revetments. In the 1950s and 1960s, weirs were constructed in the River Neder-Rijn. Embanking the Rhine distributaries has led to larger sedimentation rates in the floodplains and a raised floodplain level (Middelkoop, 1997). River channelisation works led to the disappearance of landforms characteristic of migrating rivers, such as mid-channel bars and secondary channels (Van Urk and Smit, 1989) and caused a strong tendency towards channel-bed degradation in the upper depositional zone (Ten Brinke et al., 1998).

At present, mean discharge near Lobith is 2300 $m^3 s^{-1}$, which is the runoff from an area of approximately 165,000 km^2 in size. The maximum discharge measured here during the 20th century was 12,600 $m^3 s^{-1}$. The embanked floodplains are flooded mainly from December to April due to rainfall and low evapotranspiration in winter, but flooding also occurs in May to July as a result of snowmelt in the Alps. The River Waal receives approximately 2/3 of the discharge of the River Rhine, whereas the River Neder-Rijn and the River IJssel receive 2/9 and 1/9, respectively.

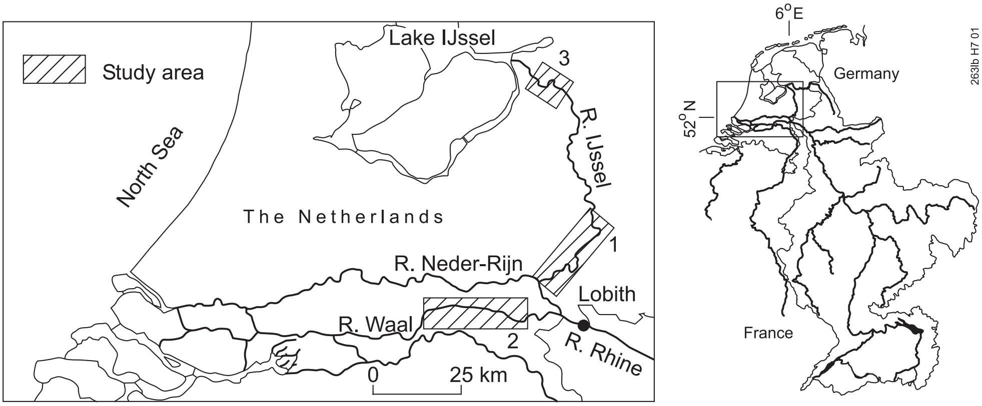


Fig. 7.1.
Locations of the Upper-IJssel (1), Middle-Waal (2) and Lower-IJssel (3) study reaches in the River Rhine distributary zone

Geomorphological maps

The present-day landform configuration in the Dutch floodplains originates largely from the period before the late 19th century river channelisation, but clay and sand extraction works have altered much of the topography since then. Therefore, the original landforms and the changes in time were studied by means of historical maps. Recently, historical maps were successfully used for a detailed study of local developments in the floodplains along the River Waal and the River Neder-Rijn (Middelkoop, 1997). In the present study, three reaches representative of the River Rhine distributary system have been investigated, for which a sufficient number of historical maps was available: (1) a high-sinuosity reach of the River IJssel (km 880–928, on the topographical maps of the Netherlands), representing upstream reaches, (2) a low-sinuosity reach of the River Waal (km 885–916), representing middle reaches, and (3) a low-gradient reach of the River IJssel (km 981–993), representing downstream reaches (Fig. 7.1).

Many historical maps were collected from various archives (Table 7.1). The oldest usable maps date from 1596 (Upper-IJssel), 1601 (Middle-Waal) and 1534 (Lower-IJssel). Maps have been selected which satisfy criteria for topographic, geometric and chronometric accuracy when analysing historical geomorphological development (Middelkoop, 1997). Most of these maps were made for land registry and tax payment or local river training purposes (Fig. 7.2). Their accuracy could be improved by comparing them with the first River Map of the Netherlands (scale 1:10,000), surveyed during the period 1830–1850. This map covers the entire Dutch Rhine system and shows topographic features and land use in a geometrically correct way.

Reconstruction of the geomorphology of an entire river reach was only possible for those reaches where a complete coverage was provided by maps surveyed during a certain period. Accordingly, historical geomorphological maps (scale 1:25,000) could

Fig. 7.2.
One of the historical maps showing part of the Middle-Waal in the period before river channelisation; this map was made by Beijerink in 1778 for land registry and tax payment purposes

Table 7.1.
Numbers of historical maps used in this study

STUDY REACH	PERIOD				
	1500–1600	1600–1700	1700–1750	1750–1800	1800–1851
Upper-IJssel	10	46	20	8	3
Middle-Waal	0	18	8	22	15
Lower-IJssel	2	4	1	4	4

be made showing the Upper-IJssel in the 1750s and 1840s, the Middle-Waal in the 1780s and 1830s and the Lower-IJssel in the 1840s. The legend to these maps was based on commonly distinguished landforms and deposits of sand-bed alluvial rivers (e.g. Leopold et al., 1964; Reineck and Singh, 1980). The translation of historical map information into a geomorphological map was based on information on the presence of water, channel banks, deposited sand, marsh, floodplain forest, agriculture and parcelling, indicating differences in water depth, surface elevation and soil characteristics. An analysis of floodplain changes in time as well as some available soil maps (Mulder et al., 1992; Brouwer, 1997) helped in the genetic interpretation of the various landforms. The maps were digitised using the software package ARC/INFO (ESRI, Redlands, CA) enabling quantitative analysis of areas. Data on channel migration and on the stability or succession of the landforms distinguished were obtained by means of an overlay procedure.

Hydrogeomorphological parameters

Hydrogeomorphological parameters were calculated to understand the processes causing differences between the river reaches investigated. For in-channel geomorphological processes, such as island and bar formation, the width–depth ratio and the Shields parameter are appropriate, supplementary parameters. Classifications of channel pattern often have been related to the width–depth ratio (Schumm, 1977; Fredsøe, 1978; Rosgen, 1994). It reflects the force-resistance relationships between the channel and its geological environment. The Shields parameter reflects the relationships between the fluid shear stress and the gravitational force exerted on the sediment grains. Thus, this parameter enables investigation of the role of sediment size on channel planform, which is generally regarded as an important factor too (Van den Berg, 1995; Thorne, 1997). Both parameters can be expressed independently of the water discharge, which facilitates comparison between the study reaches. Following an example given by Ferguson (1987: p. 136), the two parameters were used to construct a diagram in which the various river reaches could be plotted. This diagram includes zones of different bar types which are derived from theoretical studies by Struiksma et al. (1985) and Struiksma and Crosato (1989), introducing a correlation with some of the units incorporated in the geomorphological map legend.

For the river floodplain, the water flow velocities when inundated and the frequency of water level exceedance were calculated. These parameters have been described as influencing the rate of suspended sediment deposition (Middelkoop, 1997).

For calculation of the parameter values in historical time, some detailed historical maps from around 1800 – made for local river training purposes – were available. These indicate river depths measured in several cross sections (Table 7.2). In addition, information could be used on water levels measured daily at gauges installed at 11–24 km-intervals along the Rhine distributaries in the periods 1765–1850 (River IJssel) and 1772–1856 (River Waal), and on discharges measured in the period 1790–1846 near Lobith and both river bifurcation points (Fijnje and Lebret, 1852; Van der Kun 1854; Lely, 1890). The parameters have been calculated according to commonly used equations (e.g. Richards, 1982), for which the following assumptions had to be made. The bankfull water level was assumed to be at the elevation of the top of recently formed bars, on which willows (*Salix spp.*) recently had became established. Water levels at bankfull and those exceeding the 90%, 75%, 35% and 10% frequencies were calculated by means of extrapolating along the slope of the water level between the gauges in or near the study reaches. The procedure is treated in detail by Schoor et al.

Table 7.2.

Historical maps indicating cross sections used in this study

RIVER REACH	RIVER KM	MAP SURVEY	CROSS SECTIONS (n)
Upper-IJssel	897–903	Beijerinck, 1776	7
Middle-Waal	889–896	Beijerinck, 1801	17
Lower-IJssel	981–990	Augier, 1851	6

(1999). Since no reliable data were available on the bedload texture in historical time, values of the present-day bed load texture were used instead.

Mean flow velocities in the floodplains were calculated for the Upper-IJssel and Middle-Waal reaches, by means of the one-dimensional hydraulical model SOBEK (Barneveld et al., 1994). For calculation, the historical cross sections were schematised into cross sections approximately 500 m apart, each divided into four parts – the channel, the groynes area, the free flowing floodplain area and the floodplain area behind minor dikes ('summer dikes') – for which mean values of width, depth cq. elevation and percentage of woodland were given. Mean flow velocities were calculated for a discharge of 1050 $m^3 s^{-1}$ in the Upper-IJssel and of 5000 $m^3 s^{-1}$ in the Middle-Waal. The bankfull discharge of the River Waal and the River IJssel was calculated by means of extrapolating towards the 1835–1846 stage-discharge graph for Lobith using the discharge data measured near the two bifurcation points.

RESULTS

Landform configuration

The historical landform configurations are depicted in Fig. 7.3. The characteristics of the various landforms incorporated in the map legend are presented in Table 7.3 and the surface areas of these landforms in Table 7.4. Clearly, the three reaches had a different geomorphology.

Associated with the high-sinuosity channel, the Upper-IJssel was mainly characterised by a very distinct scroll-bar and swale topography adjacent to the convex banks of meander bends. Other floodplain elements were the extensive natural levees and the diversity in floodplain channel types, of which the most prominent were the large oxbow lakes. Also typical of this reach were the floodplain channels which were abandoned by the river, but still discharged water supplied by lowland streams coming from the adjacent uplands.

In contrast, the Middle-Waal was a low-sinuosity river, and although its channel was rather wide, its floodplain was relatively narrow. Characteristics of the river channel were the many mid-channel bars and associated secondary channels. Also, large point bars developed along concave banks. Natural levees were relatively inconspicious. In planform, sloughs and abandoned channels were typically concave, seen from the river – which is clearly different from the pattern of scroll bars and swales along the Upper-IJssel. Many sloughs were connected to the main channel at their downstream ends, while marshy vegetations were characteristic of their upstream parts.

The Lower-IJssel shows a combination of aspects mentioned for the other reaches. Related to the high-sinuosity channel, a distinct scroll-bar and swale topography and some prominent natural levees were mapped. Elongate, high islands separating up to three river channels, were characteristic of this river reach. Also typical was the relatively large area of marshes fringing the sloughs.

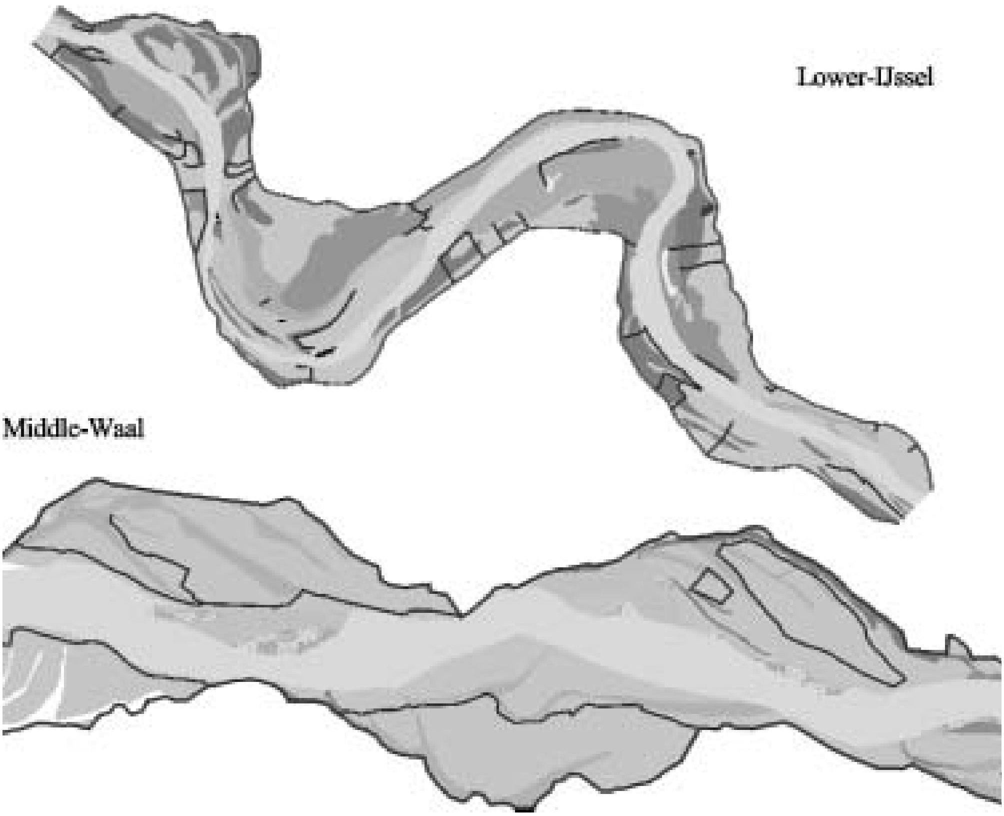
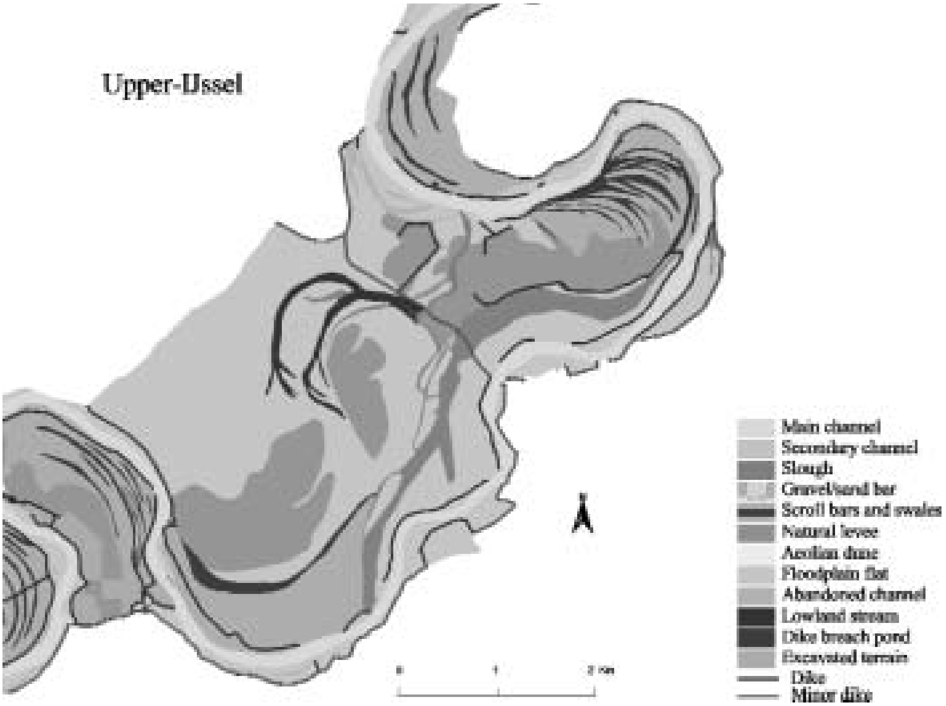


Fig. 7.3.
Historical geomorphology of the Upper-IJssel (1840s), Middle-Waal (1830s) and Lower-IJssel (1840s) river reaches

River reach dynamics

The rates of channel migration in the Upper-IJssel and Middle-Waal are indicated in Table 7.5; no reliable data could be obtained for the Lower-IJssel reach. Obviously, around 1800, migration rates of the River Waal were larger than those of the River IJssel. In the Middle-Waal, the relative migration rate, expressed per unit channel width (cf. Nanson and Hickin, 1983) was about twice as high and resulted in a loss of floodplain area which was even ten times larger than that in the Upper-IJssel reach. Surprisingly, the difference in newly formed floodplain area is less distinct. In the Middle-Waal, the area eroded is larger than the area deposited, indicating a marked increase in channel capacity during this period. In contrast, the River IJssel experienced a decrease in channel width at that time. Comparison of historical maps reveals a different mode of migration: the Upper-IJssel reach was mainly characterised by lateral migration of meander bends, whereas longitudinal migration was the dominant process in the Middle-Waal reach, inducing the gradual downstream movement of channel bends (Fig. 7.4).



Figures on the stability or dynamics of the various landform types could be obtained for the Middle-Waal reach (Table 7.6). Comparison of subsequent maps reveals that changes in the landform configuration of the river reaches were related mainly to three out of four floodplain forming processes (cf. Carey, 1969): (1) island formation, (2) point-bar accretion and (3) overbank deposition. Formation of natural levees (4) has not been found important during the period studied.

The formation of mid-channel bars was enabled in the Middle-Waal by the downstream migration process, which led locally to considerable widening of the channel and diverging flow (Fig. 7.5). Growth of willow shrubs on the highest parts resulted in stable islands and associated secondary channels. As bank erosion continued, flow concentrated in the main channel, inducing deposition of sand in the secondary channel entrances and their transformation into sloughs. This process is comparable to eddy accretion (Carey, 1969) or counterpoint accretion and the formation of concave bank benches (Page and Nanson, 1982; Middelkoop, 1997). Large islands, opposite point bars in bends are shown by the oldest maps of the Upper-IJssel. These may be interpreted as point-bar islands (cf. Carey, 1969) which are the result of strong lateral migration of meander bends. Younger historical maps also show the formation of small islands in less sinuous parts of the main channel of the River IJssel. This development is believed to be initiated by the natural decrease in channel width, but was stimulated through land reclamation activities (Fig. 7.6).

Table 7.3.
Classification and characteristics of landforms of the River Rhine depositional zone

LANDFORM	MORPHOLOGY	ARCHITECTURAL ELEMENT/ LITHOLOGY	GENESIS	VEGETATION/LAND USE
Main channel	Major channel, with alternating thalweg; deep near concave banks	Channel deposits; slightly gravelly coarse sand	Scour and bank collapse during bankfull; formation of bars at low stages	Water
Secondary channel	Shallow channel, connected to the main channel at both ends; deeper in downstream direction	Channel deposits; slightly gravelly coarse sand	Results from formation of mid-channel island; deposition of sandy bed load at entrance	Water
Slough[1]	Shallow backwater channel, connected to the main channel at downstream end only; deeper in downstream direction	Thin cover of channel-fill deposits on top of channel deposits; sand, loam and clay	Results from closure of secondary channel; deposition rates decrease in downstream direction	Water; in upstream parts succeeded by reed marsh, willow shrubs and softwood forest along the banks
Gravel/sand bar	Mid-channel islands, point–bar islands and point bars	Channel deposits; slightly gravelly coarse sand	Deposition due to divergent flow or to secondary flow in bends	Unvegetated; on higher parts succeeded by willow shrubs and softwood forest
Swale	Elongate depressions in between subsequent point-bar scrolls	Thin cover of overbank deposits on top of channel deposits; sand, loam and coarse organic material	Deposition during waning of flow events	Reed marsh succeeded by willow shrubs and softwood forest; also meadows and moist pasture
Natural levee	Shallow ridge along the main channel	Overbank deposits; sand and loam	Deposition of bedload due to overtopping of banks	Meadow and pasture; locally arable land
Aeolian dune	Chaotic dune morphology	Aeolian deposits; sand	Deflation of sandy overbank deposits by wind	Meadow; locally unvegetated patches
Floodplain flat	Slightly undulating flat	Overbank deposits; loam and clay	Deposition of suspended load during flood events	Pasture; locally reed marsh and willow shrubs
Abandoned channel	Shallow channel, completely isolated from the main channel at low stages	Channel-fill deposits; loam, clay and organic matter	Deposition of suspended load during flood events; some sedentation	Patches of water surrounded by reed marsh, willow-shrubs or meadow
Lowland stream	Slough discharging water supplied from the surrounding area	Stream channel deposits on top of river channel deposits; sand	Deposition of stream bedload	Water
Dike breach pond	Small, deep depression	Channel-fill deposits; clay	Scour caused by dike breach	Water
Excavated terrain	Large, undulating or flat-bottomed depression	Residual, thin cover of overbank deposits on channel deposits; loam and clay	Sand and clay extraction by man	Pasture

[1] *cf. Leopold and Wolman, (1957); Howard, (1992)*

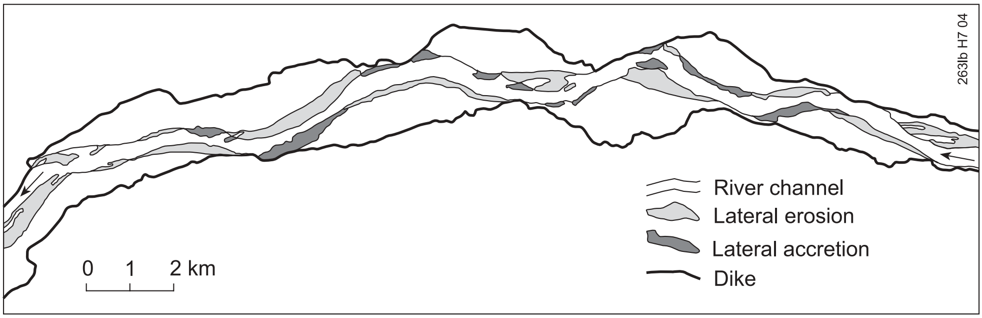


Fig. 7.4.
Extent of downstream migration of meander bends in the Middle-Waal during the period 1780–1830

Table 7.4.
Occurrence of landforms in river reaches around 1800

LANDFORM	UPPER-IJSSEL	MIDDLE-WAAL		LOWER-IJSSEL
	1840[1] (% area)	1780[2] (% area)	1830[3] (% area)	1840[4] (% area)
Main channel	10.4	29.2	32.5	18.5
Secondary channel	-	1.0	3.5	4.7
Slough	0.2	3.5	1.3	1.6
Gravel/sand bar	0.3	4.2	1.3	0.3
Scroll bars and swales	22.1	-	-	12.2
Natural levee	10.1	1.2	1.5	9.9
Aeolian dune	-	-	-	0.2
Floodplain flat	48.0	53.6	49.2	35.8
Abandoned channel	6.5	7.0	9.7	14.1
Lowland stream	1.6	-	-	-
Dike breach pond	0.1	0.2	0.9	0.2
Excavated terrain	0.9	-	-	2.5

[1] *investigated area: 5070 ha;* [2] *4650 ha;* [3] *4677 ha;* [4] *1058 ha*

Point-bar formation was especially manifest in the Middle-Waal reach, notably where the sinuosity of the main channel was very low. From 20 historical cross sections, an alternating helical flow pattern can be inferred, associated with gentle slopes and platforms typical of point bars (Fig. 7.7). Prominent point-bar platforms have developed opposite the deepest parts of one-thread channels, formed near concave banks defended by groynes. In the River IJssel, during the study period, a marked decrease in the area of recently deposited point bars was noted. Around 1800, point-bar formation in the high-sinuosity Upper-IJssel resulted in small bars of low elevation only.

In general, sloughs were filled in with fines from suspension in relatively short periods of time, were isolated from the main channel during this process and eventually transformed into marshy floodplain flats (Table 7.6). The most upstream parts of channels were filled in first. Unlike the other reaches investigated, the downstream parts of sloughs along the Middle-Waal experienced much less change: many sloughs remained connected to the main channel during the entire study period. Thus, along

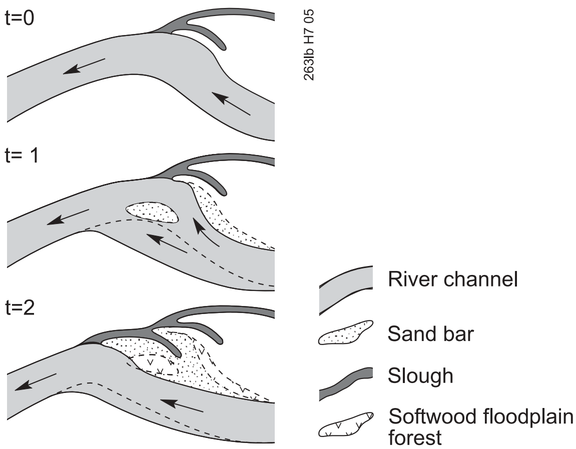


Fig. 7.5.
Schematic presentation of island formation and subsequent evolution of secondary channels in the Middle-Waal, as a result of the downstream migration process

Table 7.5.
Channel migration rates in river reaches around 1800

RIVER REACH	PERIOD	LATERAL EROSION			LATERAL ACCRETION		
		Area (ha)	M (m yr^{-1})	M/w (yr^{-1})	Area (ha)	M (m yr^{-1})	M/w (yr^{-1})
Upper-IJssel	1750–1840	72	0.296	0.0026	86	0.354	0.0031
Middle-Waal	1780–1830	478	2.988	0.0054	181	1.131	0.0020

M, migration rate; M/w, relative migration rate; w, channel width

Table 7.6.
Landform transformations (% area) in the Middle-Waal during the period 1780–1830 (stable areas are indicated in bold)

LANDFORM ANNO 1780		LANDFORM ANNO 1830													
		Free flowing floodplain									Floodplain behind minor dikes				Ea
		Mc	Sc	S	Gb	Sb	Nl	Ff	Ac	Dbp	Nl	Ff	Ac	Dbp	
Free flowing floodplain	Mc	**83**	5	1	-	2	1	8	-	-	-	-	-	-	-
	Sc	47	**29**	3	-	6	-	8	6	-	-	-	-	-	-
	S	3	-	**17**	-	-	2	8	27	1	-	6	35	1	1
	Gb	80	-	-	-	**15**	4	2	-	-	-	-	-	-	-
	Sb	43	23	1	-	**11**	1	20	-	-	-	-	-	-	-
	Nl	35	-	-	-	-	**55**	5	-	-	-	5	-	-	-
	Ff	11	2	1	-	-	1	**24**	1	-	-	56	2	-	1
	Ac	3	-	-	-	-	-	4	**6**	-	-	10	71	1	5
	Dbp	-	-	-	-	-	-	-	-	**5**	-	22	17	54	1

Mc, main channel; Sc, secondary channel; S, slough; Gb, gravel bar; Sb, sand bar; Nl, natural levee; Ff, floodplain flat; Ac, abandoned channel; Dbp, dike breach pond; Ea, embanked area

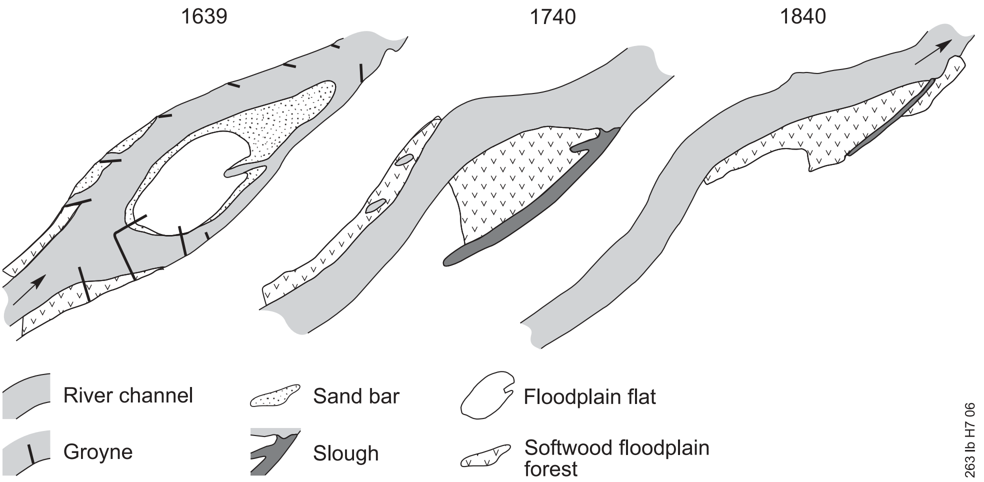


Fig. 7.6.
Land reclamation activities around small islands in the Upper-IJssel, triggered by the decreasing transport capacity

the Waal a typical downstream sequence of abandoned channel–slough–secondary channel was found, which reflects repeated rejuvenation initiated by the downstream migration of bends (Fig. 7.5). Many scour holes along the dikes appeared on maps of the Middle-Waal, which resulted from dike breaches during the 19th century (Driessen, 1994). Because of their large depth, these have remained present as ponds.

Overbank deposition was stimulated for land reclamation purposes in all three of the study reaches. Groynes were constructed and reeds and willows planted, to increase sedimentation rates. As soon as possible, the willow-coppices on reclaimed land were cleared to create pastures, except for the Lower-IJssel where permanently high groundwater levels and unripened clay soils prevented farming. Aggradation was even more accelerated when many minor dikes were constructed around 1800, capturing flood water when water levels fall and thus prolonging the period of deposition from suspension. During the period 1780–1830, a small part of the floodplains along the River Waal were embanked (Table 7.6).

Channel and flow dimensions

The values of the hydrogeomorphological parameters in historical time are presented in Table 7.7. The width–depth ratio and the Shields parameter values are combined with the findings of the geomorphological surveys in Fig. 7.8, indicating envelopes of values related to discharges occurring in 95%, 75%, 35% and 10% of the time in the Middle-Waal and Lower-IJssel, and values related to bankfull discharge in the Upper-IJssel.

Around 1800, recently formed islands were found in the Middle-Waal only (zone

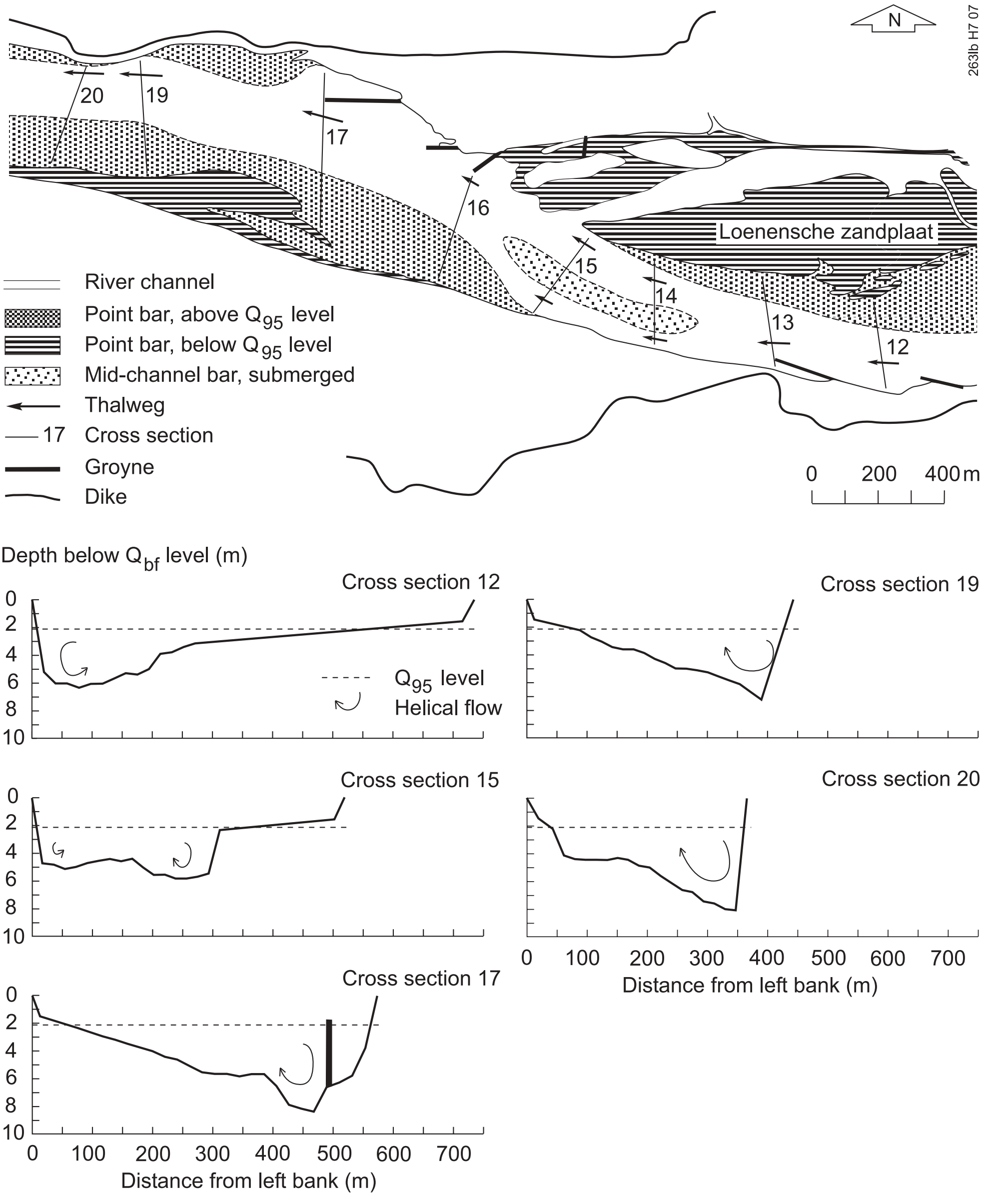


Fig. 7.7.
Point-bar formation in the low-sinuosity Middle-Waal around 1800

Table 7.7.

Hydrogeomorphological parameter values of river reaches

RIVER REACH	w (m)	d (m)	F (-)	R (m)	S_w (-)	D_{50} (m)	θ (-)	Q_{bf} (m^3 s^{-1})	V_{ch} (m s^{-1})	V_{fl} (m S^{-1})
Upper-IJssel (1776)	114	3.19	37	3.02	0.000128	0.0018	0.14	260	1.00	0.33
Middle-Waal (1801)	557	4.01	151	3.96	0.000129	0.0009	0.34	2350	1.44	0.47
Lower-IJssel (1851)	228	2.96	78	2.88	0.000027	0.0004	0.12	-	-	-

w, width; d, mean depth; F = w/d, width–depth ratio; R = wd/(2d+w), hydraulic radius; S_w*, water level slope;* D_{50}*, median bed material size;* $\theta = RS_w/1{,}65D_{50}$*, Shields parameter;* Q_{bf}*, bankfull discharge;* V_{ch}*, channel flow velocity;* V_{fl}*, floodplain flow velocity*

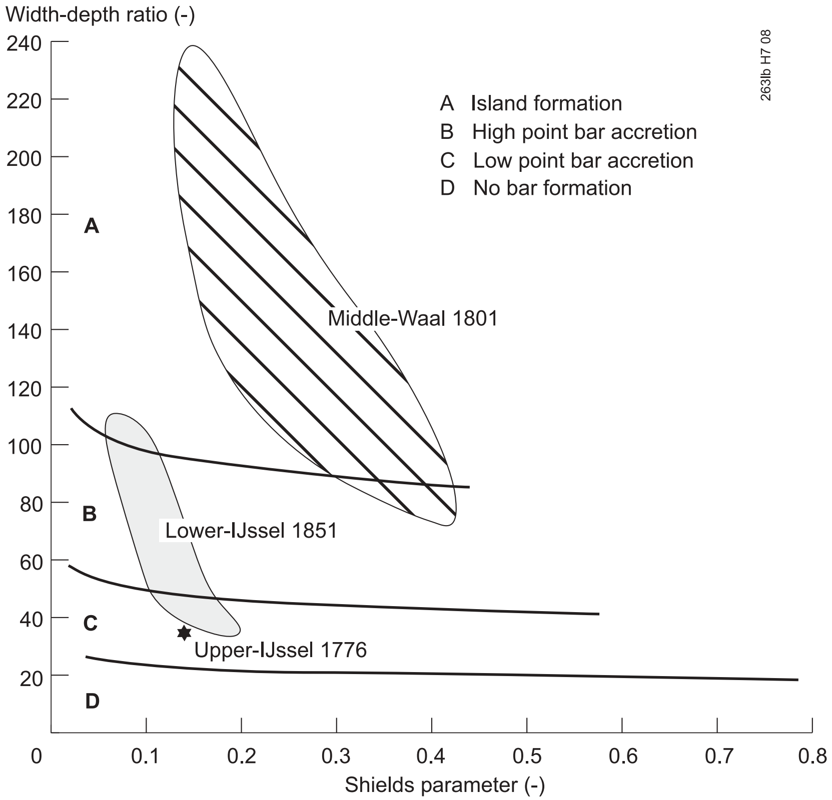


Fig. 7.8.

Boundary values relevant for island formation and point-bar accretion in the Rhine distributaries before river channelisation, indicating the bankfull value for the Upper-IJssel and ranges including $Q_{95\%}$, $Q_{75\%}$, $Q_{35\%}$ and $Q_{10\%}$ in the Middle-Waal and Lower-IJssel

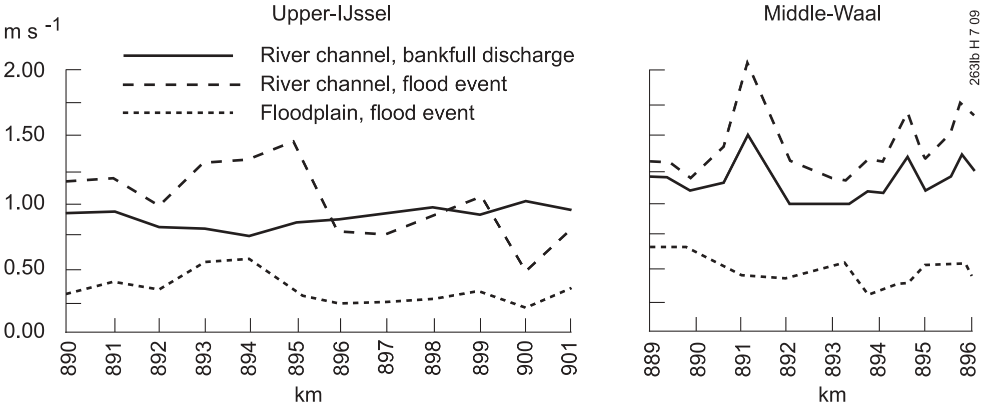


Fig. 7.9.
Downstream variability in flow velocities in the channel and over the floodplains during inundation around 1800

A), which is related to the large values of the width–depth ratio and Shields parameter. High point bars were formed in the Middle-Waal and Lower-IJssel. High point bars were formed instead of real alternate bars (typical of zone B, cf. Struiksma et al., 1985; Struiksma and Crosato, 1987) due to the sinuosity of the Rhine distributaries. High point bars are defined here as those aggraded above the 75% frequency of water level exceedance, which enables recruitment of softwood floodplain forests species (e.g. *Salix spp*.) to survive subsequent minor floods (Johnson, 1994). Transformed into an almost passively meandering river (cf. Thorne, 1997), the 19th century River IJssel only showed minor point-bar accretion, related to its low width–depth ratio values. Low point bars with a height corresponding to the 95% frequency of water level exceedance are interpreted as subcritically damped bars (i.e. local, shallow bars caused by geometrical constraints inducing relatively large bed oscillations which are not immediately damped; typical of zone C). Moreover, the lower Shields parameter values indicate low rates of bed-load transport in the River IJssel. This may also explain why the secondary channels in the Lower-IJssel persisted as long as the entire period covered by historical maps, while the secondary channels in the Middle-Waal were generally blocked by sandy channel deposits within several decades.

Compared with the Upper-IJssel, the Middle-Waal also shows larger flow velocities during flood events, not only in its main channel, but also over the floodplains (Fig. 7.9). The proportion of water transported over the Middle-Waal floodplains, however, is much smaller than in the Upper-IJssel. Floodplains along the Upper-IJssel are wide, while those of the Middle-Waal are narrow. Moreover, the Lower-IJssel is different because of its very low slope. The frequency distribution of water level exceedance (Fig. 7.10) shows that the yearly changes in water levels in the Lower-IJssel are considerably smaller than those in the other river reaches. Both the high and the low water levels occurred less frequently in the Lower-IJssel.

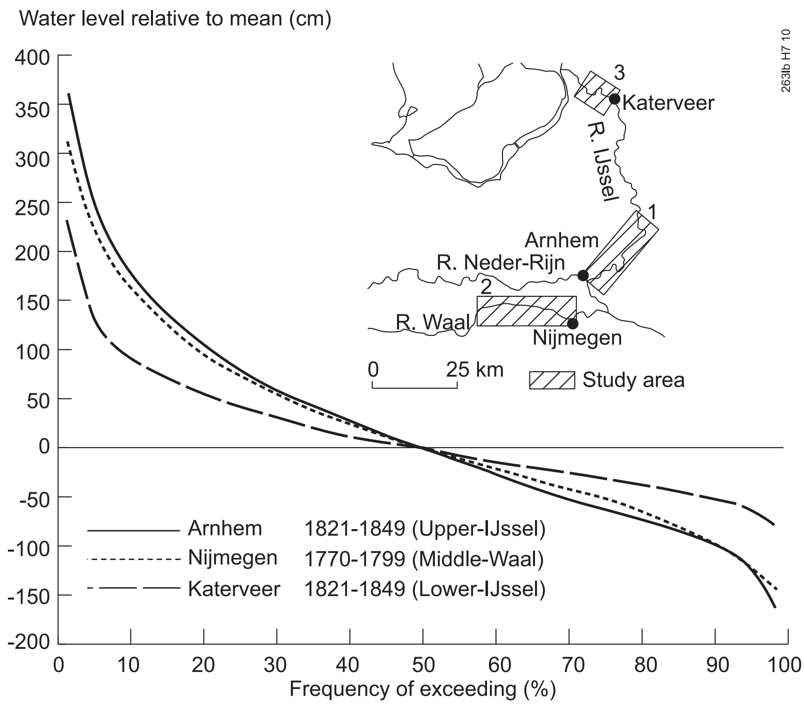


Fig. 7.10.
Frequency of water level exceedance in historical time

DISCUSSION

Landform succession

A conceptual model of the evolution of landforms and the cyclical renewal of floodplains along the embanked distributaries of the River Rhine depositional zone is presented in Fig. 7.11. In this model, the landforms are schematically arranged according their 'natural' succession in time and their elevation in the floodplain resulting from aggradation. The relative importance of the various succession paths may be deduced from Table 7.6. Vegetation succession and land use are not incorporated in the diagram. In reality, however, vegetation growth and land management is known to interfere with the landform formation and vice versa (e.g. McKenney et al., 1995; Middelkoop, 1997). Which of the various succession paths indicated in Fig. 7.11 will be followed, or whether a succession will be completed or not, is related to the hydrogeomorphological parameter values of river reaches. The time-span of existence of landforms, as derived from the data in Table 7.6, indicate that the shorter cycles of succession are limited to the channel and the proximal part of the floodplain (Fig. 7.12).

Fig. 7.8 shows that the main boundary values relevant to the formation of islands,

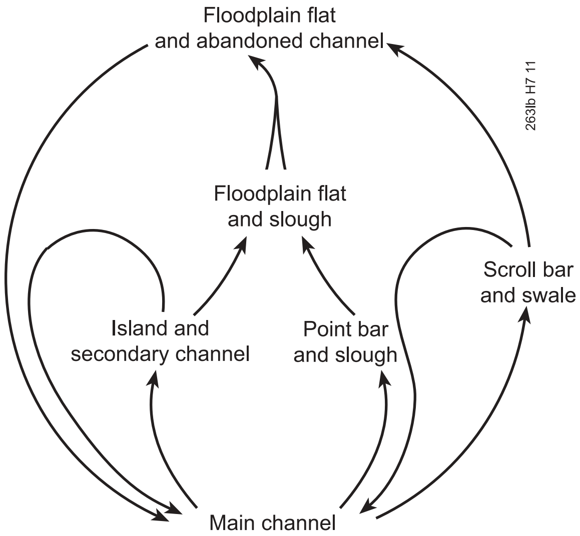


Fig. 7.11.
Conceptual model of the succession of landforms and the cyclical renewal of floodplains in historical time

high point bars and low point bars in the Rhine distributaries are the width–depth ratio values of approximately 90, 45 and 20 respectively. Hence, these may be regarded as predictors of the initial phase of landform succession. When values are larger than 90, for instance, a substantial part of floodplain formation will start with the formation of islands and secondary channels. When values lie between 45 and 20, the formation of high point bars may eventually result in new scroll-bar and swale areas. Although the theoretical boundary values presented in Fig. 7.8 are almost the same for the three river reaches investigated, they do vary among rivers in general. Therefore, they may differ from width–depth ratio values based on theory and observation of flumes or contemporary rivers elsewhere (e.g. Schumm, 1977: 40 and 10; Fredsøe, 1978: 52 and 12; Rosgen, 1994: 40 and 12). A diagram comparable with Fig. 7.8 was suggested earlier by Ferguson (1987) to demonstrate the influence of width–depth ratio and stream power on river channel planform variability. Replacing the Shields parameter by specific stream power in the diagram presented here yields the very same boundary values for island and bar formation as found here.

The evolution of sloughs and abandoned channels is the result of the combined action of processes typical of the floodplain environment, such as overbank deposition during flood events and the subsequent establishment of vegetation. A notable feature is the evolution of sloughs, of which the connection to the main channel persisted much longer in the Middle-Waal than in the Upper-IJssel. Obviously, less sediment could be deposited in the sloughs in the former river reach. This seems to be related to flow velocities over the floodplain during inundation, since flow velocities over the relatively narrow River Waal floodplain are higher than those over the Upper-IJssel floodplain (Fig. 7.9) and so less favourable for the settling of suspended material. Using models of meandering with floodplain sedimentation, Howard (1992) also explained sloughs as sites of retarded deposition owing to large velocity perturbations. From visual

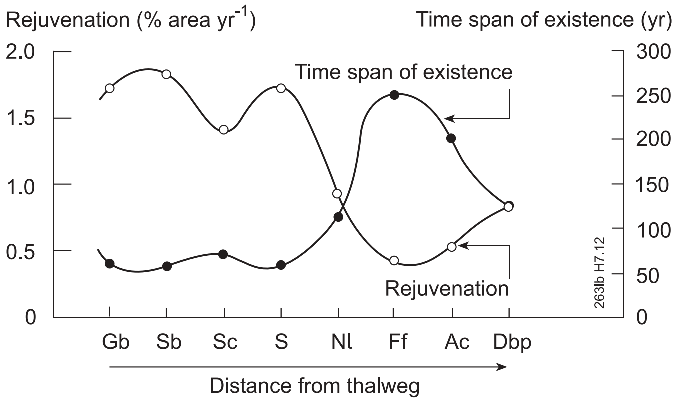


Fig. 7.12.
Differences in time-span of existence and proportion of rejuvenation of landforms in a schematic cross section perpendicular to the main channel in the Middle-Waal (for explanation of abbreviations of landform names see Table 7.6)

inspection of the flow velocity data in Fig. 7.9, a mean boundary value of 0.4 m s^{-1} can be tentatively proposed as a predictor of the evolution of sloughs, assuming that flooding frequency and sediment load are equal in both distributaries.

The vegetation succession in sloughs, from open water via reed marsh in abandoned channels to forested floodplain flats, was not completed in the Lower-IJssel. Here, reed marsh was the climax vegetation along sloughs and in abandoned channels. The establishment of softwood forest species depends on fluctuations in water levels. Willows, for instance, require low water levels and bare soil to germinate in the period seeds are dispersed by the wind (Van Splunder, 1998). From the information presented in Fig. 7.10, the vegetation succession – whether natural or man-induced – is assumed to halt when water levels remain higher than 50 cm below mean values for 95% of the time. Obviously, the sloughs in the most downstream reaches are not quickly filled in with sediment, otherwise this boundary value would have been crossed.

River metamorphosis

Not all parts of the 18th and 19th century landform configurations can be explained by the hydrogeomorphological parameter values of that time. Appearently, the dynamics of the distributary channels could change, without immediately causing a change in the floodplain topography. Influential changes in the behaviour of the River Rhine distributaries are generally ascribed to: (1) the clearing of forests when land in the drainage basin was brought under cultivation in the Middle Ages, (2) the embankment works in that period, (3) the river engineering works on the Rhine distributary points around 1700, and (4) the channelisation of the Rhine drainage network around 1900 (Van de Ven, 1976; Berendsen, 1982; Middelkoop, 1997). Developments in the River IJssel were different from those in the River Waal.

Many parts of the floodplains along the River IJssel are characterised by a prominent scroll-bar and swale topography, suggesting a very actively meandering river. The migration rates measured from 17th and 18th century maps, however, appear to be relatively small. Moreover, during the period studied, the river channel width–depth ratio and, consequently, the number of islands and the area with recently deposited point-bar sediments showed a strong decline. From this it is concluded that much of the floodplain sediments were deposited before the 17th century. Most probably, floodplain formation coincided with a 150-year period of delta growth in the Zuiderzee (i.e. the present Lake IJssel; Fig 1) which started around 1200. Much of the present-day River IJssel delta has been reclaimed from 1364 onwards (Dirkx and Hommel, 1996), indicating a strong decrease in sediment supply at the mouth of the river around that time. Upstream, silting up of channels has been documented, and around 1700 this prompted the construction of large engineering works where the Rhine distributaries bifurcate (Van de Ven, 1976). Both these features point to a decrease in transport capacity of the pre-18th century River IJssel. Qualitative models illustrating the direction of geomorphological response indicate that a decrease in discharge of water and sediment usually leads to a decrease in width exceeding the decrease in depth in magnitude, leading to a strong decline of the width–depth ratio (Schumm, 1969; Richards, 1982).

Like the Upper-IJssel, the Middle-Waal was originally a high-sinuosity river. This is shown by the strong curvature of some of the older channels, which are found in abandoned meander belts or buried beneath younger floodplain sediments (Schoor, 1994). Apparently, a major change in fluvial style occurred along the Middle-Waal, which during the period studied here was a low-sinuosity river migrating mainly in downstream direction. Relatively fast downstream migration and the formation of concave bank benches and distinct sloughs are associated with rivers that are confined by hard rock or other erosion-resistant materials bordering a narrow river floodplain (Howard, 1992). The same elements can also be caused by artificial river-training structures. For instance, the associated formation of islands due to eddy accretion in the Mississippi River not only occurred where the river impinged upon a terrace bluff, but also where it encountered one of its artificial levees (Carey, 1969: p. 983). Consequently, most parts of the historical Rhine distributaries are considered to have been confined rivers since the completion of the embankment in the 14th century. Lateral migration stopped where the main channel encountered dikes, which were defended by wooden groynes and revetments made from willow twigs (see Fig. 7.6). Instead, downstream migration was induced leading to the low-sinuosity channel pattern, a development which may have been enhanced as soon as the channel became out of phase with the sinuous alignment of the dikes (Ikeda, 1989). A similar change in fluvial style has also been observed along one of the smaller rivers in the eastern part of the Netherlands, the Overijsselse Vecht, where it enters its embanked reaches in the depositional zone (Wolfert et al., 1996).

The decrease in transport capacity of the River IJssel is believed here to be the result of the natural tendency for avulsion, because, simultaneously, the River Waal increased its transport capacity. This is reflected in the growth of its inland estuarine delta – within the Biesbosch estuary, which was formed in 1421 – since the 16th century (Zonneveld, 1960). Changes cannot be interpreted as a delayed response to the pre-

18th century increase in transport capacity. In 1707, engineering works around the upstream bifurcation point resulted in an increased discharge of the River IJssel and the River Neder-Rijn and decreased discharge of the River Waal. The construction of minor dikes in the River Waal floodplains from 1770 onwards and a slight increase in the discharge of the river from 1805 onwards (Van der Beek, 1990) may have accelerated lateral erosion. Whatever the case, the historical geomorphology depicted on the historical geomorphological maps of both River IJssel and River Waal must be interpreted as a dynamic equilibrium configuration rather than a steady state configuration (cf. Schumm, 1977).

Fluvial style continuum

Four types of fluvial styles and associated landform configurations have been described in this study: (1) a high-sinuosity, laterally migrating, meandering sand-bed river, represented by the pre-18th century landform configuration of the Upper-IJssel, (2) a confined, low-sinuosity, downstream migrating sand-bed river, of which the Middle-Waal is a typical example, (3) a low-gradient, tidal-island river, exemplified in this study by the Lower-IJssel, and (4) a passively meandering river, of which the 18th century Upper-IJssel is an example. The first two styles mentioned represent relatively dynamic environments. The low-sinuosity, downstream migrating river is the most typical of the embanked lowland fluvial environment. However, although completely embanked, it does not occur everywhere in the River Rhine depositional zone. Instead, a typical downstream sequence of river reaches with different fluvial styles is found (Fig. 7.13).

The upper reaches of the Rhine depositional zone are characterised by the high-sinuosity, laterally migrating fluvial style. This style not only characterises the Upper-IJssel, but also the more dynamic Upper-Waal and the River Rhine above its bifurcation point. After repeated slumping of dikes the village of Herwen was rebuilt along one of the meanders in the Upper-Waal around 1770. This indicates high rates of lateral migration continuing for several centuries after the embankment works were started (Van de Ven, 1976). Geographically, this high-sinuosity pattern is related to the area where the thickness of Holocene flood basin deposits is less then the depth of the river (Fig. 7.13). The underlying Pleistocene fluvial gravels and sands are generally more erodible than the clayey cover, leading to higher channel migration rates. A similar change in geological setting was assumed by Törnqvist (1993) to differentiate between meandering and anastomosing styles in the period before embankment. The influence of the distribution of fine-grained cohesive deposits on planform and migration pattern of the River Teshio and one of its tributaries has been demonstrated by Ikeda (1989). Sandy material underneath the younger, clayey deposits has been shown to have a great influence by Berendsen (1982), who found a higher sinuosity where the modern river channel crosses older sandy meander belts.

The most downstream river reaches are dominated by the low-gradient, tidal-island fluvial style. This resembles anastomosing rivers, but the branches do not enclose flood basins, which is typical of real anastomosing systems (Makaske, 1998). Characteristic

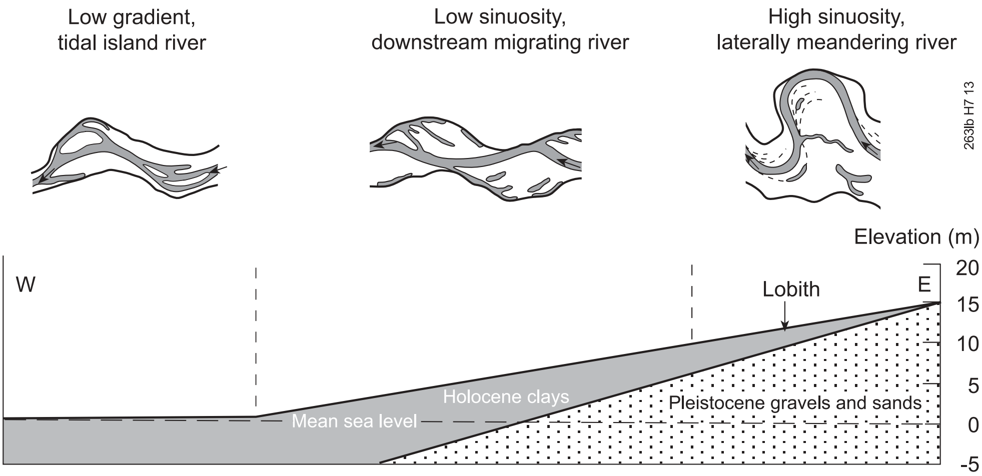


Fig. 7.13.
Conceptual model of the continuum of fluvial styles in actively migrating distributaries in the embanked River Rhine depositional zone (valley slope and deposits from Törnqvist, 1993)

for this fluvial style are the exceptionally stable islands. These are associated with relatively low width–depth values of the surrounding channels and low Shields parameter values. The stability of secondary channels is probably provided by the lack of bed-load transport. The different character of these reaches is clearly related to the low gradient and low elevation above sea level. The features mentioned above are commonly associated with tidal river mouths (Orton and Reading, 1993). Moreover, if the river environment consists of thick marine clays, these deposits prevent bank collapse (Ikeda, 1989). As a result, the low-gradient, tidal-island river can be fairly straight, as is shown by the Lower-Waal reaches. This fluvial style completes a continuum of fluvial styles which can be found along embanked, actively migrating rivers.

CONCLUSIONS

Various river-reach landform configurations and different landform dynamics were shown to exist in embanked, large alluvial river systems. In the embanked River Rhine depositional zone, four types of fluvial styles could be distinguished in the period before river channelisation: a high-sinuosity, laterally migrating, meandering river; a confined, low-sinuosity, downstream migrating river; a low-gradient, tidal-island river and a passively meandering river. Each of these styles was associated with specific sequences of landforms showing repetition in the longitudinal direction, thus delimiting river reaches.

Combining qualitative geomorphological maps and quantitative hydrogeomorphological parameters proves to be a promising tool for detecting historical processes and environmental reconstruction at the river reach level. The various landform configurations were shown to be formed by three floodplain-forming processes: island formation, point-bar accretion and overbank deposition. The in-channel processes appear to depend mainly on the width–depth ratio of channels. Floodplain water flow velocity and the frequency of water level exceedance have been proposed as predictors for slough evolution and marsh succession, respectively. Continuously changing parameter values imply changing landform configurations, which must not be interpreted as steady state configurations.

The river reach continuum along active distributaries in the depositional zone appears to be related to the physiographical setting. A key feature in the sequence of river reaches is the confined, low-sinuosity, downstream migrating style, which is the typical result of embankment in this lowland fluvial environment. Upstream, the high-sinuosity, laterally migrating, meandering style could persist after embankment, because of a thinner cover of Holocene flood basin deposits on erosive fluvial channel deposits. Downstream, the low-gradient, tidal island river style predominates, associated with a lack of bed-load transport capacity and stable, clayey river banks. The passively meandering style is the result of a decrease in transport capacity related to channel avulsion.

ACKNOWLEDGEMENTS

This research was financed by the Netherlands Ministry of Transport, Public Works and Water Management and by the Ministry of Agriculture, Nature Management and Fisheries. We thank Emiel van Velsen and Eric Mosselman for stimulating discussions and the latter for calculating the boundary values in Fig. 7.8 at Delft Hydraulics. Valuable comments on a draft of this paper were given by Henk Berendsen, Jan Klijn and Ward Koster.

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8

Embanked river reaches in the River Rhine depositional zone – II. Rehabilitation planning

Submitted to Geomorphology

ABSTRACT

To incorporate geomorphological expertise into river rehabilitation projects, a cyclical planning procedure has been used as a framework in which stages of plan design and plan evaluation follow each other several times. The role of research in supporting planners in these stages is elaborated in two case studies on the embanked River Rhine depositional zone. In the first case, covering a major part of this zone, river rehabilitation priorities were derived from historical reference situations, and the suitability of river reaches for the associated geomorphological processes was examined. Measures are required that trigger or mimic the original dynamics of the river system, such as the creation of secondary channels to rehabilitate former shallow channel habitat dynamics, and the lowering of the floodplain surface to reconnect the river's channel and floodplain again. This information was applied in the second case, dealing with the landscape of the smaller Gelderse Poort area. Inspired by the differences between river reaches, two land use scenarios could be formulated with different ecological objectives, management types and spatial strategies. Insight into the varying impacts of fluvial processes was an aid in the examination of the compatibility of rehabilitation targets and the other river and land use functions and resulted in spatial layout proposals. The feasibility of measures and the effects on vegetation and fauna species were evaluated using the landscape ecological LEDESS model. During the planning process, research activities gradually changed from monodisciplinary to interdisciplinary. The results demonstrate that at least two scales should be investigated to attain a realistic plan. They also draw attention to the following: (1) the geomorphology of the river system has degraded throughout the last century, (2) contemporary river reaches still vary dramatically in both landform patterns and processes, and (3) a geomorphological analysis can help in setting realistic goals for rehabilitation.

KEYWORDS
Floodplain ecology, Geomorphology, River rehabilitation, Secondary channels, River Rhine, the Netherlands

INTRODUCTION

Rehabilitating the integrity of river systems requires space for geomorphological and ecological processes and their associated natural landforms and riparian vegetation. However, increasing the area designated for nature may have serious impacts on functions such as flood defence and navigation. Enlarged areas vegetated by natural floodplain shrubs and forests will increase the flow resistance of the floodplain and may raise the water stages during high discharge events to unacceptably high levels. Removing bank protection structures, or re-creating secondary channels, may result in deposition and an unacceptable shallow depth of the main channel. River rehabilitation thus requires a careful balancing of multiple uses of floodplain land and water resources. Addressing the conflicting interests has become one of the main challenges of modern, integrated water management in the late 1990s.

The solution to many problems can be found in an integrated planning process, in which the various land use claims are assigned to those parts of the river system that are most suitable. Such a planning process can follow a cyclic procedure (Fig. 8.1), in which plan design and plan evaluation alternate (Harms et al., 1993). Plan design is a creative activity, often resulting in one or more scenarios for future land use. Baseline information, rehabilitation priorities and spatial concepts are the building blocks of the planner in this stage. Plan evaluation is a more analytical procedure in which the effects of the scenarios are investigated. Usually, models are used in this assessment. The results of the evaluation may lead to a new and more detailed planning cycle (Fig. 1.1). The cyclic procedure was applied successfully in the planning of both large and small areas (400,000–12,000 ha), and thus may be used at various spatial scales.

Generally, scientists supporting the planning process will raise the following four questions where nature is concerned (Klijn and Harms, 1990): (1) Are there reference

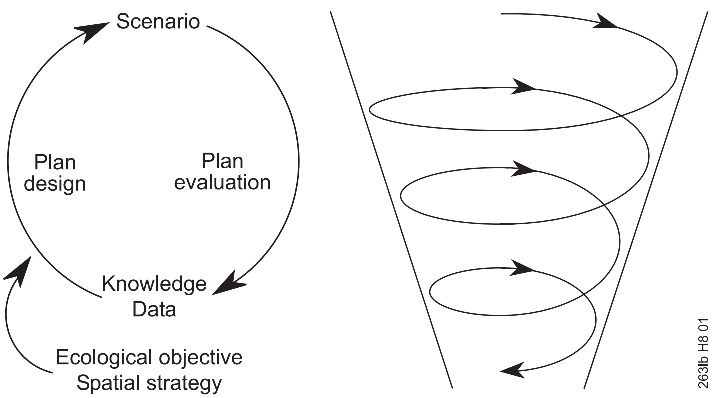

Fig. 8.1.

The cyclic planning procedure

situations for nature rehabilitation? (2) What conditions must be fulfilled to realise such situations? (3) Which areas are suitable for successful rehabilitation? (4) What measures must be part of the spatial layout? Answers to these questions should be based on sound knowledge of the disciplines involved, one of which is geomorphology. The role of geomorphology in river rehabilitation is, however, only beginning to be addressed (Brookes, 1995a; Boon, 1997) and certainly requires further development in a spatial planning context with which most geomorphologists are not familiar. This paper provides a framework for integrating geomorphological expertise in the process of river rehabilitation planning. The aims are: (1) to indicate the type of studies involved in the design and evaluation stages, and (2) to demonstrate that at least two scale levels should be investigated to attain a realistic plan.

As an example, two related case studies are presented which build on the results of the study described in Chapter 7 on the historical geomorphology of the River Rhine depositional zone (Fig. 8.2). The first case covers the major part of this zone. At the level of river reaches, rehabilitation priorities are identified (design stage) and the contemporaneous suitability of the various reaches explored (evaluation stage). The results are applied in the second case, dealing with the landscape of a much smaller area, the Gelderse Poort. Different land use scenarios are formulated and implemented in a spatial layout at the landform level (design stage), and the feasibility of proposed measures is analysed (evaluation stage). First, the connections between geomorphology and river rehabilitation policies, ecological concepts and planning instruments are outlined.

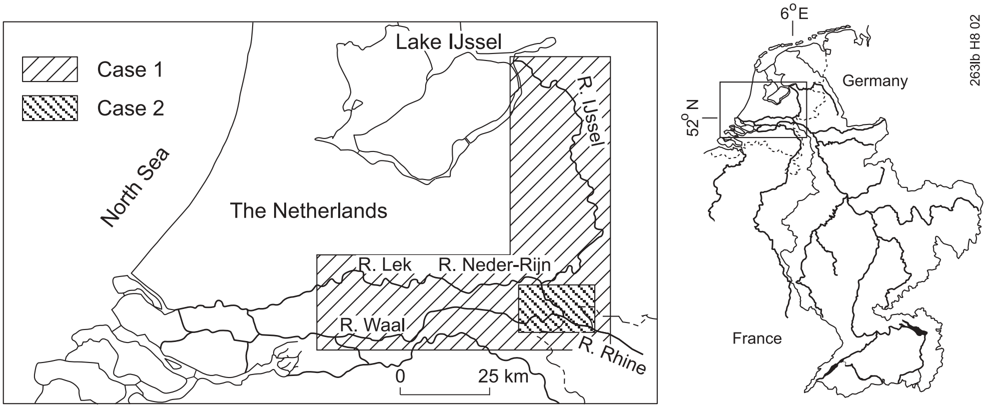

Fig. 8.2.

Locations of the two study areas within the River Rhine depositional zone

ROLE OF GEOMORPHOLOGY

Rehabilitation policies

At present, river rehabilitation policies in the Netherlands are an important source of inspiration for many scientists. The prospects for applied geomorphology have been growing steadily since the late 1980s, induced by developments in river ecosystem management, spatial planning and flood control (Table 8.1).

Large amounts of toxic chemicals were released into the River Rhine during a fire at the Sandoz chemical factory near Basle, Switzerland, in 1986. It caused the death of enormous numbers of fish and focussed attention on the ecological function of the river. Although international cooperation to improve water quality began in 1950s, the accident triggered the formulation of additional policies to improve the situation for migratory fish and increase the diversity of species (Van Dijk et al., 1995). In 1987, the Rhine Action Programme was published, followed by an Ecological Master Plan describing how the targets agreed upon by the Rhine countries are to be achieved by measures encompassing both the channel and the floodplain areas (Schulte-Wülwer-Leidig, 1991).

Meanwhile, a new strategy for nature conservation in the Netherlands has been introduced. As the Netherlands is one of the most densily populated countries of Western Europe, increasing urbanisation and the associated needs for infrastructure are seriously threatening the values of Dutch landscapes (Vos and Zonneveld, 1993). It was recognised that nature conservation policies alone cannot safeguard these values, and a more offensive approach was advocated. Aspects of the new strategy are separation of the high-dynamic land use functions of rural areas (e.g. agriculture, infrastructure) from low-dynamic land use functions (e.g. nature, recreation), and the creation of relatively large areas for both categories so that they can develop more independently (De Bruin et al., 1987; Sijmons, 1990). The new ideas on rural land use planning were elaborated in the Nature Policy Plan. The central element in this plan is the National Ecological Network: a network of natural areas that are connected with each other by smaller stepping stones, enabling migration of species (Ministerie van Landbouw, Natuurbeheer en Visserij, 1990). For its realisation, various rehabilitation projects have been proposed. Within the 29,000 ha of Rhine floodplains, the 8000 ha designated for nature at present are to be enlarged by another 8000 ha by 2018. These areas mainly include riparian grasslands and wetlands.

Major floods in the German and Dutch parts of the River Rhine system occurred in 1993 and 1995. In January 1995 more than 200,000 people had to be evacuated from the area adjacent to the embanked river floodplains. These floods raised awareness once again that the discharge of water and flood protection will remain the first priority river function. Moreover, studies on the impact of future climate change indicate a 5% increase in peak discharges during winter and early spring, which may be expected around 2050 (Kwadijk, 1993; Haasnoot et al., 1999). In the light of this information, policy making and the implementation of integrated rehabilitation plans were speeded up considerably. As a result, rehabilitating the integrity of river systems has become a major issue in forthcoming national and regional policies for spatial planning (Waterloopkundig Laboratorium, 1999; Ministerie van Verkeer en Waterstaat, 2000).

Table 8.1.
Main events guiding the direction to the spatial planning in the River Rhine system

PERIOD	TRIGGER EVENT	POLICY DOCUMENT	RESULT/TARGET
1050–1300	Reclamation	-	Embankment
1850–1900	Industrialisation	Rivers Act	River regulation
1985–2000	Sandoz accident	Rhine Action Programme	Ecological rehabilitation
	Casco planning	Nature Policy Plan	Ecological networks
	Floods 1993/1995	Flood Action Plan	Integrated planning

River ecosystem concepts

Ecological concepts describing the functioning of the river system are crucial for river rehabilitation (Townsend, 1996; Lorentz et al., 1997). Following such concepts, rehabilitating geomorphological processes and patterns is essential to the success of rehabilitation policies. The most fundamental and most widely applied concepts are the River Continuum Concept (Vannote et al., 1980) and the Flood Pulse Concept (Junk et al., 1989).

The River Continuum Concept emphasises the longitudinal gradient within temperate river systems. Associated with the increase in discharge and channel dimensions in the downstream direction, various biologically important features – such as availability of light, water temperature and food resources – change as well. This results in a continuum of habitat types. The river continuum is related to the establishment of an equilibrium river profile and is maintained through the transport and downstream fining of sediment and organic matter. Depending on the geological setting, these processes result in various river reaches, each with characteristic landform patterns and related habitat conditions.

The Flood Pulse Concept emphasises the function of flooding events in the exchange of nutrients and species between the river channel and the various floodplain habitat types. The flood pulse is associated with the processes of erosion and deposition, which are essential to rejuvenating the floodplain ecosystem. The storage of sediment results in an important lateral zoning in process dynamics, to which the river biota are adapted. Restrictions imposed by the flow and sediment transport decrease away from the channel, but restrictions imposed by flooding increase with decreasing height of floodplain landforms.

System classification and modelling

Generally, the planning process starts with a resource inventory to gain sufficient knowledge of the various land units and associated potentials (Peck, 1998). A resource inventory implies the use of a classification system, enabling the collection and presentation of information in a systematic way (Lotspeich and Platts, 1982). It provides a common language for scientists and planners as well as a basis for setting up rules in landscape ecological models. As a consequence of its role in ecological concepts, geomorphology is among the most essential aspects in any system classifying natural resources of rivers. In the Netherlands, geomorphology has been incorporated into the River Ecotope System, which has been developed as an integrated classification system to be used in policy oriented research and rehabilitation planning in large river systems (Rademakers and Wolfert, 1994). The land and water units distinguished are called ecotopes, defined as spatial ecological units at the landscape level. The composition and development of ecotopes are determined by specific combinations of abiotic, biotic and anthropogenic conditions (cf. Leser, 1976). Following the Flood Pulse Concept, the three most important disturbance factors able to set back the vegetation succession have been selected as classification criteria (Table 8.2): morphodynamics (encompassing flow velocity, erosion and sedimentation rates); hydrodynamics (timing, frequency and duration of flooding) and anthropodynamics (land use and management). Morphodynamics are reflected in the landform configuration and hydrodynamics in the floodplain relief. Accordingly, most ecotopes may be identified and mapped by means of delineating ecologically relevant landforms. In the landscape ecological

Table 8.2.
Excerpt from the River Ecotope System

LAND UNIT		**CLASSIFICATION CRITERION**		
Physiotope	**Ecotope**	**Morpho dynamics**	**Hydrodynamics**	**Anthropo-dynamics**
Deep sand-bed channel	Deep sand-bed channel	Large–very large	Deep water	Natural– cultural
Shallow sand-bed channel	Shallow sand-bed channel	Large	Permanently flooded	Natural– cultural
Secondary channel	Secondary channel	Large	Deep water–permanently flooded	Natural– seminatural
Slough	Slough	Moderate	Deep water–permanently flooded	Natural– seminatural
Sand bar / shoreface	Sand bar / shoreface	Large	Shoreface	Natural– seminatural
Natural levee	Levee ruderal vegetation	Large	Periodically–seldom flooded	Natural– seminatural
	Levee hardwood forest	Large	Periodically–seldom flooded	Natural–seminatural-cultural
Floodplain flat	Floodplain grassland	Moderate	Frequently–periodically flooded	Natural– cultural
	Floodplain softwood forest	Moderate	Frequently flooded	Natural– seminatural
	Floodplain ruderal vegetation / macrophyte marsh	Small-moderate	Frequently–periodically flooded	Natural–seminatural-cultural
Abandoned channel	Abandoned channel aquatic vegetation	Small	Seldom–never flooded	Natural– seminatural
Gravel-pit lake	Gravel-pit lake	Large	Deep water–shoreface	Natural– cultural
Built-up terrain	Built-up terrain	Small	Never flooded	Cultural

terminology, such landforms are called physiotopes.

In rehabilitation strategies, measures usually aim at mitigating human interference or restoring natural situations from the past. The effects are often assessed by means of models, either to anticipate on failures and success of such measures, or even as part of an environmental impact assessment. Among the instruments used in the Netherlands, is LEDESS–Landscape Ecological DEcision Support System (Roos-Klein Lankhorst, 1991; Harms et al, 1993). LEDESS is a deterministic knowledge-based system, that simulates the spatial and temporal development of vegetation and fauna. An operations model of LEDESS is shown in Fig. 8.3. Its two main functions are: (1) checking the ecological feasibility through confrontation with the geomorphological and hydrological conditions, and (2) determining the developments in vegetation and fauna. The River Ecotope System is incorporated in LEDESS when it is applied to river systems. Vegetation types are determined by physiotope, management and time required to reach a certain stage in the vegetation succession, eventually leading to the target vegetation, i.e. the vegetation type desired when implementing measures. Subsequently, vegetation determines the area suited for breeding, foraging or refuge of fauna species. Information on the succession of plant communities and habitat requirements was derived from the literature. Data on the actual situation and on the planned developments are stored in a grid-based geographical information system (GIS).

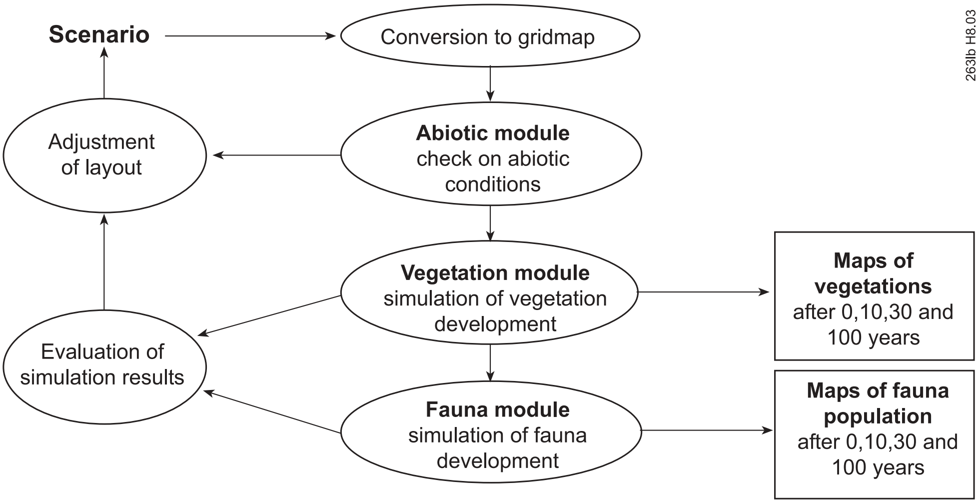

Fig. 8.3.
The operation process of the LEDESS model

RHINE DEPOSITIONAL ZONE

Historical reference situation

The inspiration for river rehabilitation may be derived from descriptions of past situations or from relatively pristine river systems elsewhere, revealing the existence of more natural landscapes and biologically more diverse ecosystems (Bisseling et al., 1994). For instance, the international agreement to restore habitats of migratory fish in the River Rhine (Schulte-Wülwer-Leidig, 1991) refers to 19th century information about changes in channel and bar formation and about salmon, which was sold in large quantities on the markets of towns along the river. Comparing reference situations with the river system to be rehabilitated enables investigation of which phenomena and processes have been degrading through time and, consequently, the identification of the direction of change that has to be pursued (Kern, 1994; Pedroli et al., 1996). Accordingly, more comprehensive scientific data on such reference situations are useful in the rehabilitation planning process.

The geomorphological maps and description of the River Rhine in historical time, presented in Chapter 7, can be regarded as an adequate historical reference situation. It not only provides information on the various pre-channelisation landform configurations, but also aids understanding the role of fluvial processes and identifying the variables responsible for the river reach variability, such as physiographical setting and river systems history. This is why a historical approach is preferred here: not all of this information is easily transferred from other river systems since river systems can differ greatly (Hobbs and Norton, 1996). The maps were digitised, thus providing quantitative information on landform areas and changes. Following the set up of the River Ecotope System (see Table 8.2), information on ecotopes could be derived from the landform (i.e. physiotope) data, when combined with information on land use and land cover as depicted on the historical maps. The results are presented in Table 8.3.

To examine the degradation of the river ecosystem and to identify river rehabilitation priorities, the historical description is compared in Table 8.3 to the present-day distribution of ecotopes, derived from data from Silva and Kok (1996). The differences between the 18th and 19th century data can be regarded largely as the river systems' natural variability in time. Most of the differences between the 19th and 20th century data, however, are the result of the late 19th century channelisation, which resulted in a decline of natural values, indicating which of these phenomena and processes are to be rehabilitated. The construction of groynes and revetments resulted in some major changes in channel dynamics and floodplain aggradation.

As a consequence of the channelisation works the main channels decreased in width – and increased in depth – and all secondary channels disappeared. As a result, fauna communities depending on tranquil flowing, shallow water have been reported to be degrading too (Admiraal et al., 1993). The present river ecosystem lacks islands and recently deposited sand bars, where bar formation once triggered the establishment of vegetation pioneer communities. The decrease in softwood floodplain forest cover is partly the result of this development. On the other hand, the shoreface of the main

Table 8.3.
Historical and contemporaneous occurrence of ecotopes in the floodplains of the Upper-IJssel and Middle-Waal river reaches

ECOTOPE	UPPER-IJSSEL			MIDDLE-WAAL		
	1750 (%)	1840 (%)	1990[1] (%)	1780 (%)	1830 (%)	1990[1] (%)
Deep/shallow channel	10.42	10.36	10.04	29.18	32.56	24.66
Secondary channel	0.16	0.00	0.00	0.99	3.55	0.00
Slough	2.40	0.56	2.62	3.29	1.40	4.67
Sand bar/ shoreface	0.40	0.25	0.23	4.17	1.25	4.19
Levee/dune dry ruderal vegetation	3.03	2.88	0.30	0.90	1.29	0.34
Levee/floodplain softwood forest	3.27	2.20	0.60	8.50	7.69	1.17
Levee/floodplain hardwood forest	0.10	0.10	0.10	0.00	0.00	0.00
Floodplain softwood timber forest	0.71	0.76	1.36	2.19	0.56	0.28
Floodplain grassland	63.05	66.53	0.20	44.90	47.43	0.00
Floodplain pasture	0.00	0.00	64.07	0.00	0.00	48.07
Floodplain moist ruderal vegetation / macrophyte marsh	0.24	0.31	0.50	4.71	1.48	0.98
Abandoned channel with aquatic vegetation	1.43	1.45	0.97	0.09	1.30	0.12
Gravel-pit lake	0.06	0.06	8.19	0.19	0.94	9.48
Arable floodplain land	14.22	14.12	8.55	0.77	0.40	1.78
Built-up area	0.36	0.42	2.38	0.13	0.18	4.23

[1] *derived from: Silva and Kok (1996)*

channel is more dynamic now, which is reflected in the wide, sandy beach and the local presence of aeolian river dunes and small, sandy natural levees along the River Waal.

In the floodplains, sloughs and abandoned channels, and their associated marshes and reedlands decreased in size. The decrease of vegetation types characteristic of riparian wetlands has continued in the last few decades (Van den Brink et al., 1991; Jongman, 1992) and is considered here to be the result of lower water levels, caused by the main channel bed degradation. The intensified use of floodplain land resulted in a decrease in area of natural grasslands and a strong increase in deep sand and gravel pits and built-up areas.

Suitability of river reaches

In ecosystem rehabilitation, it is common sense to follow the philosophy of 'design with nature' (McHarg, 1969; Nunnally and Keller, 1979), in which natural processes are preferred as tools to achieve rehabilitation targets. In turn, it makes sense to assess the contemporaneous suitability of river reaches for reinstating geomorphological processes which were characteristic in the historical period, such as island formation, point-bar accretion and overbank deposition. Pre-conditions for the development of fluvial landforms underlying dynamic ecosystems of the Rhine distributary system have been identified in Chapter 7. It is assumed here that the very same conditions have to be fulfilled in the present-day regulated river system.

The contemporaneous values of the predictors of island formation and bar

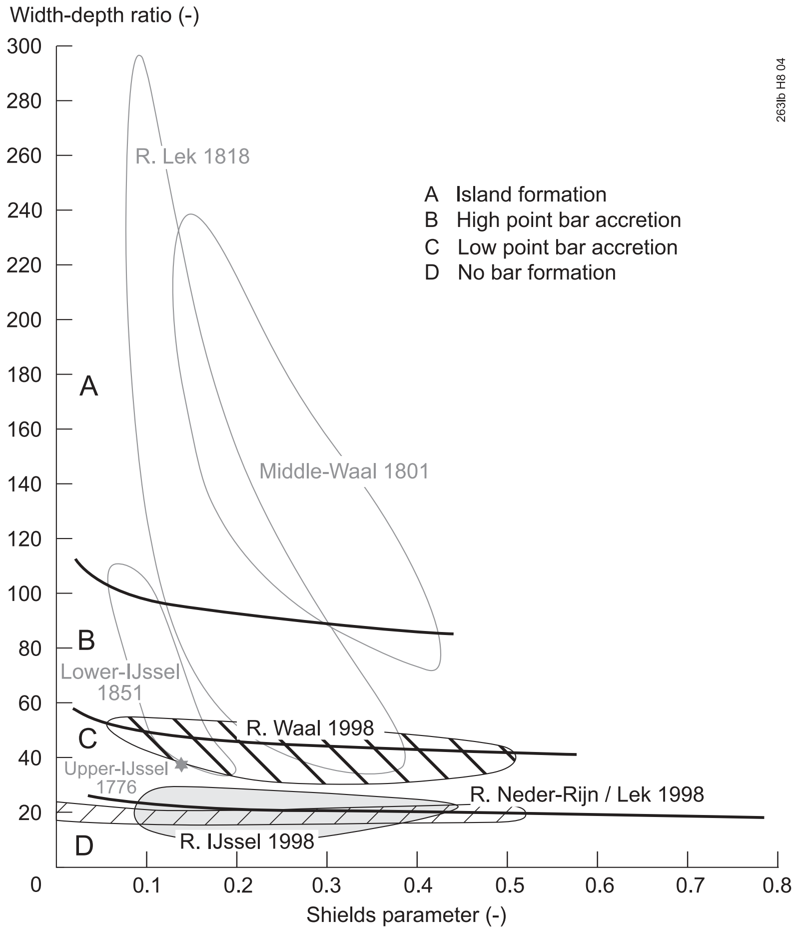

Fig. 8.4.
Present-day possibilities for island formation and point-bar accretion in the three Rhine river distributaries, compared with the situation before channelisation (partly adapted from: Lambeek and Mosselman, 1998)

development and the historical data on the River Lek were calculated by Lambeek and Mosselman (1998) according to the methods described in Chapter 7. The width–depth ratio and the Shields parameter were calculated for the discharges (Q) occurring in 95%, 75%, 35% and 10% of the time, at various locations in the three Rhine distributaries. Envelopes of values related to these discharges are given in Fig. 8.4 and compared with historical data. This indicates the differences between past and present suitability for island and bar formation. The suitability changed dramatically since the width–depth ratio values strongly decreased due to the river regulation works. The suitability for point-bar formation, though, still varies among the river reaches. High point bars can be formed in the uppermost and lowermost reaches of the River Waal

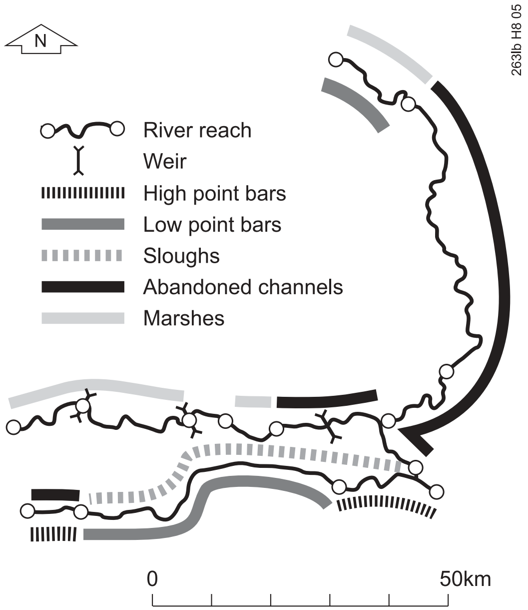

Fig. 8.5
Suitability of river reaches for some of the river rehabilitation targets

(Fig. 8.5), especially during low discharges when width–depth ratio values are relatively large and the Shields parameter value is high. These point bars, however, are not stable features: when discharges increase the width–depth ratio values decrease while the Shields parameter values remain high, indicating high transport rates and the breakdown of the bar. Only in the Lower-Waal reach, which is slightly tide-influenced, the width-depth ratio values remain constant so that a stable high point bar may develop there. In the River IJssel no point bars can develop at all, except in its lowermost reach, which is suitable for the formation of low point bars in bends.

Similarly, the suitability for sloughs, abandoned channels and marshes has been explored (Fig. 8.5). Sloughs may remain connected to the main channel along the River Waal as a result of the higher flow velocities over the floodplains during inundation. Elsewhere, the future presence of abandoned channels is guaranteed by a relatively low flooding duration where floodplains are inundated at Q10**%** water levels or less, such as along the Upper-IJssel and Middle-IJssel reaches. In contrast, floodplain channels tend to silt up relatively fast in the Lower-IJssel reach and (parts of) the channelised River Neder-Rijn/Lek, because of the relatively long flooding duration there – flooding already starts at $Q_{35\%}$ water levels. This, and the extremely small fluctuations in water levels, make these reaches very suitable for the development of marsh vegetation.

Rehabilitation measures

Historical reference situations may help to set directions, but cannot be simply seen as targets for river rehabilitation plans (Bal et al., 1995). With changing socio-economic circumstances, functions such as navigation, flood control and fresh-water supply gained in importance during the last century, and this is not likely to change in the near future. Moreover, the return of some of the original fluvial processes will be hampered because of irreversible effects of human influences on the river and its floodplains (e.g. Amoros et al., 1987). Bed degradation, for instance, is difficult to undo. A totally natural river system, therefore, is generally acknowledged to be an unrealistic option (Brookes, 1995b; Hobbs and Norton, 1996; Pedroli et al, 1996). Consequently, reintroducing the patterns and processes of the former river ecosystem as much as possible is the challenge of the planner. In addition, artificial measures may be required to create new circumstances that trigger or mimic the original dynamics of the various river and floodplain ecosystems. As indicated by the historical reference situation and the contemporaneous suitability of river reaches, two such measures are acknowledged to be especially relevant for the river rehabilitation process in the River Rhine distributary system: creating secondary channels and lowering of the floodplain surface.

The creation of secondary channels is an objective of various large river rehabilitation projects (e.g. Bernhart, 1992; Harberg et al., 1993; Marchand, 1993). In the Netherlands, secondary channels have been proposed as an alternative means to rehabilitate the former shallow aquatic environments with year round, tranquil water flow (Cals et al., 1998), thereby re-introducing important habitats for fish and invertebrates. Whereas groynes and revetments prevent any pronounced bar development in the main channel, secondary channels may even provide space for the development of small bars, provided that the width–depth ratio is relatively large.

The artificial lowering of (parts of) the floodplain surface is seen as a method to reconnect the river’s channel and floodplain again (Van de Kamer et al., 1998). A lowered floodplain surface will increase rates of natural levee formation, which may rehabilitate the morphodynamics of the former sand and gravel bar environment. It will certainly increase flooding duration, which will lead to the rehabilitation of the former wetland environments. Both types of measures will not only increase habitat diversity, but will also decrease the hydraulic roughness of floodplains.

GELDERSE POORT AREA

Rehabilitation scenarios

River rehabilitation planners are confronted by interests and land use claims from other sectors (urbanisation, navigation, recreation, agriculture, etc.) which often conflict with nature. The prospects and expected future developments in these various sectors is uncertain. Scenario studies are believed to be useful tools for delaing with this uncertainty in the decision-making process (Schoute et al., 1995). A scenario is a description of (1) the current situation, of (2) a possible or desirable future situation, as well as (3) a series of events that could lead from the current state of affairs to this future situation. Scenario studies usually comprise more than one scenario, since the combined impacts of external factors and scenario building assumptions generally leads to different series of events, and therefore to different future states. It is not the ambition of the scenario approach to predict the future, but to explore possible futures or the feasibility of desired futures.

One of the river rehabilitation projects in which a scenario approach was adopted was the Gelderse Poort project. The Gelderse Poort area is situated in the eastern part of the Netherlands (Fig. 8.2) at the apex of the River Rhine depositional zone. Here, the River Rhine splits up into two distributaries: the River Waal and the River Neder-Rijn. Due to its position, the area was designated as one of the core areas of the National Ecological Network (see section 2.1). Its 1000 ha of nature reserves will have to be extended by approximately 3000 ha in the near future. The Province of Gelderland started a rehabilitation planning project in which the emphasis has been on nature, but other river and land use functions were also involved, namely outdoor-recreation, agriculture, river management and sand and clay extraction. Although plans have been made for the entire area, which encompasses 12.000 ha, this paper concentrates on the 3500 ha of floodplains.

An important impetus for the formulation of the scenarios in the process of plan design was given by historical reference situations concerning the Upper-IJssel and Middle-Waal river reaches (Chapter 7). The differences in fluvial style described helped the authorities, NGOs and other stakeholders to order their thoughts on the future of nature in the Gelderse Poort area. As a result, two scenarios were formulated in which different ecological objectives could be coupled to different types of nature management and to different spatial strategies for nature rehabilitation: the Macrogradient scenario, and the River Dynamics scenario (Table 8.4; Fig. 8.6).

The Macrogradient scenario aims at diversity of species and species communities. Important ecosystem gradients are emphasized, not only within floodplains, but also between the riverine environment and the land protected by embankments. The Upper-IJssel reach is the reference situation, which is a low dynamic fluvial environment in which many types of wetlands can occur, partly influenced by seepage water coming from nearby ice-pushed ridges. Accordingly, in the Gelderse Poort area only half of the 3000 ha of new nature will be developed in the floodplain area.

Table 8.4.
Characteristics of the two rehabilitation scenarios for the Gelderse Poort area

SCENARIO	HISTORICAL REFERENCE SITUATION	ECOLOGICAL OBJECTIVE	NATURE MANAGEMENT	SPATIAL STRATEGY
Macrogradient	Upper-IJssel; Low dynamic environment	Bio-diversity; variety of ecosystems	Maximum variation in management	Integrating and zoning of land use
River Dynamics	Middle Waal; High dynamic environment	Natural processes; self-sustaining ecosystems	Little interference	Segregating land use

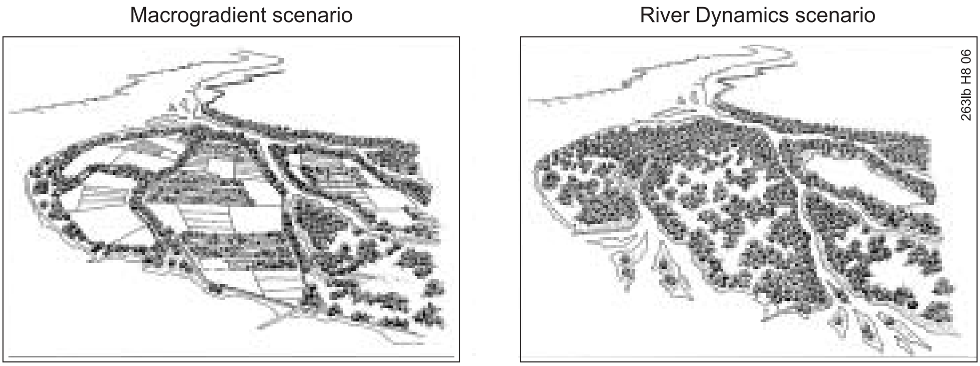

Fig. 8.6.
The two rehabilitation scenarios envisaged from a bird's-eye view

Biodiversity is to be improved by a spatial strategy of integration and zoning of land use functions, and maintained by a maximum variation in management. The result will be a landscape with a great variety of wooded plots, shrubs, hedges, grasslands and marshes. Agricultural practices in the floodplain will be reduced, both in area and in intensity. There will be space for outdoor recreation and forestry. Clearly, the objective of the Macrogradient scenario is intermediate between traditional nature conservation and the new strategy of nature rehabilitation.

The River Dynamics scenario, however, emphasises the nature rehabilitation strategy. It focusses on natural ecosystem processes, and it concentrates on the river floodplains. This scenario is based on the historical reference situation of the Middle-Waal reach, which describes a highly dynamic environment, largely controlled by the river itself. Rehabilitation of an ecosystem that is functioning as naturally as possible requires segregation of land use and excluding dynamic land use functions, such as agriculture, from the floodplain area. Human interference through nature management will be reduced to a minimum. The resulting landscape will consist mainly of floodplain forests and wetlands in which climax vegetations can develop.

Impacts of fluvial processes

Development of these two scenarios into a spatial layout proposal was based on a comparison with the area's physical and socio-economic structure. The geomorphological input to the spatial layout was strongly guided by the impacts erosion and depossition were expected to have on the various river and land use functions in the Gelderse Poort area. Insight into fluvial processes, derived from the historical reference situation, made it possible to anticipate the effects rehabilitation measures were likely to have. These processes are not restricted to the location of a particular measure, but may have implications further downstream or upstream, which complicates the design. During the design stage, however, it was shown that the benefits and restrictions from nature rehabilitation measures vary considerably within the Gelderse Poort area, so that enough space remains where nature and other functions are compatible. This will be exemplified below for two measures: creating secondary channels and lowering the floodplain surface aimed at an increase in the rates of natural levee formation.

Creating secondary channels is typical of the River Dynamics scenario. When creating such a channel, the influence of the river flood pulse will increase considerably because the minor river dikes within the floodplain will have to be lowered as well. Consequently, flooding duration and flow velocities will increase not only in the vicinity of the new channel, but also in more distant parts of the floodplain. Various factors are involved in the allocation of new secondary channels. First, the intensive use of the river for navigation hampers the development of secondary channels. New secondary channels will divert part of the water flow from the main channel, where reduced flow velocities will probably result in in-channel deposition of sediment. Such a measure thus runs the risk of contradicting the international agreement on navigation, which guarantees a minimum 2.5 m depth of the river when discharges are small. Moreover, narrowing the main channel to compensate for the loss in flow velocities is not a realistic solution in the River Waal due to its many bends, which already impose constraints on navigation by modern barges and tow-vessels. Second, the safety of embanked areas is at stake, since the creation of secondary channels is often combined with the desire to establish a greater area of floodplain hardwood forest. A floodplain forest will increase the roughness of the floodplain considerably, but this could be compensated for by excavating a new secondary channel in the same river reach. Nevertheless, in general, forests are not likely to develop where the floodplains are narrow and flow velocities during inundation are relatively high. The highest flow velocities are found along the River Waal. Third, the nature management costs have to be considered. The historical analysis showed that many secondary channels in the River Waal were blocked by sandy deposits. Until they were replaced as a habitat by younger channels downstream, the life cycle of these channels lasted for approximately 30–50 years. As the river Waal is still transporting large quantities of sand, it may be expected that the new secondary channels will need to be maintained by dredging every now and then, which is rather expensive. In contrast, the secondary channels in the River IJssel were much more stable features, a situation which is more or less comparable with the present state of the River Neder-Rijn. As a result of this analysis, two secondary channels were proposed in the Gelderse Poort area, to be situated along the rivers Rhine and Neder-Rijn.

Lowering the floodplain surface to increase the rates of natural levee formation, relies on the knowledge that levee sedimentation rates decrease as the height of the levee rises. Moreover, a broad river shoreface is known to increase the aeolian dynamics as well, and will result in small aeolian dunes on top of the levee. As this measure involves the excavation of a zone along the main channel, which will not have much impact on the remainder of the floodplain, it fits into both the Macrogradient and the River Dynamics scenario. Two factors were relevant in the planning of this measure. First,

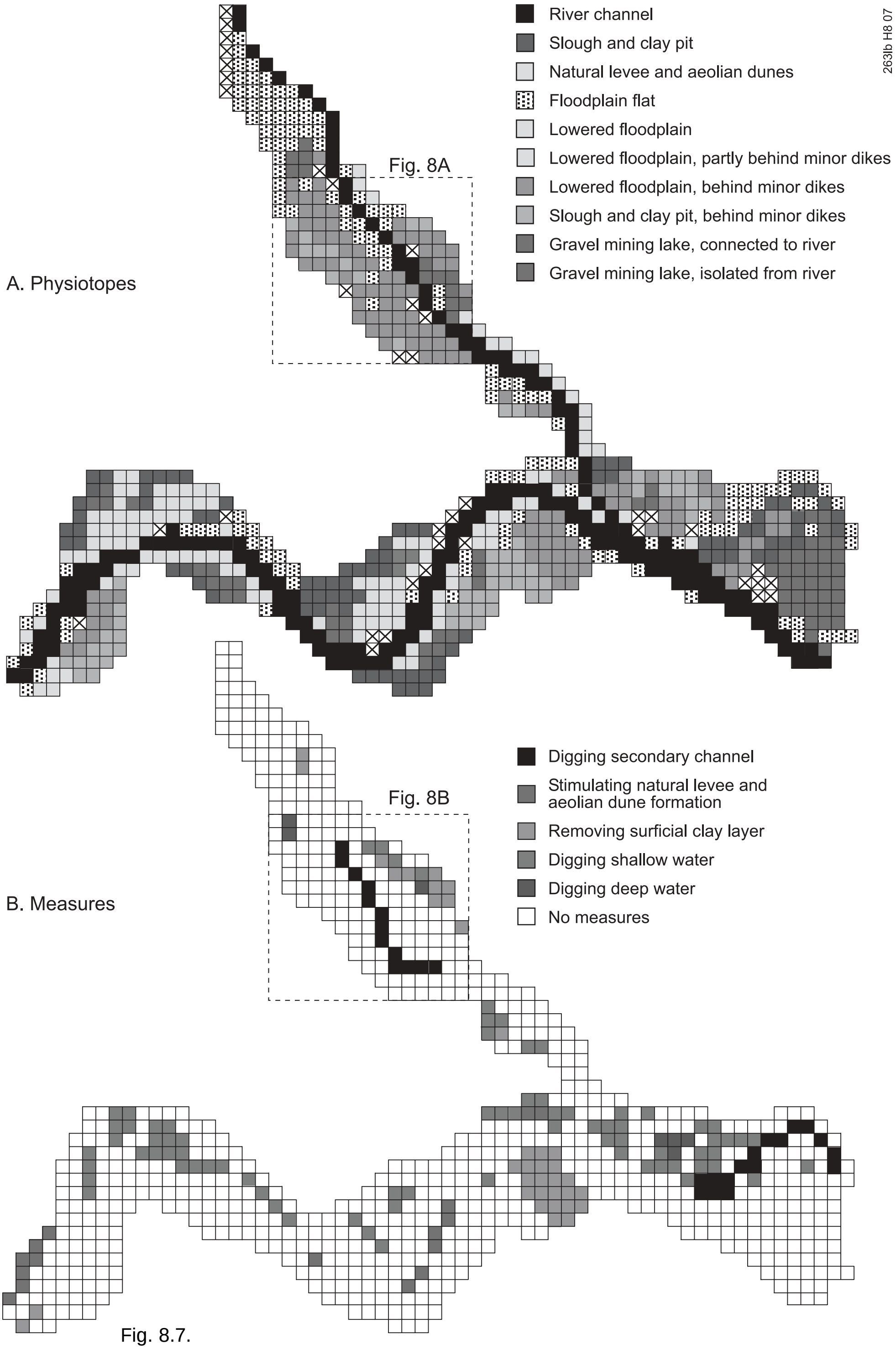

Fig. 8.7.

The contemporaneous landform configuration in the database of LEDESS (A) and the rehabilitation measures proposed in the River Dynamics scenario (B) excavating part of the floodplain may be financed by selling the extracted sand and gravel to the nearby construction industry or specifically for use in the dike reinforcement projects in the Gelderse Poort area. The most appropriate parts of the floodplains are likely to be found in the former point-bar environments along bends of the River Waal. Second, the success of the measure requires the availability of large quantities of sand stored in a broad, gently sloping, sandy river shoreface. These circumstances occur in the upper part of the River Waal and are related to its potential for forming low point bars. For these reasons, the stimulation of natural levee formation was proposed on various locations along the River Waal (Fig. 8.7).

Feasibility of measures and effects

The LEDESS model was used to evaluate the feasibility of the spatial layout proposal and to give an impression of the consequences of the different scenarios chosen (see section 2.3). The procedure (Fig. 8.2) started with the construction of a grid-based physiotope map with 250 m x 250 m cells (Fig. 8.7 and Fig. 8.8, A and B). Information on landforms and morphodynamics in the Gelderse Poort area was derived from historical maps and existing geomorphological and soil maps on a scale of 1:50,000. Information on hydrodynamics was derived from daily discharge data for the period 1901–1985, stage-discharge relationships for several points along the river and from information on the elevation of the floodplain surface and minor dikes within the floodplains (cf. Knotters et al., 1993). Drawing on an understanding of the relationships between vegetation and landforms, the proposed layout could be compared with the physiotope map. Where proposed land use functions were not possible under the present-day abiotic conditions, additional measures had to be proposed or the proposed layout had to be changed. The anticipated measures clearly differ in the two scenarios chosen (Fig. 8.8, C and D) and resulted in new physiotope maps indicating the conditions after measures are executed.

Eventually, these physiotope maps served as a basis to simulate the vegetation and fauna developments. These were calculated for periods of 10, 30 and 100 years. The results of the evaluation were expressed as the area suited for the vegetation and fauna communities considered. The calculation of the suitability for fauna species also considered chorological relationships between habitats and species. The effects of rehabilitation of the secondary channel is described as an example. The creation of secondary channels in the River Dynamics scenario results in a clear change in vegetation, both in the channel itself and in its surroundings (Fig 8, E and F). The development of softwood floodplain forest (*Salicetum albo-fragilis* and *Salici-Populetum nigrae*) fringing the channel is attributed to the higher rates in morphodynamics. Being pioneers in the vegetation succession, softwood floodplain forests can only be maintained in areas with processes of active geomorphological renewal. Development of a hardwood floodplain forest (*Fraxino-Ulmetum impatientosum*, *Fraxino-Ulmetum typicum* and *Fraxino-Ulmetum alnetosum*) in the surroundings of the channel is a consequence of the higher rates of hydrodynamics related to the removal of minor

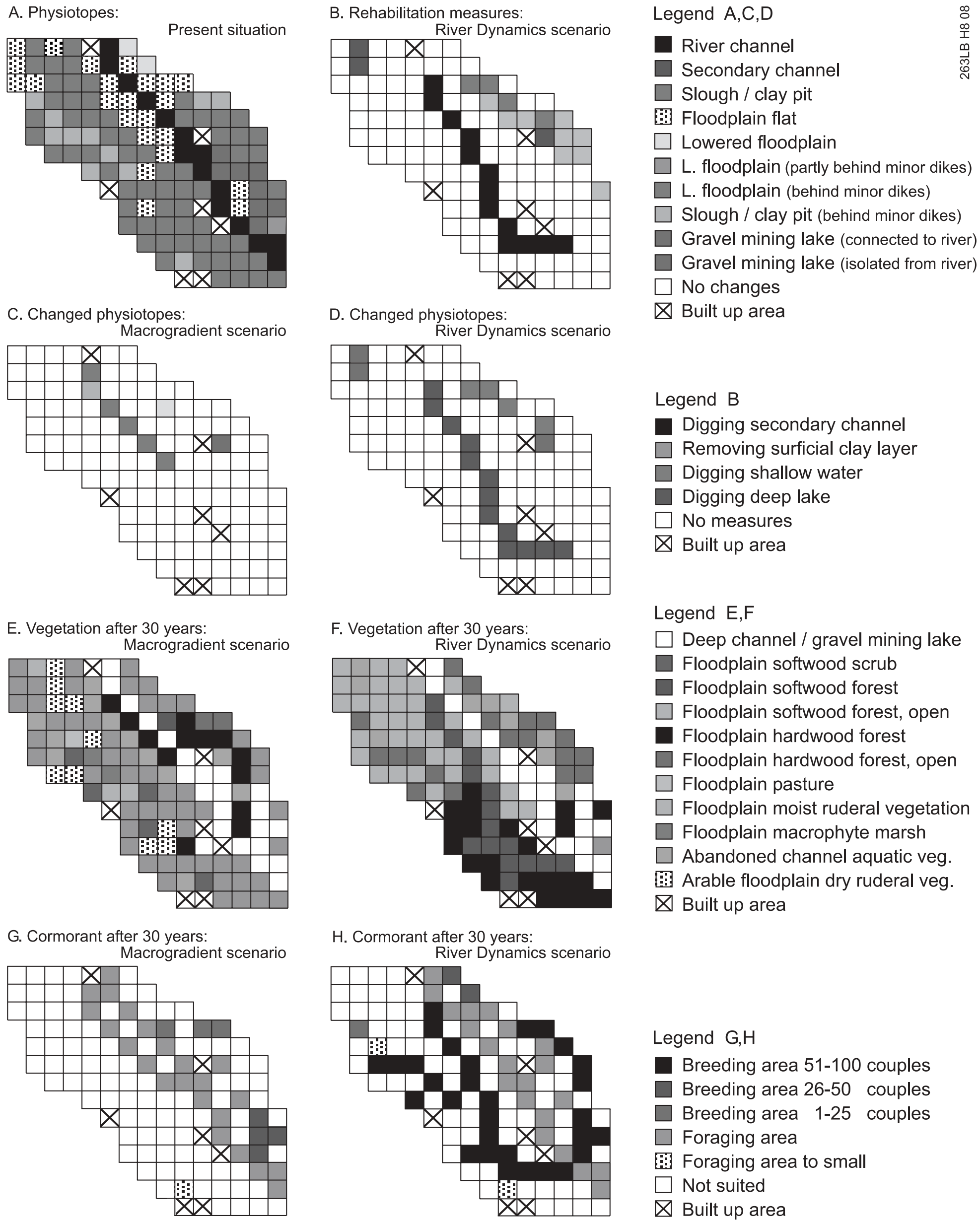

Fig. 8.8.

Comparison of the two scenarios: changes in physiotopes and the resulting developments in vegetation and cormorant community after 30 years in a part of the study area dikes. One of the animal species that clearly benefits from the secondary channel physiotope in the area is the cormorant (Fig. 8.8, G and H). The cormorant (*Phalacrocorax carbo*) requires open water rich in fish for foraging, and a combination of marshy woodland and open water for breeding. The cormorant is a bird species that can react quickly to changes in environment, and is therefore often found in juvenile habitats characteristic of areas with high rates of fluvial dynamics. The results of the scenarios were also compared with the situation that will exist after present developments have continued for 10, 30 and 100 years.

DISCUSSION AND CONCLUSIONS

Going through successive cycles in the planning procedure, the spatial planner will start with formulating desirable and possible futures, but in the end will aim at envisaging a probable future (De Jong, 1992). This is relevant to the activities and skills of the geomorphologists involved in the process. In the beginning of the planning process, research generally starts as a rather monodisciplinary action. From a geomorphological point of view, rehabilitation priorities can be suggested and planners can be informed of the associated processes and the places where these are likely to be an aid in river rehabilitation – or not. This is the type of study most geomorphologists are familiar with. But when possible futures are investigated, studies become more interdisciplinary in approach. The chances and risks of geomorphological processes have to be studied together with other experts, as was done in the second case study, with ecologists (nature), hydrologists (flood control), economists (sand and clay extraction), landscape architects (responsible for the design) and others. This requires insight into other sciences and a willingness among the project members to work with a common language and on common targets. It is the type of work which nowadays is generally awarded to consultants. In the domain of the probable future, planners will have to negotiate with politicians and stakeholders on the organisation of the land use changes and future management. It requires a transdisciplinary approach in which communication on the functions of the chosen geomorphological processes and the associated effects and costs of measures goes into details. The involvement of geomorphologists in this phase is still rare, but it might be an important challenge for applied geomorphology, leading to further improvement of the quality of plans.

The changing nature of research is also reflected in the amount of detail in the studies. In this study, a functional-geographical approach to geomorphology has been preferred above a realist approach (Richards, 1982; Petts, 1995). The realist approach relies heavily on high quality data for the detailed explanation of causal mechanisms operating in the smaller spatio-temporal domains. Often, the resulting models and data required are not available at the start of a planning project. Instead, the case studies presented have shown that description and classification – characteristics of the functional-geographical approach – can be adequate tools in the planning process. However, there are also limitations, which can be exemplified by the outcomes of the LEDESS model. Its results are indicated as numbers of grids of 6.25 ha, the size of which is derived from the largest mapping scale of the soil maps available for the entire area and which can be regarded as the basic mapping unit of the GIS. Since maps are never a hundred per cent accurate, the corresponding basic planning unit, based on experiences of soil surveyors, is two to four times as large (Vink, 1963), between 12.5 and 25 ha. This implies that the results of the study should not be used for decisions on smaller areas. Realist models, therefore, gain in importance when the planning process advances into the possible and probable domains.

In this paper it has been demonstrated that geomorphological research on historical reference situations, and on the impacts of fluvial processes on the various river and land use functions, are meaningful to the design stages in a cyclical river rehabilitation planning process. The evaluation stages were shown to greatly benefit from the exploration of the suitability of river reaches for geomorphological processes and from the analysis of the feasibility of rehabilitation measures and their effects on vegetation and fauna. It has also been demonstrated that studying an area larger than the true planning area first, and on a larger spatial scale, results in information very valuable to the planning process. Applying such a framework to river rehabilitation planning processes, will draw attention to the following: (1) the geomorphology of river systems has degraded throughout the last century, (2) contemporary river reaches still vary dramatically in both landform patterns and suitability for processes, and (3) a geomorphological analysis can help in setting realistic goals for rehabilitation; thereby enabling politicians to make balanced choices for the future development of river systems.

ACKNOWLEDGEMENTS

This research was financed by the Netherlands Ministry of Transport, Public Works and Water Management and by the Ministry of Agriculture, Nature Management and Fisheries. The case study on rehabilitation scenarios for the Gelderse Poort area was commissioned by the Province of Gelderland. I thank Margriet Schoor for stimulating discussions on the suitability of river reaches. Valuable comments on a draft of this paper were given by Bert Harms, Jan Klijn and Ward Koster.

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General discussion and conclusions 9

This study followed a functional-geographical approach to research into river rehabilitation and to expand our knowledge of the geomorphology of lowland fluvial systems in the Netherlands. The advantages and disadvantages of this approach are discussed here. The results of six case studies on streams, small and large river systems, and recommendations for river rehabilitation planning have been discussed in the chapters 3 to 8. The similarities and differences between case studies are set in a wider perspective and recommendations for river rehabilitation are discussed.

THE FUNCTIONAL-GEOGRAPHICAL APPROACH

The functional-geographical approach, based on concepts of Frissell et al. (1986) and Petts and Amoros (1996), has been elaborated for use in river rehabilitation planning. By combining this with land evaluation methods most of the information relevant to the spatial planning process could be acquired: (1) historical as well as contemporaneous reference situations were described and (2) associated process conditions identified; based on this knowledge, (3) areas suitable for rehabilitation and spatial requirements were indicated and (4) recommendations on the design of measures were made. In the study on the River Rhine distributaries, the approach was coupled to physical-mathematical methods, as promoted by the realist approach in geomorphology, to further explain the phenomena observed. This combination of the two approaches in geomorphology strengthened the predictive power of the research and is considered to be the best way forward.

Geomorphological surveys and geomorphological map interpretation are indispensable research techniques in the functional-geographical approach. Maps have three functions. (1) Maps help to identify and quantify the large spatial variety of the fluvial environment as well as the conspicuous changes over time and thus help to make planning recommendations. (2) Map interpretation aids detection of the causes of spatial and temporal geomorphological change. Relatively unknown relationships were observed more than once, so that the techniques used proved to be valuable tools for stimulating the reenchantment of geomorphology (Baker and Twidale, 1991). (3) Engineers, biologists, planners, and even geomorphologists (pers. comm. A.D. Harvey) find maps impressive. In this way, they contribute to the general understanding of river functioning, which is an important aspect in the acceptance of rehabilitation plans in general.

The study focused on the spatio-temporal domains of river reaches and macro bedforms or landforms. Data at this level could be derived easily from historical maps and archive documents, geomorphological and soil maps, and aerial photography, or could be extracted by using GIS methodology. Data covering entire planning areas could be obtained relatively fast and at low cost. Data could also be linked to simple hydrogeomorphological data or data on flora and fauna in nearly all cases, allowing expertise from different disciplines to be integrated. This allows geomorphologists to get involved early on in integrated planning processes, which improves the quality of rehabilitation plans. Applying river system hierarchies when viewing rivers and structuring information is useful. Hierarchies, however, are difficult to use unambiguously, as illustrated by the difficulties with assigning independent and dependent variables to certain spatio-temporal domains. The concept of hierarchy, therefore, is best used in a pragmatic manner.

The benefits of the functional-geographical approach depend on the level of detail of the information available in comparison with the size of the river. For instance, if only small-scale maps are available, topographic information might not be accurate enough to reliably measure the lateral activity of a small meandering river. Also, monitoring of geomorphological change in small streams cannot rely on topographical maps or aerial photographs, but requires a time-consuming programme of work. In such monitoring projects, geomorphological mapping is recommended for use only at well chosen locations.

GEOMORPHOLOGICAL CHANGE: LANDFORM CONFIGURATIONS AND PROCESS VARIABLES

Three main types of fluvial styles were described in this study, occurring at specific locations along the river gradient and each characterised by a specific bedform or landform configuration (Fig. 9.1). Meandering streams, occurring in the erosion zone (cf. Schumm, 1977) of valleys in the Dutch lowland area, have mainly in-stream bedforms, such as pools and riffles and small bars, due to obstruction of the water flow by aquatic vegetation. In both the small and large rivers, a high-sinuosity meandering channel changes into a low-sinuosity channel, confined by dikes, further downstream. These two types characterise the transfer and deposition zones. The floodplains of high-sinuosity rivers are mainly formed by lateral channel migration, as shown by large scroll-bar and swale areas, but in low-sinuosity rivers downstream migration prevailed, as reflected by the pattern of sloughs. These types of rivers were observed in either a pre-channelisation or post-channelisation situation and thus indicate fluvial styles likely to occur after rehabilitation. Another embanked reach with a strong tidal influence would complement the lowland sequence depicted in Fig. 9.1 in a seaward direction.

The different fluvial styles were described by a relatively small set of erosional and depositional bedform and landform types. For instance, point bars and concave bank benches were observed in small streams as well as in large rivers, and natural levees, flood basins and abandoned channels were observed in the floodplains of both small and large rivers. Sedimentologists also characterise various fluvial environments by means of a limited set of architectural elements (Miall, 1985; Brierley and Hickin,

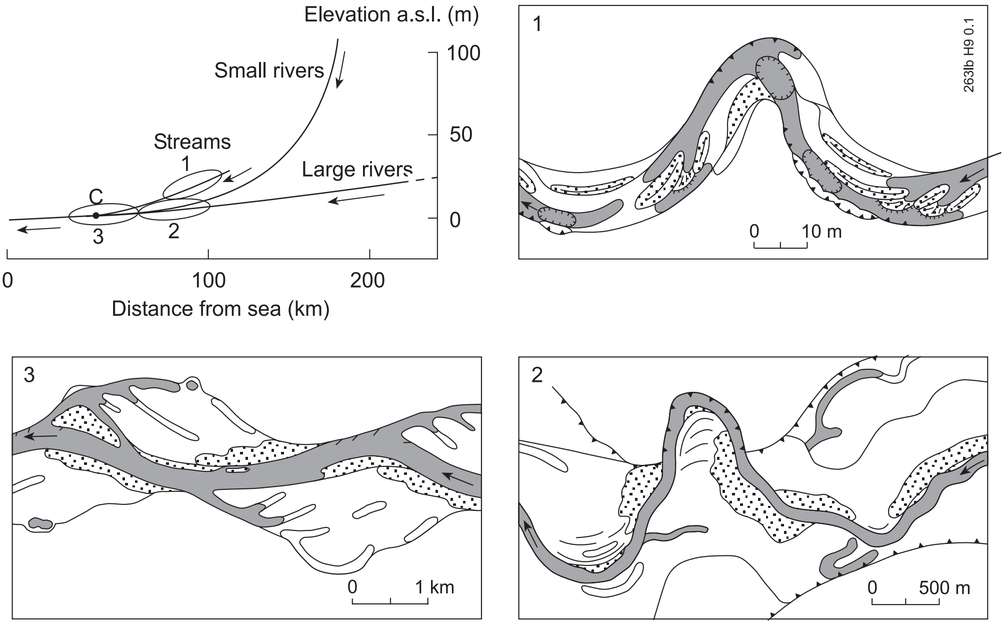

Fig. 9.1.
Main types of fluvial styles observed in lowland river systems in the Netherlands, and their characteristic position in the river continuum (C = imaginary point of confluence)

1991). These observations stress the universal nature of fluvial processes, pointing to the fact that it is not the processes in general that change along a river, but their relative importance, yielding a continuum of landform configurations from source to mouth. This, in general, justifies applying an understanding of fluvial processes observed in one river to other rivers, whether they are smaller or larger.

The river channel changes were quantified enabling a first comparison of migration rates of lowland river systems in the Netherlands (Fig. 9.2). Analysis of data reveals that when channel migration is not hampered by resistant bank material (Keersop stream) or decreased flow capacity (River IJssel), both the maximum and mean values of migration rates increase as the size of the river increases. A similar relationship has been described by Hooke (1980) and Lawler (1993). Their data encompass both maximum and mean values, so that only a rather loose relationship could be detected. Comparison of data shows that the channel changes in Dutch rivers are of the same order of magnitude as those measured along natural rivers elsewhere, in spite of their lowland setting and associated low channel gradient and low specific stream power. A comparison of the migration rates with the width of the floodplain of the Rivers Vecht, IJssel and Waal, however, clearly indicates that most of the floodplain landforms have a time-span of existence of at the least several centuries.

Variables usually mentioned in relation to the hierarchical domain of river reaches can be seen as responsible for the continuum of fluvial styles observed, between and

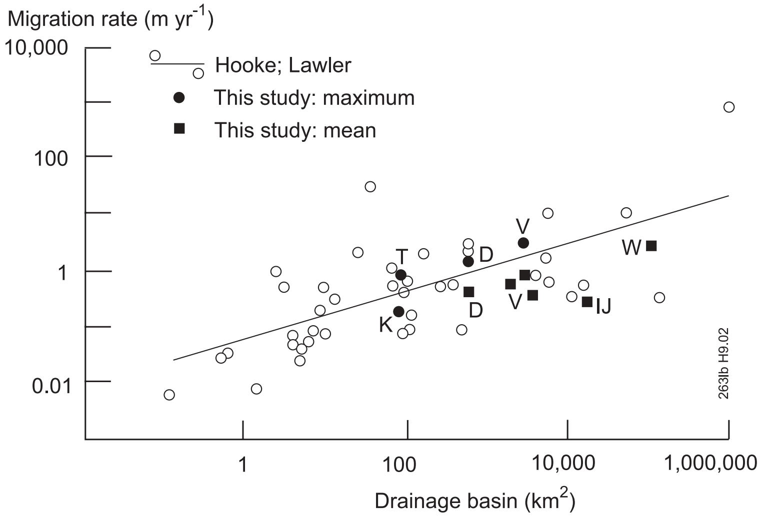

Fig. 9.2.
Relationship between lateral migration rates and drainage basin area in lowland river systems in the Netherlands, compared with data from Hooke (1980) and Lawler (1993); letters refer to the rivers investigated (K, Keersop; T, Tongelreep; D, Dinkel; V, Vecht; IJ, IJssel, W, Waal)

within rivers. Differences between river types can be related to differences in the discharge of water and sediment, channel slope, bank material, and influence of vegetation. Longitudinal differences along a river, however, were mainly associated with changes in the geomorphological setting and associated bank materials. Differences in bank material composition not only induced different fluvial styles but also a different response time following re-meandering of streams. Consequently, the width–depth ratio, which reflects the force-resistance relationships between the channel and its geological environment, is a good predictor of bedform formation. More research on the variables influencing lateral channel change is necessary. For the time being, it is proposed that maximum and mean migration rates are predicted using data on the size of the drainage basin or the bankfull discharge of the rivers in which migration was not hampered (i.e. Tongelreep stream, River Dinkel, River Vecht reaches A and B and River Waal; Fig. 9.2). Time is also an important factor. Landform patterns and migration rates were observed to be related to the time elapsed since the occurrence of a bankfull flow, a meander cutoff or an avulsion. When interpreting geomorphological maps, one should be aware that landform patterns do not always represent an equilibrium situation, but may be adapting to changes that occurred long ago.

RIVER REHABILITATION: AREAS AND DESIGN GUIDANCE

The legitimacy of motives for rehabilitating rivers is supported by the outcomes of this study. (1) The pre-channelisation rivers were characterised by a large diversity of both channel bedforms and floodplain landforms and large differences between river reaches. This diversity has been largely lost since channelisation. (2) The former river environment was a dynamic environment in which landforms and processes adapted readily to new conditions and land was continuously renewed. This certainly contrasts sharply with the present-day channelised rivers. Interest in river rehabilitation generally stems from the fact that these physical changes, among others, have led to a biologically degraded ecosystem. However, the changes observed also justify the rehabilitation of geomorphological processes from an earth-heritage point of view alone, since dynamic processes and their associated landforms have been described as contributing to the quality of the Dutch landscape in general (Wolfert, 1995).

Some guidelines for rehabilitating the morphodynamics of rivers emerge from this study and may help in drawing up cost-effective plans. (1) Work with nature as much as possible (Nunnally and Keller, 1979). This seems to be a plausible option in lowland systems too, since geomorphological change was observed in all rivers whether in a pre-channelisation or post-channelisation state. (2) Create space for geomorphological processes. Most important here is the rehabilitation of entire erosion–transfer–deposition bedform sequences within river reaches, since the upstream supply of sediment was argued to be a prerequisite for the formation of bedforms such as point bars and natural levees. (3) Make targets correspond to the possibilities of river reaches, because potentials of river reaches for the formation of landforms and their time-span of existence differ. This requires the incorporation of the higher levels of organisation of the river system in rehabilitation planning. (4) Commitment to the long term (Kondolf, 1995), because final results of measures cannot be expected to appear before large channel-forming events have occurred and the uniform flow in the present, straightened channel may hamper quick restoration. (5) Historical landform configurations should be treated with care, since channel change in some river reaches was observed to be very slow and so landforms are not easily replaced.

Parts of the river system that are suitable for rehabilitation should preferably be selected according to an understanding of the conditions required for the rehabilitation of geomorphological processes. Suitable river reaches are those where (1) the desired processes are likely to occur, but (2) do not endanger important river functions (e.g. navigation) or properties along the river. Both aspects are related to differences between rivers, river reaches and locations within reaches. These have been described to determine the possibilities for processes, such as bend migration to obtain new floodplain land, for sustainable secondary channels, and for meander cutoffs inducing the formation of natural levees. The presence of intensive navigation or densily built-up areas and associated infrastructure may lead planners to seek other rivers or river reaches. Where rehabilitation of geomorphological processes is hampered by economically important international agreements on the navigability of the large rivers, it might be worthwhile to make a comparison of rivers and direct attention and financial means to smaller river systems in need of rehabilitation. A good example is the River Vecht, which is not used for navigation, but from a geomorphological point of view seems to be very suitable for the rehabilitation of many of its original fluvial dynamics.

The design of river rehabilitation measures can be used as a tool to initiate the desired geomorphological processes and associated formation of bedforms. Three general aspects of design arose from this study. (1) The width–depth ratio of river channels is related to the formation of bedform features such as islands, alternating bars and point bars. This knowledge can be used to initiate a natural evolution of these bedforms, in the main channel or in secondary channels. (2) The ratio of channel curvature to channel width was observed to have a large influence on bend migration. This can be used to obtain higher or lower migration rates along a river. Creation of very tight bends results in very stable bends and at the same time is an effective measure for creating relatively deep pools in a stream. (3) Detailed design of the channel cross-sections or bedforms, such as pools and riffles, is not needed. When appropriate channel dimensions are chosen, i.e. not too large, the flow itself was observed to be capable of forming a natural bed.

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Summary

GENERAL INTRODUCTION (Chapter 1)

The geomorphological variety in landforms and associated processes of erosion, transport and deposition of sediment make rivers diverse and dynamic ecosystems. Many rivers, however, have been embanked, channelised, dammed and diverted, which has resulted in biologically degraded ecosystems. Awareness of the adverse effects of channelisation has led to the initiation of many river rehabilitation projects since the mid 1980s. Rehabilitating the integrity of river systems requires space for geomorphological processes amongst others, but increasing the area designated for nature may have serious impacts on other land use functions, such as navigation, flood control and agriculture. Sustainable solutions, therefore, require an integrated spatial planning process which is based on sound scientific knowledge. Reference situations, conditions to be fulfilled, areas suitable for rehabilitation and the type of measures are addressed. Many geomorphological aspects of the planning process, however, require further development.

In the study of river systems both the theoretical, realist approach, which is concerned with the detailed explanation of causal mechanisms, and the empirical functional-geographical approach, in which research is based on the observation of phenomena with regular relationships, can be adopted. Although these approaches are complementary, the realist approach is well known to river managers, but the functional-geographical is not. To develop the applicability of the functional-geographical approach, two concepts developed in the context of applied river ecological research seem to be promising: a hierarchical framework for habitat classification and the fluvial hydrosystem concept. Typical functional-geographical aspects of these concepts are viewing rivers as four-dimensional systems, and the application of a nested hierarchy of spatio-temporal domains in which the levels are defined as distinct land units. The application of these concepts in the river rehabilitation process has received little attention to date. The purpose of this study is to optimise this application, while emphasising the role of geomorphology.

The study focussed on fluvial environments in the Netherlands for two reasons. First, a realistic background for applied research has been formed by the designation of rivers to a National Ecological Network and second, the rivers in the Netherlands are lowland rivers, on which little knowledge was available to meet the specific demands of water managers in setting up reliable plans. For research purposes the rivers, including the channel and floodplains, have been classified into streams, small rivers and large rivers, of which physiographical characteristics as well as the main water functions are different. Representatives of each group were studied: the Tongelreep, Keersop and Aa representing streams, the rivers Dinkel and Overijsselse Vecht representing small rivers, and the rivers Waal, IJssel and Neder-Rijn / Lek representing large rivers.

The specific objectives of this thesis are to: (1) recommend procedures to implement the functional-geographical approach in the river rehabilitation planning process, (2) describe and explain the ecologically relevant landform configurations and related sediments in the various types of river systems, and their variability in space and time, (3) detect the role of the various variables influencing the fluvial processes related to the formation of landforms, and their significance to management, (4) identify areas where rehabilitation of geomorphological processes and subsequent formation of landforms is likely to be successful, and the associated spatial requirements, (5) provide design guidance for effective rehabilitation measures. The methodological aspects are dealt with in Chapter 2 and applied in the chapters 3 to 8. Each type of river is investigated in two case studies that examine the study objectives listed above. A synthesis is provided in Chapter 9.

FUNCTIONAL-GEOGRAPHICAL APPROACH (Chapter 2)

From a water management perspective, scientific information supporting the decision-making process should meet the user requirements that information must cover entire plan areas, can be linked to research in other disciplines, should be related to rehabilitation measures, and must be gathered efficiently. Gathering this type of information has a long tradition in land evaluation studies for rural land use planning. To optimise the application of the functional-geographical approach in river rehabilitation planning, methods of land evaluation applied successfully in spatial planning processes are linked to the hierarchical framework for habitat classification and the fluvial hydrosystem concept.

A land resource inventory using a system of classification of land and water units and a top-down methodology, is advocated for use in the spatial planning process because the planner is concerned with the designation of areas. In the classification of land units in the dynamic river system, the topological interactions between the abiotic and biotic components of land units can be viewed as a simple model of hierarchical influence, in which the landform is the central and most meaningful subsystem. Consequently, geomorphological maps are especially recommended as planning tools. They provide information on patterns and processes and provide a basis for integrating information from other disciplines.

A means to provide information attuned to the mission, legal powers and land under the responsibility of the organisations involved in water management is to address the appropriate spatio-temporal domain in the hierarchy used to describe the river system. Here, a process-functional hierarchy is proposed for use in river rehabilitation studies. The levels of this hierarchy can be detected in all types of river systems and form a consistent nested hierarchy related to specific variables. The levels are: (1) the river domain, composed of a characteristic set of river reaches, (2) the river reach domain, characterised by recurring patterns of macro bedforms, and (3) the river macroform domain, showing superimposed small-scale bedform patterns. The river reach domain should be emphasised in river rehabilitation studies as this level is central to rehabilitation planners. River reaches and their characteristics require a long period to develop and so historical studies are considered very relevant.

AQUATIC MACROPHYTE GROWTH AND SEASONAL BEDFORM PATTERN CHANGES IN A LOWLAND SAND-BED MEANDERING STREAM (Chapter 3)

The interactions between macro, meso and micro bedforms, seasonal variations in discharge and aquatic vegetation cover in the Keersop stream were studied to obtain a post-channelisation reference situation for small sand-bed meandering streams. A two-bend reach of the Keersop was studied by means of detailed geomorphological mapping and cross-sectional surveys in March, July and November, for a period of three years following re-meandering.

Macroforms (pools, erosional channels, point bars and platforms) were related to the flow paths of the two pairs of alternating helical flow cells. The development of mesoforms (chute channels, obstacle bars, chute bars) was related to the obstruction of flow by the submerged species *Elodea spp.* and *Callitriche spp.* Microforms (sand ripples) occurred superposed on both these groups. Establishment of submerged macrophytes was inhibited in pools because of attenuation of light and in erosional channels because of permanently high flow velocities. Maximum coverage of the stream bed by macrophytes was 47%. An expanding cover was associated with an increase in the area of gravel lags and exposed peat layers in between solitary plant stems. A high density of plants induced the deposition of silts and particulate organic matter.

A cyclical sequence of events is envisaged. In winter, when macrophyte cover is relatively small, large discharge events activate the macroforms. Since stream banks are stable, point bars along convex banks are eroded while chute channels at crossovers were filled with sand. In summer, smaller discharges and expansion of plant cover led to the formation of mesoforms, whereas the sand eroded from chute channels was used to restore the point-bar surface. Thus, point bars and mesoforms are the main sediment storage features and sediment is exchanged between them. This model of seasonal change is considered useful in both the design and evaluation of meander rehabilitation strategies.

CHANNEL AND BEDFORM RESPONSE TO MEANDER REHABILITATION IN LOWLAND SAND-BED STREAMS (Chapter 4)

The short-term impact of artificial re-creation of a meandering channel in the Tongelreep, Keersop and Aa streams is investigated to provide answers to questions of allocation and design often posed in this context. The geomorphological responses were studied in two-bend reaches by means of cross-sectional surveys and detailed geomorphological mapping in March, July and November, during a period of 2 to 3 years.

Bedform adjustments in the Tongelreep and Keersop included local scouring of pools, undercutting of banks, coarsening of bed material and the formation of depositional bedforms. Initial responses led to a strong increase in the diversity of bedforms and associated bedform materials. The largest sediment production rates, however, were associated with the first bankfull discharge event. Differences in bank materials had a major influence on rates of bank failure and consequently on the amount of sediments stored in the channel. Both the balance between sediment input and output and a bedform configuration similar to that of natural sand-bed rivers were restored in the Keersop, but not yet in the Tongelreep. This difference was caused by the greater stability of the banks of the Keersop. The application of various cross-section types and the excavation of a by-pass channel had no effect, but channel migration rates decreased and the depth of pools increased with an increasing ratio of radius of bend curvature to channel width, due to a different flow pattern. The response in the Aa was almost nil because of oversized cross-sectional dimensions.

The increase in diversity of bedforms in the Tongelreep and Keersop was expected to enhance the stream habitat function, but an associated increase in macroinvertebrate species richness could not be demonstrated, probably because this takes longer to occur. These results underpin the notion that this type of monitoring is important for arriving at effective strategies for river rehabilitation.

THE FORMATION OF NATURAL LEVEES AS A DISTURBANCE PROCESS SIGNIFICANT TO THE CONSERVATION OF RIVERINE PASTURES (Chapter 5)

The influence of natural levee overbank deposition on riverine grasslands along the small river Dinkel was examined to provide a conservation strategy based on geomorphological disturbance processes. Here, the rare vegetation type *Diantho-Armerietum*, characterised by *Dianthus deltoides*, *Thymus pulegioides*, *Pimpinella saxifraga* and *Galium verum*, has been identified as important to nature conservation.

Diantho-Armerietum shows a strong preference for dry, nutrient-poor, sandy and relatively young soils, with an elevation approximately 30–50 cm above bankfull discharge level, corresponding to a flooding frequency of 2 to 3 times per year. The lower zones are strongly influenced by nutrient-rich water, whereas the higher zones are vulnerable to soil acidification. In the intermediate zone, soil development may be reset due to the supply of calcium, adsorbed to recently deposited levee sands.

Since deposition rates will decrease with increasing levee heights, new levees are regularly needed to stop the decline of this floriferous vegetation type. The formation of new natural levees is favoured by the occurrence of meander cutoffs, causing a cyclic succession of landforms along the river. Therefore, a conservation strategy for this vegetation type needs to aim at the rehabilitation of the natural levee disturbance process, in conjunction with encouraging the meandering of the river.

ARIABILITY IN MEANDERING OF A LOWLAND RIVER CONTROLLED BY BANK COMPOSITION (Chapter 6)

The morphodynamics of the lower River Vecht prior to channelisation and the influence of geomorphological setting and bank composition on meander migration was studied to identify relevant variables for selecting areas for re-meandering. River dynamics were studied by means of reconstructing the pre-channelisation landform configuration on a scale of 1:25,000, using historical maps from 1720, 1850 and 1890 and other data.

A downstream sequence of reaches was observed, each with a typical fluvial style and channel migration rate: (A) a narrow meander belt and a highly sinuous channel with intermediate migration rate, in the middle of an extensive floodbasin, (B) a wide meander belt and high rates of lateral channel migration, especially where large meanders impinged upon valley bluffs, as part of an incised setting, (C) a low sinuosity, embanked channel with low rates of downstream migration confined by dikes, occurring in an inland delta with sandy sediments. Local variation was observed within reach B.

Different migration rates were caused by the spatial variability of bank resistance as reflected by the width–depth ratio of the channel and the silt–clay ratios of deposits. River banks are: (1) very erodible when composed of channel deposits, aeolian dune deposits or when coarse fluvio-periglacial deposits occur at their base, (2) erodible when dominated by overbank deposits or aeolian sand sheet deposits, (3) resistant when a plaggen layer is exposed, and (4) very resistant when dominated by floodbasin deposits. These implications of meander variability have been used to select locations suitable for a meander rehabilitation experiment.

EMBANKED RIVER REACHES IN THE RIVER RHINE DEPOSITIONAL ZONE – I. HISTORICAL GEOMORPHOLOGY (Chapter 7)

Historical developments of the large River Rhine distributaries were analysed to describe a pre-channelisation reference situation, emphasising downstream changes in channel-floodplain interactions in embanked, sand-bed lowland rivers. In three river reaches, representative of the Rhine depositional zone, the pre-channelisation geomorphology was studied by means of analysing 16th–19th century historical maps. Landforms were mapped on a scale of 1:25,000 and width–depth ratio, Shields parameter, flow velocity and the frequency of water level exceedance were calculated.

Landforms were the result of island formation, point-bar formation and overbank deposition. However, the three river reaches showed consistent differences in configuration, development and hydrogeomorphological parameter values. Developments have been summarised in a conceptual model of landform succession and floodplain renewal. Width–depth ratio values may be regarded as a predictor of the initial phase of the succession, i.e. whether or not islands and secondary channels, (high or low) point bars and sloughs or, eventually, scroll bars and swales will be formed.

Flow velocity over the floodplain during inundation has been proposed as a predictor of the evolution of sloughs and abandoned channels into floodplain flats.

Four types of fluvial styles have been distinguished, of which three occurred in a continuum of river reaches, typical of active distributaries. Central in this sequence is a confined, low-sinuosity, downstream migrating style, which is the result of embankment in this lowland fluvial environment. Upstream, a high-sinuosity, laterally migrating meandering style could persist after embankment, due to a thinner cover of Holocene flood basin deposits on erosive Pleistocene channel deposits. Downstream, a low-gradient, tidal island river style predominates, associated with a lack of bed-load transport capacity and stable banks in marine clays. A passively meandering style is the result of a decrease in transport capacity related to channel avulsion.

EMBANKED RIVER REACHES IN THE RIVER RHINE DEPOSITIONAL ZONE – II. REHABILITATION PLANNING (Chapter 8)

To incorporate geomorphological expertise into river rehabilitation, a cyclical planning procedure has been used as a framework in which stages of plan design and plan evaluation follow each other several times. The role of research in supporting planners in these stages is elaborated in two case studies on the embanked River Rhine depositional zone.

In the first case, covering a major part of this zone, river rehabilitation priorities were derived from historical reference situations, and the suitability of river reaches for the associated geomorphological processes was examined. Measures are required that trigger or mimic the original dynamics of the river system, such as the creation of secondary channels to rehabilitate former shallow channel habitat dynamics, and the lowering of the floodplain surface to reconnect the river's channel and floodplain again.

This information was applied in the second case, dealing with the landscape of the smaller Gelderse Poort area. Inspired by the differences between river reaches, two land use scenarios could be formulated with different ecological objectives, management types and spatial strategies. Insight into the varying impacts of fluvial processes was an aid in the examination of the compatibility of rehabilitation targets and the other river and land use functions and resulted in spatial layout proposals. The feasibility of measures and the effects on vegetation and fauna species were evaluated using the landscape ecological LEDESS model. During the planning process, research activities gradually changed from monodisciplinary to interdisciplinary.

The results demonstrate that at least two scale levels should be investigated to attain a realistic plan. They also draw attention to the following: (1) the geomorphology of the river system has degraded throughout the last century, (2) contemporary river reaches still vary dramatically in both landform patterns and processes, and (3) a geomorphological analysis can help in setting realistic goals for rehabilitation.

GENERAL DISCUSSION AND CONCLUSIONS (Chapter 9)

Procedures for applying the functional-geographical approach in river rehabilitation were optimised by linking existing functional-geographical concepts in river ecology to methods of land evaluation applied successfully in spatial planning. In the various case studies information could be provided on historical and contemporaneous reference situations and on associated process conditions. Based on this knowledge, information could be provided on areas suitable for rehabilitation and the spatial requirements and on the design of measures. Combining these procedures with methods originating from the realist approach in geomorphology strengthened the predictive power of research and is considered the best way forward. Geomorphological maps were emphasised as a tool in the land resources inventory to aid the identification of spatial and temporal variability of the fluvial environment and to detect causes and relatively unknown relationships. Maps, therefore, contributed to the general understanding of river functioning. Due to the focus on the domains of river reaches characterised by macro bedforms, geomorphological data could be derived relatively quickly and at low costs from existing map information and other data. Besides, at this level data could be linked to hydromorphological and biological data, facilitating an integrated planning process. These benefits of the functional-geographical approach, however, depend on the detail of available information.

Reference situations for streams, small rivers and large rivers in the Netherlands have been described. Three main types of fluvial styles have been observed to occur in non-channelised situations, each characterised by a specific landform configuration and occurring in specific positions within the river system. Meandering streams with in-stream bedforms mainly occur in small upstream valleys. In larger, alluvial valleys high-sinuosity meandering rivers occur with laterally migrating channels. Low-sinuosity meandering rivers with a downstream mode of channel migration occur in the most downstream, embanked parts of rivers. These fluvial styles could be described by a relatively small set of landform types, thus stressing the universal nature of fluvial processes. Comparison of data on channel migration rates shows that when channel migration is not hampered by resistant bank materials or decreased flow capacity, rates increase with increasing size of the rivers. In spite of their lowland setting, channel migration rates are of the same order of magnitude as those observed in natural rivers elsewhere.

Conditions relevant for the development of the various fluvial styles are related to differences in water discharge, supplied sediment, channel slope, bank material and in-stream vegetation growth. Longitudinal differences along a river, however, were mainly associated with changes in geomorphological setting and associated bank material composition. Consequently, the width–depth ratio, which reflects the force-resistance relationships between the channel and its environment, is considered a good predictor of bedform formation. More research on the variables influencing lateral channel change is necessary. For the time being, migration rates may be predicted using data on the size of the drainage basin or the bankfull discharge.

Some guidelines for river rehabilitation emerge from the above and may help in developing cost-effective plans. It is recommended to work with nature as much as possible, to give room to the processes involved, to ensure that rehabilitation targets correspond to potentials of river reaches, to commit to the long term, and to treat historical landform configurations with care. The selection of parts of the river system that are suitable for rehabilitation should preferably be guided by an understanding of conditions to be fulfilled for the rehabilitation of geomorphological processes. Therefore, the differences between rivers, between river reaches and between locations within reaches should be considered in every rehabilitation project. Where economically important river functions hamper rehabilitation of processes, it might be worthwhile directing attention and financial means to smaller river systems. Accordingly, rehabilitation of the River Vecht should be prioritised.

Three general aspects of design arose from this study. Both the width–depth ratio and the channel curvature can be used to influence the development of a variety of natural bedforms and bend migration. Choosing appropriate channel dimensions enables the river itself to form a natural bed, making detailed channel design unnecessary.

Samenvatting (summary in Dutch)

Geomorfologische dynamiek en rivierherstel: onderzoek in Nederlandse laaglandriviersystemen

ALGEMENE INLEIDING (hoofdstuk 1)

De geomorfologische variatie in terreinvormen en onderliggende processen van erosie, transport en afzetting van sediment brengen met zich mee dat rivieren dynamische ecosystemen zijn met een hoge biodiversiteit. Veel rivieren, echter, zijn bedijkt, gekanaliseerd, afgedamd of verlegd, wat heeft geleid tot in biologisch opzicht sterk gedegradeerde ecosystemen. Bewustwording van deze effecten werd vanaf het midden van de jaren tachtig gevolgd door vele rivierherstelprojecten. Rivierherstel vraagt om ruimte, onder andere voor geomorfologische processen, maar een toename van dynamiek en van natuurlijk terrein kan ernstige gevolgen hebben voor andere gebruiksfuncties zoals scheepvaart, waterberging en landbouw. Duurzame oplossingen vereisen dan ook een integrale ruimtelijke planning, ondersteund door deugdelijke wetenschappelijke inzichten. Het gaat daarbij om referentiebeelden, voorwaarden aan processen, kansrijke gebieden en het ontwerp van maatregelen. Veel geomorfologische aspecten van het planproces vragen echter nader onderzoek.

In het onderzoek naar riviersystemen kan, naast de zogenaamde realistische benadering die zich richt op de theoretische en gedetailleerde verklaring van oorzakelijke verbanden, de meer proefondervindelijke functioneel-geografische benadering gevolgd worden waarin onderzoek gebaseerd is op de waarneming van verschijnselen en hun onderlinge samenhang. Alhoewel deze benaderingen elkaar aanvullen, is de realistische benadering goed bekend bij rivierbeheerders, maar de functioneel-geografische niet. Voor het verbeteren van de toepassingmogelijkheden van de functioneel-geografische benadering zijn twee concepten, ontwikkeld zijn in toegepast rivierecologisch onderzoek, veelbelovend: een hiërarchisch raamwerk voor habitat classificatie en het concept van fluviatiele hydrosystemen. Typisch functioneel-geografische aspecten van deze concepten zijn het beschouwen van een rivier als systeem met vier dimensies en de toepassing van een geneste hiërachie van ruimte-tijdschalen, waarin de onderscheiden niveaus gedefinieerd zijn als concrete terreineenheden. De concepten zijn nog maar weinig toegepast in het rivierherstel. Het is de bedoeling van dit onderzoek deze toepassing te verbeteren, terwijl daarbij de rol van de geomorfologie benadrukt wordt.

Het onderzoek richtte zich op fluviatiele systemen in Nederland. Dat had twee redenen. Een realistische achtergrond voor toegepast onderzoek ontstond door de opname van alle beken en rivieren in de Ecologische Hoofd Structuur van Nederland. Daarnaast bleek dat er over de laaglandrivieren in Nederland niet genoeg kennis aanwezig was om de specifieke vragen van waterbeheerders te beantwoorden. Voor het onderzoek zijn de rivieren, waartoe zowel het zomerbed als het winterbed gerekend wordt, onderverdeeld in beken, kleine rivieren en grote rivieren. Deze typen verschillen in geomorfologische eigenschappen en gebruiksfuncties. Vertegenwoordigers van elke groep zijn onderzocht, te weten de beken de Tongelreep, de Keersop en de Aa, de kleine rivieren de Dinkel en de Overijsselse Vecht en de grote rivieren de Waal, de IJssel en de Neder-Rijn / Lek.

Doelen van het onderzoek zijn om: (1) procedures aan te bevelen voor de toepassing van de functioneel-geografische benadering in de ruimtelijke planning voor rivierherstel, (2) ecologisch relevante patronen van terreinvormen en bijbehorende sedimenten in de verschillende riviertypen te beschrijven, alsmede de variatie in ruimte en tijd, (3) de rol van factoren die invloed hebben op geomorfologische processen vast te stellen en hun betekenis voor het rivierbeheer, (4) gebieden aan te wijzen die kansrijk zijn voor rivierherstel, alsook het benodigde ruimtebeslag, en (5) aanbevelingen voor ontwerp van herstelmaatregelen te geven. De methodologische aspecten worden behandeld in hoofdstuk 2, en toegepast in de volgende zes hoofdstukken waarin voor elk type rivier de overige doelstellingen in twee hoofdstukken aan de orde komen. Een synthese volgt in hoofdstuk 9.

DE FUNCTIONEEL-GEOGRAFISCHE BENADERING (hoofdstuk 2)

Vanuit het perspectief van het waterbeheer moet wetenschappelijke informatie voldoen aan een aantal vereisten om beslissingen in de ruimtelijke planvorming te kunnen ondersteunen. Informatie moet gehele gebieden omvatten, moet gekoppeld kunnen worden aan informatie van andere disciplines, moet gerelateerd zijn aan herstelmaatregelen en moet efficiënt verzameld worden. In de landevaluatie heeft men vanouds veel ervaring met het verkrijgen van dergelijke informatie voor landelijke gebieden. Om het gebruik van de functioneel-geografische benadering verder te brengen, worden methoden van landevaluatie die met succes zijn toegepast in de ruimtelijke planvorming dan ook gekoppeld aan het bovengenoemde hiërarchisch raamwerk voor habitat classificatie en het concept van fluviatiele hydrosystemen.

Een inventarisatie van natuurlijke hulpbronnen die gebruikt maakt van een classificatie van landeenheden volgens een top-down methode wordt aanbevolen voor gebruik in de ruimtelijke planvorming, omdat de planner zich bezig houdt met de bestemming van gebieden. Bij de classificatie van landeenheden in het dynamische riviersysteem kunnen de topologische interacties tussen abiotische en biotische landschapscomponenten gevat worden in een eenvoudig model van hiërarchische invloed, waarin de terreinvorm de meest centrale component is en de meeste betekenis heeft. Geomorfologische kaarten worden daarom aanbevolen als instrument voor de planning. Deze kaarten geven informatie over geomorfologische patronen en processes en voorzien in een basis voor de integratie van informatie van andere disciplines.

Een manier om informatie te verschaffen die is afgestemd op de missie, de juridische mogelijkheden en het gebied onder de verantwoordelijkheid van organisaties die betrokken zijn bij het waterbeheer, is om precies het goede ruimte-tijd niveau aan te spreken in de hiërarchie die gebruikt wordt om het riviersysteem te beschrijven. Hier wordt voorgesteld een hiërarchie te gebruiken die gebaseerd is op de werking van processen, en waarvan de niveaus een consistente, geneste hiërarchie vormen en gerelateerd zijn aan specifieke variabelen. De niveau's zijn: (1) het domein van de rivier, dat bestaat uit een aaneenschakeling van riviertrajecten, (2) het domein van het riviertraject, dat zich kenmerkt door zich herhalende patronen van grootschalige beddingvormen, en (3) het domein van de grootschalige beddingvorm waarop kleinschalige beddingvormen voorkomen. Het domein van het riviertrajecten dient benadrukt te worden in onderzoek voor rivierherstel, omdat dit niveau zich precies in de invloedsfeer van planners bevindt. De ontwikkeling van riviertrajecten en hun kenmerken duurt lange tijd, wat historisch onderzoek relevant maakt.

AQUATISCHE VEGETATIE EN JAARLIJKSE VERANDERINGEN VAN BEDDINGVORMEN IN EEN MEANDERENDE LAAGLANDBEEK MET EEN ZANDBEDDING (hoofdstuk 3)

De interactie tussen macro,- meso- en microvormen in de bedding, de jaarlijkse variatie in afvoer van water en het voorkomen van waterplanten in de Keersop zijn bestudeerd om een referentie te verkrijgen van een meanderende beek met een zandbedding. Twee aaneensluitende bochten zijn bestudeerd door het maken van gedetailleerde geomorfologische kaarten en opnames van het dwarsprofiel van de beek, in maart, juli en november gedurende een periode van drie jaar na hermeandering.

Macrovormen in de bedding (poelen, grote geulen, grote zandbanken langs de binnenbocht en terrassen) hangen samen met het patroon van twee alternerende paren helicoïdale stromingscellen. De ontwikkeling van mesovormen (kleine geulen en kleine banken) werd veroorzaakt door het voorkomen van de ondergedoken soorten *Elodea spp.* en *Callitriche spp.*, die de waterstroming belemmeren. Microvormen (zandribbels) komen op beide andere groepen voor. Vestiging van ondergedoken planten bleek niet mogelijk in de poelen, vanwege gebrek aan licht, en niet in grote geulen, doordat de stroomsnelheid voortdurend te hoog was. De maximale bedekking van de bedding door waterplanten was 47%. Tegelijkertijd met de uitbreiding van planten was er een toename van grind en blootgespoeld veen door erosie tussen de afzonderlijk stengels. Een hoge dichtheid van waterplanten veroorzaakte echter afzetting van silt en organisch materiaal.

De ontwikkelingen vertonen een jaarlijkse cyclus. In de winter, wanneer de bedekking door waterplanten beperkt is, worden de macrovormen door grote afvoergolven geactiveerd. Omdat de oevers stabiel zijn, treedt erosie op van zandbanken langs de binnenbocht, terwijl de kleine geulen tussen de bochten opgevuld worden met zand. In de zomer leiden een kleinere afvoer en uitbreidende bedekking door waterplanten juist tot de vorming van mesovormen: het zand dat vrijkomt bij de erosie van de kleine geulen wordt gebruikt om de grote zandbank langs de binnenbocht weer op te bouwen. De kleine en grote zandbanken zijn dus de belangrijkste opslagplaatsen van zand en wisselen onderling zand uit. Kennis van deze jaarlijkse ontwikkelingen is bruikbaar bij het ontwerp en de evaluatie van hermeandering.

HET EFFECT VAN HERMEANDERING OP DE LOOP EN DE BEDDINGVORMEN VAN LAAGLANDBEKEN MET EEN ZANDBEDDING (hoofdstuk 4)

Het effect op de korte termijn van kustmatige hermeandering van de Tongelreep, de Keersop en de Aa is onderzocht om een antwoord te krijgen op veel gestelde vragen over locatiekeuze en ontwerp van hermeanderingsprojecten. De geomorfologische effecten zijn bestudeerd door het meten van dwarsprofielen en het maken van gedetailleerde geomorfologische kaarten in twee aaneengesloten bochten, in maart, juli en november, gedurende een periode van twee of drie jaar na hermeandering.

De effecten in de Tongelreep en de Keersop omvatten de plaatselijke erosie van poelen, de ondergraving van oevers, het grover worden van beddingmateriaal en de vorming van beddingvormen door afzetting. Met name direct na oplevering onstond er al snel een grote variatie aan beddingvormen en daarbij behorende substraten. De grootste sedimentproductie vond echter pas plaats tijdens de eerste afvoergolf van maatgevende omvang. Verschillen in oevermateriaal hadden een grote invloed op de mate van oeverafkalving en dus op de hoeveelheid sediment die werd opgeslagen in de bedding. In de Keersop werden zowel de balans tussen sedimentaanvoer en -afvoer als een voor meanderende beken met een zandbedding natuurlijk patroon van beddingvormen hersteld. In de Tongelreep was dat niet het geval vanwege een grotere instabiliteit van de oevers. Effecten van het graven van verschillende dwarsprofielen en een overloopgeul zijn niet waargenomen. Daarentegen ging een scherpere bochtstraal, door een ander stromingspatroon, gepaard met een kleinere migratie van de buitenbocht en de vorming van diepere poelen. Het effect van hermeandering in de Aa was verwaarloosbaar vanwege de te grote dimensionering van het dwarsprofiel.

Alhoewel verwacht werd dat een toename van de variatie aan beddingvormen in de Tongelreep en de Keersop zou leiden tot een verbeterd beekhabitat, kon een toename van het aantal soorten macro-invertebraten niet worden aangetoond. Waarschijnlijk omdat hiervoor meer tijd nodig is. De resultaten van het onderzoek onderstrepen de noodzaak van dit type monitoring om tot effectieve strategieën voor beekherstel te komen.

DE VORMING VAN OEVERWALLEN ALS EEN BELANGRIJK VERSTORINGSPROCES VOOR HET BEHOUD VAN STROOMDALGRASLANDEN (hoofdstuk 5)

De invloed van oeverwalvorming op stroomdalgraslanden langs het riviertje de Dinkel is onderzocht ten behoeve van een natuurbehoudsstrategie, die gebaseerd is op natuurlijke, geomorfologische verstoringsprocessen. Het vegetatietype Diantho-Armerietum kenmerkt zich door de soorten *Dianthus deltoides*, *Thymus pulegioides*, *Pimpinella saxifraga* and *Galium verum***,** is zeldzaam geworden en dientengevolge een belangrijk doeltype in het natuurbeheer.

Diantho-Armerietum heeft een sterke voorkeur voor droge, nutriënt arme en relatief jonge bodems, die gelegen zijn op een hoogte van ongeveer 30-50 cm boven het waterpeil van de maatgevende afvoer, wat overeenkomt met een overstromings-frequentie van 2 tot 3 keer per jaar. Lager gelegen zones worden sterk beïnvloed door nutriëntrijk water, terwijl hoger gelegen zones gevoelig zijn voor verzuring. De bodemontwikkeling kan in de tussenliggende zone teruggezet worden door de aanvoer van calcium, dat geadsorbeerd is aan het zandige sediment van de oeverwallen.

Aangezien de afzetting van zand afneemt naarmate de oeverwallen hoger worden, zijn nieuwe oeverwallen nodig om het verval van dit bloemrijke vegetatietype tegen te gaan. Nieuwvorming van oeverwallen wordt vooral bewerkstelligd door meanderafsnijdingen, die een cyclische opeenvolging van terreinvormen langs de Dinkel met zich mee brengen. In de strategie voor het behoud van deze stroomdalgraslanden dient dus aandacht geschonken te worden aan het herstel van het proces van oeverafzetting, en tegelijkertijd aan het herstel van het proces van meanderen.

VARIATIE IN MEANDERGEDRAG VAN EEN LAAGLANDRIVIER DOOR VERSCHILLEN IN OEVERMATERIAAL (hoofdstuk 6)

De geomorfologische dynamiek van de Overijsselse Vecht, en met name de invloed van het geomorfologische landschap en de samenstelling van de oevers op de meandering vòòr de kanalisatie, zijn onderzocht om variabelen te identificeren op basis waarvan gebieden geselecteerd kunnen worden die geschikt zijn voor hermeandering. De rivierdynamiek is bestudeerd door middel van een reconstructie van de geomorfologische gesteldheid voor de kanalisatie op een schaal van 1 : 25.000, met behulp van historische kaarten uit 1720, 1850 en 1890 en andere gegevens.

Van bovenstrooms naar benedenstrooms werd een opeenvolging van riviertrajecten waargenomen, elk met een eigen rivierpatroon en migratiesnelheid van het zomerbed: (A) een smalle meandergordel met een sterk kronkelende geul en een gemiddelde migratiesnelheid, temidden van een uitgestrekte overstromingsvlakte, (B) een brede meandergordel en hoge migratiesnelheden, in het bijzonder waar grote meanders opbotsten tegen dalwanden, waar de rivier door een dal stroomt, en (C) een zwak kronkelende rivier, met een langzame en stroomafwaarts gerichte migratie, voorkomend in een binnendelta die bestaat uit zandige sedimenten.

Verschillen in migratiesnelheid werden veroorzaakt door de ruimtelijke variatie in stevigheid van de oevers, hetgeen weerspiegeld werd door de breedte–diepte verhouding van het zomerbed en de silt–klei verhouding van afzettingen. Oevers zijn: (1) zeer erosiegevoelig wanneer ze bestaan uit geulafzettingen, eolische duinafzettingen of wanneer de onderzijde bestaat uit grove fluvio-periglaciale afzettingen, (2) erosiegevoelig wanneer ze hoofdzakelijk bestaan uit oeverafzettingen of lemige dekzanden, (3) erosieresistent wanneer een plaggenbodem is blootgespoeld, en (4) zeer erosieresistent wanneer ze hoofdzakelijk bestaan uit komkleien. Deze bevindingen zijn gebruikt om locaties te selecteren die geschikt zijn voor een experiment met hermeandering.

BEDIJKTE RIVIERTRAJECTEN IN THE DEPOSITIEZONE VAN DE RIJN – I. HISTORISCHE GEOMORFOLOGIE (hoofdstuk 7)

De historische ontwikkeling van de Rijntakken is onderzocht om een referentie te beschijven van de situatie voor de normalisatie. Daarbij lag de nadruk op stroomafwaartse veranderingen in de interacties tussen het zomerbed en de uiterwaard in bedijkte laaglandrivieren met een zandige bedding. In drie riviertrajecten die representatief zijn voor de depositiezone van de Rijn, is de geomorfologische gesteldheid van voor de normalisatie bestudeerd door analyse van kaarten uit de 16^{e} tot en met de 19^{e} eeuw. Terreinvormen werden gekarteerd op schaal 1 : 25.000 en de breedte–diepte verhouding, de Shields parameter, de stroomsnelheid en de overschrijdingsduur van waterstanden werden berekend.

Terreinvormen waren het resultaat van de vorming van kronkelwaarden en oeverafzetting. De drie riviertrajecten vertoonden echter verschillen in patroon, in ontwikkeling en in waarden van de hydrogeomorfologische parameters. De ontwikkelingen zijn samengevat in een conceptueel model van de successie van terreinvormen en vernieuwing van uiterwaarden. Met behulp van de breedte-diepte verhouding kan de initiële fase van de successie voorspeld worden: dat wil zeggen of er wel of niet eilanden en nevengeulen, (hoge of lage) kronkelwaardbanken en strangen of, uiteindelijk, kronkelwaardrelief zal ontstaan. De stroomsnelheid van het water in ondergelopen uiterwaarden lijkt gebruikt te kunnen worden om de successie van open strangen, naar afgesloten strangen en vervolgens naar uiterwaardvlakten te kunnen voorspellen.

Vier typen rivierpatronen konden onderscheiden worden, waarvan er drie een continuüm vormen dat kenmerkend is voor actieve riviertakken. Centraal in deze sequentie staat de zwak kronkelende, in benedenstroomse richting migrerende rivier, die het resultaat is van bedijking in dit laagland. Bovenstrooms daarvan kon een sterk kronkelende, zijwaarts migrerende rivier zich na de bedijking handhaven, doordat de laag van holocene komkleien die zijn afgezet op de erosiegevoelige pleistocene zanden hier dunner is. Benedenstrooms daarvan komt een getijdenrivier met eilanden en een zeer klein verhang voor. Het vierde type, de passief meanderende rivier, is het gevolg van een afname van de transportcapaciteit die samenhangt met het proces van stroomgordelverlegging.

BEDIJKTE RIVIERTRAJECTEN IN DE DEPOSITIEZONE VAN DE RIJN – II. RIVIERHERSTEL (hoofdstuk 8)

Om geomorfologische kennis te betrekken bij rivierherstel, kan gebruik gemaakt worden van een cyclisch planproces waarin fasen van ontwerp en toetsing elkaar opvolgen. De wijze waarop onderzoek planners in deze fasen kan ondersteunen is uitgewerkt in twee studies over de bedijkte rivieren in de depositiezone van de Rijn.

In de eerste studie, die betrekking had op een groot deel van de depositiezone van de Rijn, zijn in de ontwerpfase prioriteiten voor rivierherstel afgeleid uit historische referenties, en is vervolgens de kansrijkdom van riviertrajecten voor geomorfologische processen getoetst. Maatregelen zijn nodig die de oorspronkelijke rivierdynamiek weer op gang brengen of nabootsen. Voorbeelden zijn het creëren van nevengeulen voor het herstel van habitats van de vroegere ondiepe delen van het zomerbed, en het afgraven van de uiterwaard om de samenhang tussen rivier en uiterwaard te herstellen.

Deze informatie is toegepast in de tweede studie, betreffende een kleiner gebied: de Gelderse Poort. Geïnspireerd door de verschillen tussen riviertrajecten, werden twee landgebruiksscenario's geformuleerd, elk met een eigen ecologisch doel, beheerstype en ruimtelijke strategie. Inzicht in de gevolgen van fluviatiele processen kon gebruikt worden in de verkenning van mogelijkheden van multifunctioneel ruimtegebruik, en resulteerde in twee voorstellen voor een ruimtelijk plan. De haalbaarheid van maatregelen en de effecten daarvan op de vegetatie en diersoorten werd getoetst met het landschapsecologische model LEDESS. Tijdens het planproces veranderde het onderzoek geleidelijk van monodisciplinair naar interdisciplinair.

De resultaten laten zien dat uit de hiërarchie die gebruikt wordt om riviersystemen te beschrijven, tenminste twee niveaus bij het onderzoek betrokken moeten worden om realistische plannen te verkrijgen. Tevens wordt de aandacht erop gevestigd dat: (1) de geomorfologische gesteldheid van het riviersysteem de laatste eeuw sterk is achteruitgegaan; (2) de hedendaagse riviertrajecten nog aanmerkelijk van elkaar verschillen in geomorfologische gesteldheid en dynamiek, en (3) een geomorfologisch onderzoek kan bijdragen aan het formuleren van realistische doelen voor rivierherstel.

ALGEMENE DISCUSSIE EN CONCLUSIES (hoofdstuk 9)

De procedures voor de toepassing van de functioneel-geografische benadering in het onderzoek voor rivierherstel zijn verbeterd door bestaande functioneel-geografische concepten uit de rivierecologie te koppelen aan methoden van landevaluatie die met succes in de ruimtelijke planning zijn toegepast. In de verschillende deelstudies kon zodoende informatie verkregen worden over historische en hedendaagse referenties en de randvoorwaarden voor de ontwikkeling daarvan. Met deze kennis ontstond inzicht in de gebieden die kansrijk zijn voor herstel, in de hoeveelheid ruimte daarvoor nodig is, en in de aard van maatregelen. Combinatie van deze procedures met methoden die voortkomen uit de realistische benadering in het onderzoek, vergrootten de voorspellende kracht van het onderzoek en wordt gezien als de beste manier voor verdere ontwikkeling. Geomorfologische kaarten werden benadrukt als hèt hulpmiddel in de landinventarisatie om de ruimtelijke en temporele variatie in riviersystemen te beschrijven en nog relatief onbekende oorzakelijke verbanden te ontdekken. De kaarten droegen bij aan een beter begrip van het rivier systeem. Door te concentreren op het domein van het riviertraject, dat zich kenmerkt door zich herhalende patronen van grootschalige beddingvormen, konden gegevens relatief snel en tegen lage kosten verkregen worden uit bestaande kaarten en andere bronnen. Bovendien konden juist op dit niveau gegevens makkelijk gekoppeld worden aan hydrogeomorfologische en biologische gegevens, hetgeen de integratie in het planproces ten goede kwam. Deze voordelen van de functioneel-geografische benadering hangen echter af van de mate van detail van de beschikbare informatie.

Referenties voor beken, kleine rivieren en grote rivieren in Nederland zijn beschreven. Vòòr de normalisaties kwamen drie hoofdtypen van rivierpatronen voor, elk op een specifieke locatie binnen het riviersysteem en met een kenmerkend patroon van terreinvormen. De bovenlopen van beeksystemen waren kleine meanderende beken waarin vorming van fluviatiele terreinvormen beperkt bleef tot de beekloop zelf. In grotere beekdalen kwamen sterk kronkelende riviertjes voor, die migreerden in zijwaartse richting. Tenslotte kwamen grote rivieren voor die, wanneer bedijkt, slechts zwak kronkelend waren en in benedenstroomse richting migreerden. Deze rivierpatronen kunnen alle getypeerd worden met een relatief klein aantal typen van terreinvormen, wat erop wijst dat de werking van processen sterk vergelijkbaar is. Vergelijking van de gegevens over migratiesnelheden leert dat wanneer migratie niet belemmerd wordt door erosieresistente oevers of afgenomen stroomvermogen, de snelheid toeneemt met de grootte van de rivier. De migratiesnelheden van deze laaglandrivieren zijn vergelijkbaar met die van andere, natuurlijke rivieren elders in de wereld.

Randvoorwaarden voor de ontwikkeling van de verschillende riviertypen hangen samen met de waterafvoer, het sedimenttransport, het verhang, het oevermateriaal en de aquatische vegetatie. De variatie in benedenstroomse richting is echter vooral gerelateerd aan verschillen in het geomorfologische landschap en de daarmee samenhangende samenstelling van oevers. Daarom geeft de breedte–diepteverhouding, die het evenwicht tussen de kracht van de rivier en de weerstand van het geomorfologische landschap weerspiegeld, een goede indicatie van de mogelijke vorming van beddingvormen. Meer onderzoek is nodig over de variabelen die invloed hebben op de zijwaartse migratie van rivieren. Voorlopig kunnen migratiesnelheden voorspeld worden door gebruik te maken van de relatie met de oppervlakte van het stroomgebied of met de maatgevende afvoer.

Uit het bovenstaande vloeien enkele richtlijnen voort die kunnen helpen bij het opstellen van efficiënte plannen voor rivierherstel. Aanbevolen wordt om zoveel als mogelijk, de natuurlijke, fluviatiele processen het werk te laten doen, om ruimte te geven aan deze processen, om hersteldoelen goed te laten aansluiten op de mogelijkheden van riviertrajecten, om te aanvaarden dat herstel tijd kost, en om voorzichtig om te gaan met historische patronen van terreinvormen. Het aanwijzen van kansrijke delen van het riviersysteem dient bij voorkeur gebaseerd te zijn op inzicht in de randvoorwaarden voor het herstel van geomorfologische processen. De verschillen tussen rivieren, tussen riviertrajecten en tussen locaties onderling zouden dan ook in elk herstelproject een rol moeten spelen. In het geval dat economische belangen, zoals scheepvaart, het herstel van geomorfologische processen belemmeren, is het wellicht de moeite waard de aandacht en financiële impuls op kleinere riviersystemen te richten. Herstel van de Overijsselse Vecht zou om die reden voorrang verdienen.

Drie algemene aspecten van het ontwerp van maatregelen komen naar voren uit deze studie. Zowel de breedte-diepte verhouding als de boogstraal van bochten in de rivier kunnen gebruikt worden om de variatie aan natuurlijke beddingvormen en de migratiesnelheid te beïnvloeden. Door het kiezen van de juiste dimensies in dwarsdoorsnede ontstaat de mogelijkheid dat de rivier zelf een natuurlijke bedding vormt, en wordt een gedetailleerd ontwerp overbodig.