Recent erosion and sedimentation processes in the Geul river

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Abstract

The Geul river in the southern part of the Netherlands has had a long history of channel straightening and bank protection, but during the past few decades, large stretches of the Geul have been allowed to meander freely. During fieldwork in June 2003, erosion and sedimentation processes, as well as channelisation measures, were mapped and grainsize samples were taken along a section of the Geul.

Analysis of the gathered data showed that the presence of erosion in this section is positively related to sinuosity and negatively related to the presence of bank protection. Due to the presence of bank protection measures, erosion is still localised. Lateral erosion rates up to 2 meters per year have been found. Vertical aggradation rates of the pointbars do not show a clear correlation with sinuosity. Aggradation rates up to 0.15 meters per year have been found. The depth profiles of most of the pointbars show several superimposed fining-up sequences. In one of the pointbar-transects, younger sequences were found to be thicker than older sequences, possibly due to changes in sediment supply. No downstream grain size trend has been found in the pointbars.
# Contents

Chapter 1: Introduction  
 §1.1 Introduction to the research project  
 §1.2 Meandering rivers  
 §1.3 The Geul River  
 §1.4 The ‘Wege Des Wassers’ project  

Chapter 2: The Geul river  
 §2.1 Physical and Geographical setting  
 §2.2 Land-use and management policy  
 §2.3 Specification of project area and research questions  

Chapter 3: Methods and materials  
 §3.1 The map  
 §3.2 Erosion rates  
 §3.3 Grainsizes  

Chapter 4: Riverbank erosion in the Geul  
 §4.1 Introduction  
 §4.2 The sections  
 §4.3 Discussion  

Chapter 5: Bar sedimentation in the Geul  
 §5.1 Introduction  
 §5.2 Bar sedimentation in the sections  
 §5.3 Grainsizes  
 §5.4 Vertical aggradation rates  
 §5.5 Discussion  

Chapter 6: Channelization measures in the Geul  
 §6.1 Introduction  
 §6.2 The different measures  
 §6.3 Restoring sinuosity of the Geul  

Chapter 7: Conclusions  

References  

List of figures  

List of tables  

Appendix 1: Map of recent erosion and sedimentation processes in the Geul River  

Appendix 2: Location of sampling sites  

Appendix 3: Location of pictures  

Appendix 4: Schematic pointbar-transect through P3, P4, P5, P6 and P7
Chapter 1: Introduction

§1.1 Introduction to the research project

This report presents a masters research project for the study of Quaternary Geology at the faculty of Earth and Life Sciences at the Vrije Universiteit of Amsterdam. The objective of this project was to map and study recent erosion and sedimentation processes in the Geul river in Limburg, the Netherlands. It supplements the work of the ‘Wege des Wassers’ project for which Drs. Jos de Moor is doing research into the development of the Geul river valley during the Holocene.

In the summer of 2003, fieldwork was conducted during which erosion and sedimentation processes were mapped and sediment samples were collected. In the following months, the grainsize distributions of the samples were calculated and analysed at the Vrije Universiteit.

The project was supervised by Drs. Jos de Moor and Prof. Dr. Jef Vandenberghe (head of the Quaternary Geology department of the Vrije Universiteit).

§1.2 Meandering rivers

§1.2.1 Introduction

Naturally meandering rivers are very dynamic. They are continuously adapting their gradient and cross-sectional profile to their discharge and sediment load. This is achieved through the processes of erosion and sedimentation. Erosion of the concave banks and subsequent sedimentation of the eroded material in convex bends causes continuous changes in the river’s shape and location.

Because of this river migration, freely meandering rivers are often seen as a problem. They can cause extensive damage to roads and buildings in populated areas. They also form a problem in farmlands where they can cause one land owner to gain and another to lose land. Flooding is another problem, especially in populated areas.

To limit these problems, measures are often taken to prevent river-erosion in densely populated areas. Channels are straightened, banks are protected and flow is slowed down (see paragraph 1.2.4). These measures, however, deprive a river of its capability to create a channel that is in equilibrium. This will be further reviewed in paragraph 1.2.4, but first riverbank erosion and pointbar sedimentation will be discussed briefly.

§1.2.2 Riverbank erosion

Riverbank erosion is the detachment and removal of bank material. It is often caused by a combination of three different mechanisms: mass failure, fluvial entrainment and subaerial weakening and erosion (Thorne, 1990).
Fluvial entrainment or scour is the direct removal of bank material by the physical action of the flowing water. The occurrence of scour is closely related to the flow's near-bank velocity gradient which determines the hydraulic shear (Knighton, 1998). Velocity gradients tend to be high in the concave outer bends of a river and this is where bank erosion is most common. Scour contributes to bank erosion by entraining material directly from the riverbanks. It also facilitates mass failure by undercutting and steepening of the banks.

Mass failure is the slumping or collapsing of riverbanks under the influence of gravity. It is influenced by bank geometry, structure and material and it is not a continuous process. Subaerial weakening and erosion are caused by external factors (e.g. erosion caused by cattle or rain splash) and not by fluvial processes. It can lead to direct erosion and can also weaken the riverbanks which may increase scour and mass failure.

§1.2.3 Sedimentation

Sedimentation occurs when flow falls below the settling velocity of a particle in the stream (Knighton, 1998). In meandering river systems it can be divided into channel deposits and flood deposits. Channel deposits can occur as (temporary) bed deposits or in the form of bars. Pointbars are generally the main depositional features in meandering channels. They develop on the convex river banks where flow velocity is low. Pointbars accrete laterally and generally compensate the erosion of the concave banks (Knighton, 1998). They also grow vertically during inundation of the pointbar and slowly build up to floodplain level. A fining-up trend develops as flow velocity decreases with elevation of the pointbar. Bars may also develop as islands in the channel. These will be either eroded or incorporated into pointbars as the river migrates (Knighton, 1998).

Flood deposits build up when water flows over the river banks onto the floodplain. Fine sediment is deposited there because flow velocities are very low. The amount of sediment deposited on the floodplains does not only depend on the frequency and duration of flooding, but also on the grainsize distribution of the sediment in the river (Knighton, 1998). When there is a high content of fine particles, vertical accretion during flooding will be high.

The fluvial deposits discussed above tend to have a fining-up trend. There is often also a downstream trend in grainsize along a river's course. The coarser grains are deposited first when flow decreases and therefore the ratio of the finer grains will increase downstream. This is reflected in the deposits.

§1.2.4 River channelization

During the last centuries, many lowland rivers have been channelized in order to increase agricultural production, to improve flood control and to prevent erosion. River channelization is a general term that covers bank stabilization, bank toe protection, channel straightening, flow retardation, flow diversion and water storage in reservoirs (Brookes, 1988). These measures, however, turned out to have many negative effects.
The main problem is the decrease in length which causes an increase in gradient and flow velocity. The latter are not matched by an increase in sediment availability and therefore the river will try to find a new equilibrium by upstream erosion and downstream sedimentation or by the creation of flowlines with bars and gullies within the channel (Parker and Andres, 1976). The shorter river length will also cause higher peakflows and therefore larger floods. A solution is sometimes found in flow retardation measures (dams for example) to limit the increase in flow velocity. These problems and the fact that naturally meandering rivers have more diverse flora and fauna and a higher aesthetic value have led to the restoration of many originally meandering rivers in the last decades (Brookes, 1988).

§1.3 The Geul river

The Geul is one of the few hill country rivers in the Netherlands. It has a steep gradient and high peak discharges (see paragraph 2.1). This makes the Geul a very dynamic river, capable of severe erosion and fast channel migration. For centuries, however, people living in the area have straightened the channel and protected the banks to prevent erosion. These channelization measures have lead to higher peak-discharges and have therefore contributed to downstream flooding. Water retention plans are therefore incorporated in the river management policy of the Roer and Overmaas waterboard (Waterbeheersplan waterschap Roer en Overmaas). Since 1988 large stretches of the Geul were given the space to meander freely, thereby increasing the channel’s storage capacity.

Today, parts of the river are freely meandering while other parts of the channel are still fixed. This makes it an interesting site to study river processes and the effects of channelization measures.

Previous research in the Geul river catchment has concentrated on soils in the Geul and Eyserbeek (tributary of the Geul) valleys (Van de Westeringh, 1979, 1980), on the effects of land-use and precipitation on sedimentation (Havinga and Van den Berg van Saporoea, 1980; Stam, 2002) and on heavy metal contamination in relation to mining activities (Leenaers, 1989; Swennen et al., 1994).

§1.4 The ‘Wege Des Wassers’ project

The research project described in this report is linked to the ‘Wege Des Wassers’ project (WdW) in the Euregio Maas-Rhine. The WdW is an integrative water management project that combines data from Belgium, The Netherlands and Germany to cover the complex interdependencies in whole river catchment areas. All factors influencing water bodies are considered in a holistic approach. Therefore, five different ‘Project Interest Groups’ focus on different aspects of water management. These Project Interest Groups are:

1: Fluvial Dynamics
2: Landuse Change
3: Fluvial Geo-ecology
4: Sedimentology and Soil Science
5: Data Integration

The Project Interest Group of Data Integration collects and processes the data from the other groups and makes it available to the scientific community and the public. This way the WdW aims to:

A: give input for a decision support system for operative water managers
B: survey and to network cross-bordering water related data
C: investigate the main components interacting in the catchments
D: prepare the implementation of an 'Integrative Water Management'
E: contribute to a sustainable improvement of water conditions in the Euregio Maas-Rhine according to ecology and economy

The Geul is one of the rivers that are examined in the Wege Des Wassers project. The website www.wegedeswassers.de provides more information on the project.
Chapter 2: The Geul river

§2.1 Physical and Geographical setting

The Geul river has its source near the village of Lichtenbusch in Eastern Belgium (figure 2.1). It crosses the Belgian-Dutch border just north of Sippenaeken and joins the river Meuse near Meerssen. The total length of the river is 56 kilometres and the catchment area covers 380 km². The gradient of the Geul varies from 0.02 m/m near the source to 0.0015 m/m at Meerssen with a total fall of about 250 meters.

In the catchment area, the average precipitation surplus is 300 mm/y (Dautrebande et al., 2000) and with a area of 380 km² this produces an average discharge of 3.6 m³/s. The actual discharge however, is highly variable and ranges from 0.8 m³/s to 65 m³/s (Dautrebande et al., 2000).

In Belgium, the river valley is cut into Cretaceous and Paleozoic rocks. Further downstream the valley cuts through younger rocks and sediments and north of Mechelen the Paleozoic rocks do not appear at the surface (the Cretaceous rocks do). The Geul river itself only cuts through Holocene sediments which cover the valley floor.

Figure 2.1: The Geul river catchment.
§ 2.2 Land-use and management policy

§2.2.1 Past and present land-use

The Geul Valley has an agricultural history that goes back as far as 5000 BC (Dautrebande et al., 2000). At that time, agriculture was at a small scale and did not have much impact on the Geul river. This changed during the Roman period when large parts of the forests in South Limburg were cleared for farming. This caused an increase in soil erosion and therefore in sediment supply to the river. Soil erosion further increased during the Middle Ages when sloping grasslands were cultivated and deforestation continued.

Land-use in the nineteenth and twentieth centuries has been studied by Marleen Stam (2002) and Nicole de Gier (2003). A summary of their findings will be presented below. At the beginning of the 19th century, 80 percent of the surface area of South Limburg was cultivated. In this period, lead and zinc mining along the Belgian part of the Geul were industrialized. For this purpose the Geul river was channelized in the mining area, forests were cleared, groundwater was pumped up and discharged into the Geul and the population increased. Sedimentation rates were high during this period because of the groundwater pumping and the increased sediment supply caused by deforestation.

By the end of the nineteenth century, the industrial mining had stopped. In this period there was also an agricultural crisis in this region. As a result, many arable fields were turned into pastures and there was some reforestation. This process was strengthened by the demand for labour in the colemines which called for less labour intensive agriculture. Sedimentation rates were low during this period.

The low sedimentation rates lasted until the nineteen fifties (Stam, 2002). The fifties saw massive changes in agricultural practices. The introduction of heavy machinery led to upscaling, removal of linchets, changing of plough direction from parallel to perpendicular to contour lines, conversion of grasslands into arable fields, improved drainage, introduction of crops such as maize and sugar beet that leave the fields fallow for 6 months of the year (account for an estimated 92% of total soil erosion in South Limburg) and the paving of roads (Stam, 2002). Although there was a decrease of agricultural land and increase of forest on the steeper slopes since 1970 (De Gier, 2003), the changes led to a strong increase in sedimentation rates in the Geul (Stam, 2002).

§2.2.2 Management policy

In the past, management of the Geul focussed on erosion-prevention and quick discharge of the water. For centuries, banks have been straightened and protected, at first on behalf of the water mills, later for agricultural and mining purposes.

In 1988 this policy changed (Peters, 2001). From then on, large stretches of the Geul were allowed to meander freely. Bank protection was removed in areas where erosion does not threaten buildings or infrastructure. Large areas of agricultural land were purchased by the ‘Limburgs Landschap’ foundation (private foundation which tries to retain characteristic landscapes and nature in Limburg) and turned into nature reserve. The reasons for this change in management policy were the need for water retention and
the recognition of the value of this unique landscape in the Netherlands (Bureau voorlichting, 2002). Water retention was necessary because of flooding downstream. Large floodings of the Meuse river by the end of the twentieth century called for measures to reduce peak discharges. Water retention in the tributaries is one of them. The Geul river is allowed to meander to reduce peak discharges by retaining the water. Furthermore, water retention basins were constructed. Some of the purchased areas that were turned into nature reserves are also inundated during high-water events.

§2.3 Specification of project area and research questions

§2.3.1 The project area

The research project focuses on the course of the Geul from the Belgian-Dutch border to the village of Wijlre (figure 2.2). This part includes some of the more active stretches of the river and also some protected and straightened banks. This variety makes it an interesting stretch for studying recent river processes. Furthermore, the river is easily accessible in this area and footpaths closely follow the river for much of its length. The general flow direction is from the south to the north. When the Geul is mentioned in the next chapters, it refers to the stretch described above.

§2.3.2 The research questions

Riverbank erosion and channel sedimentation, as well as the channelization measures that influence them, are the main processes that were examined. Therefore, the research questions are divided into three categories:

1 Lateral Erosion: Where are the banks being eroded?
   Why there?
   What is the rate of bank erosion and?
   Did erosion rates change over time?
2 Sedimentation: Where are sediments deposited in the channel?
   Why there?
   What is the sedimentation rate?
   Did sedimentation rates change over time?
   What are the vertical and lateral grainsize distributions in the pointbars?
3 Channelization: Which channelization measures occur?
   How effective are these measures?

River erosion in the Geul will be discussed in chapter 4, sedimentation in chapter 5 and channelization measures in chapter 6.
Figure 2.2: This topographical map (Topografische Dienst Nederland, series 1:50,000 (1998), sheet 69 Oost) shows the research area of the project. The small map in the top (from: De Grote Bosatlas, 51st edition) shows the location of the research area (the red rectangle). The Geul river flows from the south to the north.
Chapter 3: Methods and materials

§3.1 The map

To get a good overview of recent erosion and sedimentation processes in the Geul river, the processes were mapped during fieldwork in the summer of 2003. Erosion, sedimentation and channelization measures were documented on topographical maps of the area with an original scale of 1:25,000, magnified to scale 1:1.250. The field-data were then digitised using ArcView 3.3 GIS software. The map (appendix 1) provides the basic information for the following chapters in which the different processes will be discussed separately. In the next three paragraphs, the legend of the map will be clarified.

§3.1.1 Riverbanks

The riverbanks are divided into three classes of different stability: stable, unstable and erosive banks. Erosive banks are steep, unvegetated banks where the sediment is fully exposed (figure 3.1). These banks experience intensive scour which also causes frequent mass failure by undercutting and oversteepening of the banks. They occur where the flow lines of the river collide with the riverbanks. Unstable banks are partly vegetated and have not been strongly eroded for a few years. They do experience some scour or gravitational erosion (figure 3.2). Unstable banks often occur next to erosive stretches where erosion is not so severe or only occasional. Some vegetation settles on the unstable banks because the exposed sediment is not constantly removed.

Figure 3.1: Steep and unvegetated erosive riverbanks near Ter Graat. A dam is constructed in the river to reduce river flow rate and limit erosion in the downstream bend. Flow is from the left to the right.
Stable banks are fully vegetated and suffer negligible erosion (figure 3.2). They have not experienced substantial erosion for a longer time than unstable banks.

Figure 3.2: Densely vegetated stable riverbank to the right of the dashed red line and partly exposed unstable riverbank on the left (location near Gulpen).

§3.1.2 Bar sedimentation

River bars are divided into three classes of different activity: active bars, vegetated active bars and inactive bars (figure 3.3). The active bars consist mainly of gravel and coarse sands. Their top is usually around, or just above, mean low water level. The vegetated active bars are all above mean low water level. They are often flooded and mainly sand is deposited on them. Vegetation on these bars is a mixture of grasses, herbs and occasionally small shrubs on the highest bars. The inactive bars are well above mean low water level and they are only inundated during high discharges. They are densely vegetated with grasses, herbs, shrubs and trees (mainly fast growing willow). Sedimentation consists of fine sands and silts.

§3.1.3 Channelization measures

The channelization measures are divided into bank stabilization, bank toe protection, channel straightening and flow retardation methods. In the Geul river we find two types of bank stabilization measures. These are walls which replace natural banks (figure 3.4) and trees to reinforce the natural banks (figure 3.5).
Figure 3.3: Active, vegetated active and inactive pointbars near Partij. The inset shows the location of the different classes (red A=active, blue V=vegetated active, green i =inactive). Also note the highly erosive river bank in the back of the picture.

There are two types of bank toe protection: wooden wattle and boulders/concrete rubble placed at the toe of banks (figure 3.6). Flow retardation occurs in the form of dams.

Figure 3.4: Walls replacing natural riverbanks near the town of Mechelen.
Figure 3.5: Trees planted on a riverbank near Ter Gracht to stabilise the bank (picture from Jos de Moor).

Figure 3.6: Bank toe protection with boulders (location near Mechelen).

Channel straightening may occur as a single measure, but is sometimes also combined with bank stabilization, bank toe protection or flow retardation practices. Straightening in several parts of the Geul has been dated by visual interpretation of topographical maps of different age. For this purpose, sheet 85 Vaals of the Tranchot map scale 1:25.000 (1806) and sheets 767, 771 and 775 of the Topografische kaart van het Koninkrijk der Nederlanden scale 1:25.000 (1937) were used.
§3.2 Erosion rates

At certain points in the Geul River, erosion rates have been calculated. Two different methods were used. The first one uses aerial photographs and the second one uses trees in the river.

The first method compares the location of the riverbanks on aerial photographs of different ages. The maximum distance a bank has migrated in the time between the photographs were taken is measured perpendicular to the river bank. This distance is then divided by the difference in age of the photographs and provides an erosion rate in meters/year (m/y). Photographs from the years 1937, 1965, 1983, 1992 and 2003, scale 1:18.000, of section 62W were studied at the Topografische Dienst in Emmen.

The second method uses trees that used to be on the riverbank, but are now in the river. The river has eroded the bank behind the trees (see §6.2.3 for an explanation of this process).

The distance between the tree and the riverbank is measured and divided by the age of the tree. This gives an average erosion rate in meters per year. To determine the age of the tree, a small tree-corer was used and the tree rings in the core were counted. The tree, however, was not planted at an age of zero years. The actual age of the trees at the time they were planted is not known, but according to tree cultivation company Zelkova in Amsterdam, three years is a good age to plant alder trees. By that time they will be about two to three meter in height and they have developed a substantial root system that can already stabilise the riverbanks. Therefore, three years are subtracted from the age of the tree before it is used in the calculation of erosion rates.

Generally, alder trees with an average age of 22 years (based on tree corer results) are used for calculating erosion rates. They are assumed to be planted nineteen years ago. In a single case, 40-45 year old poplar trees were used. In the calculation, a planting age of 40 years is used.

§3.3 Grainsizes

Samples for grainsize analysis were taken during the fieldwork in 2003. Back at the Vrije Universiteit, the samples were prepared for the measurements. Peroxide was added to the samples to remove organic material and hydrochloric acid was used to remove carbonates. The samples were then treated with natriumpyrophosphate to prevent agglomeration of the individual grains (deflocculation).

The grainsizes were measured by the Laser Particle Sizer at the Vrije Universiteit. For more information on the Laser Particle Sizer and the pre-treatment of the samples see Konert and Vandenberghe (1997).
Chapter 4: Riverbank erosion in the Geul

§4.1 Introduction

The Geul is a dynamic river which is visible in the local high erosion rates. The average slope in the research area is about 0.0027 m/m with a total fall of 35.2 meters over thirteen kilometres. Discharge varies, but peak discharges can be as high as 65 m³/s (Dautrebande et. al., 2000). The Holocene floodplain and colluvium deposits are easily eroded. Therefore, riverbank erosion is a common process in the Geul and it occurs over the entire research area (see appendix 1).

There are, however, substantial stretches with little or no erosion at all. These are mainly the artificially straightened stretches of the river. The sinuous stretches generally suffer more erosion. In order to get a good overview of erosion processes in the Geul, erosion in the research area was mapped during fieldwork in June 2003. Because of the apparent link between sinuosity and erosion, the research area is divided into thirteen sections, based on sinuosity (figure 4.1).

Figure 4.1: The Geul river (green=stable bank, blue=unstable bank, red=erosive bank) divided into thirteen sections based on sinuosity.
For these sections the sinuosity index (Haggett and Chorley, 1969) was calculated by the following equation:

\[
\text{Sinuosity Index} = \frac{\text{stream length}}{\text{valley length}}
\]

In table 4.1, the sinuosity index is displayed for the different sections. In addition, the cumulative lengths of erosive, unstable, stable and protected riverbank in each section are presented in the table as a percentage of the total length of riverbank in each section.

<table>
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<tr>
<th>section</th>
<th>sinuosity index</th>
<th>erosive %</th>
<th>unstable %</th>
<th>stable %</th>
<th>protected %</th>
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<td>4</td>
<td>91</td>
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<td>32</td>
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<td>100</td>
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<tr>
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<td>36</td>
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<tr>
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<td>1.470</td>
<td>9</td>
<td>18</td>
<td>73</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 4.1: The sinuosity and the percentage of erosive, unstable, stable and protected riverbank for the different sections.

Erosion is present on the erosive and unstable banks. In order to deal with both of these classes when we discuss erosion, stable banks are used as a measure for the extent of erosion. In sections with a high percentage of erosive and unstable bank length, the percentage of stable bank length is low and vice versa.

Sinuosity and erosion (based on field data from June 2003) in the thirteen sections are discussed below.

§4.2 The sections

§4.2.1 Section 1

Section 1 is a straightened stretch of 250 meters in length. The banks are highly protected (because of a discharge station in the section) and there is very little erosion. Ninety-one percent of the riverbank length is stable.
Erosion does occur downstream of a bend in the river at the beginning of section 1. The banks in the bend itself are protected and are therefore not eroded. After the bend, the channel is straight but flow still has the same direction it had in the bend (because of the inertia of the flowing water). The water is directed against the unprotected riverbank and erodes it.

§4.2.2 Section 2

Section 2 has a high sinuosity index of 1.974. It has the highest degree of erosion of all thirteen sections. Bank protection is virtually absent and erosion is found on almost all concave banks. Even some straight and convex banks suffer erosion in this section.
Erosion rates were calculated at two locations, T2.1 and T2.2, using the tree method (paragraph 3.2). At T2.1, an alder tree is in the river, 7 meters from the riverbank. Assuming it was planted 19 years ago (paragraph 3.2), the erosion rate is 0.37 meters per year. The erosion rate at T2.2 is less straightforward. Poplar trees on the pointbar were used to determine the lateral growth rate of the pointbar. Assuming sedimentation in the convex bend to be equal to erosion in the concave bend, this also produces an erosion rate. A complication is that the poplar trees at this location were not dated. Instead, ages of poplar trees with comparable diameter in section 5 were used. These poplar trees are 40 to 45 years old and for the erosion rate it is assumed they were planted 40 years ago. The poplar trees at T2.2 have a maximum distance of 25 meters to the river. This means that the derived erosion rate should be 0.6 meters per year.

§4.2.3 Section 3

<table>
<thead>
<tr>
<th>section</th>
<th>sinuosity index</th>
<th>erosive</th>
<th>unstable</th>
<th>stable</th>
<th>protected</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1.974</td>
<td>24</td>
<td>32</td>
<td>44</td>
<td>100</td>
</tr>
</tbody>
</table>

Sinuosity as well as the amount of erosion is relatively low in section 3. Twice in this section, the river is split into two channels. In both cases, one of these two channels is an inlet channel for a water mill. These inlet channels are omitted in the calculations for sinuosity index and erosive, unstable, stable and protected bank length. There is no erosion in the inlet channel, because it is controlled by a dam and has a very low gradient. If this channel is also taken in the calculation, 5% of the riverbank length will be erosive, 17% unstable, 78% stable and 7% protected.

Figure 4.4: Section 3.
Erosion occurs mainly in concave banks, but also in straight and convex banks.
An erosion rate was calculated at T3. An alder tree is standing in the river, 5 meters from the riverbank. It is assumed to be planted 19 years ago and this gives an erosion rate of 0.26 meters per year.

§4.2.4 Section 4

Sinuosity in section 4 is above average and the percentage of erosive and unstable bank is quite high. Erosion is most common in concave banks, but straight and convex banks are also eroded. There is only little bank protection.
Erosion rates have been calculated by aerial photographs (paragraph 3.2) and the tree method.

The aerial photograph method was used in two places: A4.1 and A4.2 (figure 4.6). For A4.1, aerial photographs of 1965, 1983 and 2003 were compared because the banks were relatively stable before 1965. The maximum migration distance was 10 meters in the period from 1965 to 1983, giving a maximum erosion rate of 0.6 meters per year. For the period of 1983 to 2003 the maximum migration distance was 8 meters and the maximum erosion rate 0.4 meters per year. The average maximum erosion rate over the period from 1965 to 2003 is 0.5 meters per year.

For A4.2, aerial photographs of 1965 and 2003 were compared because the migration started after 1965. The maximum migration distance is 14 meters and the maximum average erosion rate is 0.4 meters per year.

The tree method is applied at two locations, T4.1 and T4.2. For both locations, alder trees were used. They are assumed to be planted 19 years ago.

At T4.1, the alder tree is 6 meters from the riverbank. This gives an erosion rate of 0.32 meters per year.

The maximum distance between the trees and the riverbank at T4.2 is also 6 meters. The erosion rate is 0.32 meters per year.
§4.2.5 Section 5

In section 5, sinuosity is below average. The percentage of stable riverbank is high and erosion is concentrated in the middle part of the section. Erosion occurs in concave and straight banks. Bank protection is high.

There are two inlet channels for water mills in this section. These are not included in the calculations for sinuosity index and erosive, unstable, stable and protected riverbanks. If they were taken in the calculations, the percentage of stable and protected bank would be higher (stable 85%, protected 28%) and the percentages of erosive and unstable bank would be lower (erosive 6%, unstable 9%).

<table>
<thead>
<tr>
<th>section</th>
<th>sinuosity index</th>
<th>erosive</th>
<th>unstable</th>
<th>stable</th>
<th>protected</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>1.307</td>
<td>9</td>
<td>12</td>
<td>79</td>
<td>100</td>
</tr>
</tbody>
</table>

Figure 4.7: Section 5.

Erosion rates are calculated for two locations in this section. At both locations, T5.1 and T5.2, the tree method was applied to alder trees planted 19 years ago. The tree at T5.1 is 4.5 meters from the riverbank. The erosion rate is 0.24 meters per year.

At T5.2, the distance between the tree and the riverbank is 5 meters and the erosion rate is 0.26 meters per year.
§4.2.6 Section 6

Section 6 has a very low sinuosity and a high percentage of protected riverbank. Erosive banks are absent and ninety percent of the bank length is stable.

<table>
<thead>
<tr>
<th>section</th>
<th>sinuosity index</th>
<th>erosive %</th>
<th>unstable %</th>
<th>stable %</th>
<th>protected %</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>1.034</td>
<td>0</td>
<td>10</td>
<td>90</td>
<td>47</td>
</tr>
</tbody>
</table>

Figure 4.8: Section 6

§4.2.7 Section 7

Section 7 has a high sinuosity and the degree of bank protection is very low. The percentage of erosive riverbank is very high and they are all concave banks. The percentage of unstable bank in this section is average and it occurs mainly, but not exclusively, in concave banks.

Figure 4.9: Section 7.
For this section, Stam (2002) has documented channel migration from 1935 to 1995 (figure 4.10) using aerial photographs. Erosion rates up to 2 meters per year occur.

Section 8 is completely straightened and the sinuosity index is 1. Bank protection is present in the form of closely spaced trees. These trees are not considered in the calculation for protected bank length. Trees occur on banks throughout the research area in different spacing and distance from the river, but they never really seem to prevent erosion. In this case they are very closely spaced (two to three meters) and therefore erosive, unstable, stable and protected bank length are only calculated for the stretch south of the bridge where the banks are not protected these by trees.

The percentage of erosive bank length is low and unstable banks occur below average.
§4.2.9 Section 9

Figure 4.12: Section 9.

Section 9 has a low sinuosity and a high percentage of protected bank. The percentage of erosive riverbank is above average while the amount of unstable bank is low. Erosive stretches are located in the concave banks of the first three bends in the section. Protection is absent in these bends. Unstable banks occur along the entire section.

<table>
<thead>
<tr>
<th>section</th>
<th>sinuosity index</th>
<th>erosive</th>
<th>unstable</th>
<th>stable</th>
<th>protected</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>1.258</td>
<td>11</td>
<td>14</td>
<td>75</td>
<td>100</td>
</tr>
</tbody>
</table>

In this section, an erosion rate was calculated for the bend that suffers the highest degree of erosion (location A9). The channel is relatively stable until 1983 and then it starts migrating. The situations in 1983 and in 2003 were compared using the aerial photograph method.
Figure 4.13: Comparison of the riverbank locations on aerial photographs of 1983 and 2003. The migration distance was measured at the arrow.

The maximum riverbank migration, measured at the arrow, was 27 meters over a period of 20 years (figure 4.13). This gives an average erosion rate of 1.35 m/y.

§4.2.10 Section 10

Section 10 is straightened and has a very low sinuosity. Bank protection is very low. Erosive banks are absent. Unstable banks are very rare and they are located in the concave banks of the two bends in the section. This section is very stable.

Figure 4.14: Section 10.
Chapter 4.2: Section 11

Section 11 has the highest sinuosity index of all thirteen sections. Bank protection is above average. The percentage of erosive bank length is low while the percentage of unstable bank is high. The unstable stretches occur mainly in concave banks, but also in straight and convex banks.

<table>
<thead>
<tr>
<th>section</th>
<th>sinuosity index</th>
<th>erosive %</th>
<th>unstable %</th>
<th>stable %</th>
<th>protected %</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>2.605</td>
<td>5</td>
<td>33</td>
<td>62</td>
<td>100</td>
</tr>
<tr>
<td>10</td>
<td>1.026</td>
<td>0</td>
<td>3</td>
<td>97</td>
<td>100</td>
</tr>
</tbody>
</table>

Chapter 4.2: Section 12

Section 12 has been straightened. Therefore, it has a low sinuosity. There is one erosive stretch in the concave bank of the bend in the middle of the section. The percentage of unstable bank length is just above average. The degree of bank protection is very low.

<table>
<thead>
<tr>
<th>section</th>
<th>sinuosity index</th>
<th>erosive %</th>
<th>unstable %</th>
<th>stable %</th>
<th>protected %</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>1.074</td>
<td>5</td>
<td>22</td>
<td>73</td>
<td>100</td>
</tr>
</tbody>
</table>
§4.2.13 Section 13

Section 13 has a high sinuosity and a low degree of bank protection. The percentage of stable bank is very low. Erosion is present over the entire section in concave banks and also occurs in convex and straight banks.

<table>
<thead>
<tr>
<th>section</th>
<th>sinuosity index</th>
<th>erosive</th>
<th>unstable</th>
<th>stable</th>
<th>protected</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>1.975</td>
<td>16</td>
<td>36</td>
<td>48</td>
<td>100</td>
</tr>
</tbody>
</table>

Erosion rates were calculated by the aerial photograph method for three bends (figure 4.18). The banks started migrating after 1993. Therefore the situation in 1993 was compared with the situation in 2003.

At A13.1, the maximum migration distance is 15 meters. Therefore the maximum average erosion rate in the period from 1993 to 2003 is 1.5 m/y.

The maximum erosion distance at A13.2 is 12 meters. The maximum average erosion rate is 1.2 m/y.

At 13.3, the maximum migration distance is 15 meters and the maximum average erosion rate is 1.5 m/y.
§4.3 Discussion

§4.3.1 The distribution of erosion

In general, erosion mostly occurs in concave riverbanks. This is the normal situation in freely meandering rivers. In the Geul, however, we also see erosion of straight and even convex banks. This is the reaction of the river to straightening and bank stabilization. The river’s ability to meander is decreased. It tries to overcome this problem by developing flowlines within the river channel. These flowlines respond to changes in sediment load and discharge. Because most erosion occurs in bends, it is related to sinuosity. In figure 4.19 we can clearly see a decreasing trend in the length of stable riverbank, with increasing sinuosity.
This relation, however, is not straightforward. Many values deviate significantly from the trendline. These deviations are caused by the differences in protected bank length in the sections.

In figure 4.20 we can see that the pattern of the graph of stable bank length very much resembles the graph of protected bank length, but the differences in bank protection alone cannot account for the decreasing trend in stable bank length. Sections with comparable degrees of bank protection, but different sinuosity, experience different degrees of erosion.

The relation between erosion and sinuosity is clear when we compare stretches with little or no protection. The three sections with the lowest percentage of protected bank length, sections 2, 7 and 8, show a distinct increase in stable bank length with decreasing sinuosity.
<table>
<thead>
<tr>
<th>section</th>
<th>sinuosity index</th>
<th>erosive %</th>
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<th>stable</th>
<th>protected</th>
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<td>2</td>
<td>1.974</td>
<td>24</td>
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<td>44</td>
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</tr>
<tr>
<td>7</td>
<td>1.879</td>
<td>24</td>
<td>20</td>
<td>56</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>1</td>
<td>4</td>
<td>15</td>
<td>81</td>
<td>0</td>
</tr>
</tbody>
</table>

Sinuosity is the primary influence on the extent of erosion. Bank protection is a secondary trend as can be seen in figure 4.21. Sections with stable bank percentages below the trendline have low protection and sections with percentages above the trendline have high degrees of bank protection.

Figure 4.21: The influence of bank protection on stable bank percentage. Where stable percentages are below trendline, bank protection is low (grey areas). Where stable percentages are above the trendline, protection is relatively high.

One section, section 10, is inconsistent with the other sections. Protection is very low, but still it has the highest percentage of stable bank length of all sections. The reason for this might be the low gradient in the first part of the section (figure 4.22). The gradient in the first five-hundred meters of the section is only 0.001 m/m. This is very low compared to the average 0.0027 m/m. Stream velocity will be lower than normal and flow less turbulent. Therefore, erosion might be almost absent. The low gradient might be caused by alluvial fans of tributaries, half a kilometre downstream. These fans can obstruct the river and cause sedimentation upstream.
Figure 4.22: Length profile of the Geul. The distance downstream is measured from the Belgian-Dutch border. Section 10 is in the grey area.

§4.3.2 Erosion rates

The most striking about the erosion rates is that the rates derived from the aerial photographs are higher than those calculated by the tree method. This might be caused by the stabilising effect the trees have on the banks. At all locations where the tree method was used, trees were protecting the banks before the river eroded around them. This means that there has been a period of relative bank stability in the first period after the trees were planted. Therefore, the average erosion rate will be lower than when the trees would not have been there.

When the aerial photograph method is used, erosion rates are calculated from the moment the river is migrating. The banks are certainly not stable at that moment. Therefore, the erosion rates will be higher than those of the tree method.

Erosion rates are related to sinuosity. Erosion rates calculated by the tree method show an increase with increasing sinuosity (figure 4.23). The erosion rates calculated by the aerial photograph method do not show this trend. This might be because they are calculated over different periods of time. Furthermore, data from before 1988 were used in the calculations. Before 1988, many bank stabilization measures were applied. Different degrees of protection in the different sections might therefore play a significant role in the calculated erosion rates.
Although erosion is very common in the Geul, the river has not migrated much over the last two centuries. This is caused by channelization practices that have been present along the Geul for centuries.
At the moment, much of the riverbank length is still protected by trees and river migration is limited to a few locations. When banks are no longer protected, which is to be expected in the future due to the new management policy (paragraph 2.2.2), channel migration will increase.
Chapter 5: Bar sedimentation in the Geul

§5.1 Introduction

Bars are common features in the Geul. They are divided into three different classes: active bars, vegetated active bars and inactive bars. Active bars consist mainly of gravel and coarse sand. Their top is generally around mean low water level, but occasionally they have elevations up to 1.5 meters above it. The vegetated active bars are a little higher than the active bars. They are vegetated by grasses, herbs and sometimes small shrubs. The sediment at the top is generally coarse and medium to fine sand. The inactive bars are well above mean low water level (half a metre or more). They are densely vegetated by grasses, herbs, shrubs and trees. Medium sand to silt is the main grain size of the sediment deposited on them. Pointbars are most abundant along sinuous stretches (see supplement). This is where low velocity gradients occur in the convex bends. Erosion, and therefore the creation of accommodation space and sediment supply, is also highest in sinuous stretches. Hardly any pointbars occur in the straightened sections. The extent of pointbars is highest in sections with high erosion rates.

§5.2 Bar sedimentation in the sections

The occurrence of pointbars in the different sections has not been quantified exactly. The sections were ranked from the one with the highest pointbar area per unit river length to the one with the lowest, based on visual interpretation. Some sections had approximately the same amount of pointbar area and they were grouped into the same class (table 5.1). In this way, all thirteen sections have been divided into six classes of different amount of pointbar area per unit river length. Class 6 has the largest pointbar area and class 1 the smallest.

<table>
<thead>
<tr>
<th>section</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
</tr>
</thead>
<tbody>
<tr>
<td>pointbar area class</td>
<td>1</td>
<td>5</td>
<td>2</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>6</td>
<td>1</td>
<td>5</td>
<td>1</td>
<td>4</td>
<td>1</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 5.1: Classification of the sections into six pointbar area classes. Class 6 has the largest pointbar area per unit river length, class 1 the lowest.

In figure 5.1, pointbar area class is plotted against sinuosity. It shows a general trend of increasing pointbar area class with increasing sinuosity. The trend seems to be exponential. Deviations from the trend show that sinuosity is not the only factor influencing the occurrence of pointbars.
§5.3 Grainsizes

From several inactive pointbars, grainsize samples were taken and analysed (see appendix 2 for locations of the sampling sites). An Edelman auger was used to take samples of the bars at regular spaced depths. In general, the sediment in the pointbars is a mixture of two members (figure 5.2): a fine member and a coarse member. The fine modal value is around 32 micron. The modal value of the coarse member, as well as the proportions of the coarse and the fine fraction, varies. Therefore, the percentage of fine grains (<105 micron) and the modal value of the coarse fraction are plotted against depth. These depth profiles will be discussed below.
§5.3.1 Sampling point P1

Sampling point P1 is located on a pointbar in a concave bend in section 2. It is a pointbar of 110 centimetres in height, which is eroded at present. The samples show a typical fining-up trend (figure 5.3). The percentage of the fine fraction increases to the top and the grainsize of the coarse mode decreases to the top. The coarse modal varies between 550 and 195 micron. The percentage of the fine fraction ranges from 13 to 77.

![Figure 5.3: Depth profile of pointbar sampling point P1.](image)

§5.3.2 Sampling points P2, P3, P4, P5, P6 and P7

Sampling points P2, P3, P4, P5, P6 and P7 are part of a sampling transect across several pointbar levels in section 2 (figure 5.4).

![Figure 5.4: Pointbar transect with the location of the individual sampling points.](image)

P7 is located on the floodplain. The samples contain more than eighty percent fine fraction through the entire depth profile (figure 5.5). It is rarely lower than ninety percent. The profiles show two short fining-up sequences. Many samples do not have a coarse fraction. This is a good example of floodplain sediment.
P6 is located on the transition of the highest pointbar level (150 cm) and the floodplain (>200 cm) at an elevation of 1.8 meters. The percentage of fine grains in the profile shows 3 fining-up sequences in the lower part and floodplain sediments (generally >80% fine fraction) in the top 60 centimetres (figure 5.6). The lower fining-up sequence is visible in the percentage of fine fraction as well as in the coarse modal. The other two fining-up trends are not clearly expressed in the coarse modal. The coarse modal value does not really change through the profile. It is on average 230 micron.

P5 is located in the middle of the oldest pointbar level with an elevation of 1.5 meters. It shows three fining-up sequences of which the top one is only present in the fine fraction (figure 5.7). The shape of the curve of the fine fraction resembles that of the top 1.5 meters of P6. The difference is that the percentages are lower in P5. The values of the coarse modal are very variable. The mean value is around 230 micron, the same as for P6.
Sampling point P4 is located on a surface with an elevation of one meter.

The depth profile of the fine fraction has the same shape as the top meter of P5. The coarse modal value shows an upward increase, except for the top sample (figure 5.8). Two fining-up trends can be recognised in the profile of the fine fraction and, less clear, in the profile of the coarse fraction.

P3 is on a stable pointbar with an elevation of 80 centimetres. The depth profile shows a decrease in fine fraction to the top and an increase in coarse modal (figure 5.9).
Sampling point P2 is located on an active vegetated pointbar and the samples consist of sand and fine gravel.

§5.3.3 Sampling points P8 and P9

P8 and P9 are located on two adjacent pointbar levels in section 3 (figure 5.10).

Figure 5.10: The location of sampling points P8 and P9.

P9 is on the highest and oldest pointbar level with an elevation of 160-200 centimetres. The depth profile shows an increase in fine fraction from the bottom to 35 centimetres beneath the surface (figure 5.11). At that depth, the percentage of fine fraction is 85. In the top 25 centimetres of the profile it is around 50 percent. The profile shows two fining-up sequences which are best visible in the diagram of the coarse fraction (in the diagram of the fine fraction the two separate sequences are difficult to distinguish).

Figure 5.11: Depth profile of pointbar sampling point P9.
Sampling point P8 is located on a pointbar with an elevation of 120 centimetres. The depth profile shows one clear fining-up sequence with a peak in fine fraction at a depth of 65 centimetres (figure 5.12). Besides this peak, the amount of the fine fraction seems to be rather stable, around 30 percent. The coarse modal is about 275 micron. It shows a peak of 325 micron at a depth of 45 centimetres.

![Figure 5.12: Depth profile of pointbar sampling point P8](image)

§5.3.4 Sampling points P10 and P11

P10 and P11 are located on two adjacent pointbar levels in section 4 (figure 5.13).

![Figure 5.13: The location of sampling points P10 and P11.](image)

P11 is on the highest and oldest pointbar level with an elevation of 150-250 centimetres. The percentage of the fine fraction is very high throughout the profile (figure 5.14). The profile shows four fining-up trends, which are expressed in the percentage of the fine fraction and in the coarse mode.
P10 is located on a surface with an elevation of 50-150 centimetres. Both the percentage of the fine fraction and the coarse modal value show a decreasing trend to the top (figure 5.15). Two fining-up sequences can be recognised.

The top meter of the fine fraction curve very much resembles that of P8 with the rather constant values and one strong peak.

§5.3.5 Sampling point P12

Sampling site P12 is located in section 4 on a pointbar with an elevation of 50-150 centimetres.
The percentage of the fine fraction is very low at this site (figure 5.16). It varies between 8 and 50 percent, but the average is around 25 percent. The coarse modal value is rather high, around 325. At the bottom it is higher. Three fining-up trends can be recognised.
§5.3.6 Sampling points P13, P14 and P15

Sampling sites P13, P14 and P15 are located on a pointbar sequence in section 7 (figure 5.17).

Sampling site P15 is located on a surface with an elevation of 200 centimetres. The percentage of the fine fraction is around 50 (figure 5.18). The coarse modal value is around 325 micron. The profiles show two fining-up trends.
The profiles of P13 and P14 are not presented here because the top of these pointbars consists of coarse sand and gravel. P14 is located on a pointbar surface with an elevation of 150 centimetres and P13 is located at a level with an elevation of 100-120 centimetres.

§5.3.7 Sampling point P16

Sampling site P16 is located on a pointbar with an elevation of 150-200 centimetres in section 13.

The depth profile shows a decreasing trend in fine fraction percentage to the top (figure 5.19). The coarse mode shows three fining-up sequences. The upper two of these are not clearly expressed in the profile of the fine fraction. The coarse modal varies around 290 micron throughout the profile.

§5.4 Vertical aggradation rates

Vertical aggradation rates are calculated at the same locations where the aerial photograph method was used for calculating erosion rates. The height of the pointbar is
divided by the time since channel migration started and the pointbar started to build up. This provides a vertical aggradation rate in meters per year.

The pointbar at location A4.1 is up to 2 meters in height and river migration started in 1965. The vertical aggradation rate is 0.05 meters per year.

At location A4.2, channel migration also started in 1965. The pointbar is 80 centimetres high. The vertical aggradation rate is 0.02 meters per year.

In section 7, the vertical aggradation rate is calculated at the location of pointbar sampling site P13. The pointbar is up to 120 centimetres high and it has been aggrading since 1981. The vertical aggradation rate is 0.5 meters per year.

Channel migration at location A9 started in 1983. The pointbar is now 50 centimetres high. The vertical aggradation rate of the pointbar is 0.05 meters per year.

The pointbar at A13.1 is up to 150 centimetres high. Migration started in 1993. The vertical aggradation rate is 0.15 meters per year.

At location A13.2, the pointbar is also 150 centimetres high and migration started in 1993 as well. The vertical aggradation rate is therefore also 0.15 meters per year.

Artefacts found at pointbar sampling sites could also provide a measure for a minimal vertical aggradation rate at that location. The height of the pointbar would have to be divided by the age of the artefact. This gives a minimal rate because the artefact has been deposited a given time after it was produced. The artefacts found at the sampling sites are not very useful. Dating is difficult and when dated, the rates would be lower than those found by the aerial photograph method. Since the artefact rates are minimal rates and they are lower than the aerial photograph rates, they would not add useful information.

§5.5 Discussion

The pointbars show a lot of variation in their grainsize distributions. The coarse modal value varies between 115 and 550 micron, but generally lies between 200 and 400 micron. The fine fraction varies between 10 and 100 percent.

All sampling sites show one or more fining-up sequences, except P3. Most of them have several fining-up trends superimposed on each other. A cross-section through the pointbar-transect of P3, P4, P5, P6 and P7 was made, which shows how the fining-up sequences in the different sampling sites are related to each other. Appendix 2 shows a schematic representation of the different pointbar levels of the transect. The percentage of the fine fraction of the grainsize samples from the pointbars is also plotted in the figure. The fining-up sequences in the depth profiles are connected to each other and to the topography. The resulting fining-up ‘sets’ are shown in figure 5.20. This figure shows the same pointbar-transect, but on true scale. The inner structure of the pointbar can clearly be seen here. As the river migrated laterally (to the left in this figure), the pointbar deposits migrated with it. At least nine different fining-up sequences have been deposited over each other.
The thickness of the fining-up sequences in the pointbar-transect vary. The younger sequences (7 and 8 in figure 5.20) are thicker than the older ones. This might have been caused by a change in sediment supply.

The coarse modal values at the top and the bottom of the individual fining-up sequences do not show any clear vertical or horizontal trend within the pointbar transect.

There is no clear downstream fining trend in the grainsize samples of the research area. The average coarse modal value of the sampling points is plotted against the distance downstream from the Belgian-Dutch border in figure 5.21. No clear trend can be distinguished, but the spread, as well as the total number of the sampling points, are insufficient to conclude that there is no downstream trend in the research area.

The vertical aggradation rates in the pointbars range from 0.02 to 0.15 meters per year. The highest rates are found in the youngest pointbars which is not surprising. As pointbars grow, the vertical aggradation rate will decrease because flooding is less frequent as pointbars get higher. The sediment deposited on the pointbars will also become finer and therefore it will take longer to deposit a layer of sediment with a certain thickness.
Chapter 6: Channelization measures in the Geul River

§6.1 Introduction

For centuries, channel migration and erosion in the Geul have been limited by bank straightening and protection. The river migrated only very little. Since 1988, part of the bank protection is removed. On the map (appendix 1) we can see that most of the remaining bank protection is located near mills, villages, roads, bridges and the confluence of tributaries. In agricultural areas, the presence of bank protection is minimal, except for a stretch north of Mechelen. There we find banks protected by boulders and concrete rubble over a length of almost four kilometres while there is no threat to buildings or infrastructure.

The bank protection measures are divided into bank stabilization, bank toe protection, channel straightening and flow retardation methods. They will be discussed in more detail in the next paragraphs.

§6.2 The different measures

§6.2.1 Channel straightening

Five sections in the research area show extensive straightening. These are sections 1, 6, 8, 10 and 12 (see Chapter 4). Section 10 and a large part of section 6 were straightened before 1806, the other sections between 1806 and 1937 (based on visual interpretation of the Tranchot map (1806) and the Topografische kaart van het Koninkrijk der Nederlanden (1937)).

§6.2.2 Bank toe protection

Bank toe protection measures in the Geul are wooden wattle and boulders and concrete rubble placed at the foot of the riverbanks. They are not always very successful against erosion. Protecting only the foot of a bank might not be enough when discharge is very variable and peak discharges are very high. Wooden wattle is not very common along the Geul. It is used at only three locations. At two of these locations it is used to protect the relatively straight banks under a bridge where the chance of severe erosion is not very high. At the other location, the banks are eroding behind the wooden wattle and its function is lost (figure 6.1).
Boulders and concrete rubble are much more common than wooden wattle. It is a relatively simple way of bank protection at low costs. It is also a successful method. On the map we can see that almost all of the riverbank length protected by this method is stable. There are some locations where the protected banks are unstable, but they are nowhere erosive.

The degree of protection this method offers might be influenced by the height up to which the banks are protected by the boulders or the concrete rubble. At some locations, only the foot of the bank is protected (figure 3.6), at other places the entire bank is covered up to the floodplain (figure 6.2) and it should be considered as bank stabilization, not bank toe protection.
§6.2.3 Bank stabilization

Bank stabilization methods include trees on the riverbanks and the replacement of natural riverbanks by walls.

Walls are the most effective way of bank protection, but also an expensive one. It is only used in locations where erosion could cause damage to valuable objects such as buildings or infrastructure (figure 3.4).

Bank stabilization by trees is found over almost all of the river’s length. Although some authors (e.g. Nolan, 1981; Thorne, 1990) suggest that the weight of trees might destabilize riverbanks, this is not the case in the Geul. Where banks are protected by trees, erosion is strongest between the trees. But bank protection by trees is not a permanent solution, it just delays erosion. A bank with a tree on it might still be eroded, but erosion will be slower than in absence of the tree.

When a bank that is protected by a tree is eroded, two things can happen. The tree can be undercut by the river and eventually fall down or the river might erode the bank around the tree, while the tree will be left standing in the river (or fall down eventually as well). Trees standing high above water level will often be undercut and will eventually fall down. Figure 6.3 shows a tree that is being undercut by the river (the tree’s capacity to limit erosion becomes clear by the development of a scour hole adjacent to the tree where erosion is more intense than directly below the tree). The tree in figure 6.4 is undercut and tipping over, but it is still protecting the riverbank. In figure 6.5, a tree that used to be on the riverbank has now fallen down after it was undercut by the river. Once at tree has fallen down into the river it will divert the flow sideward and thereby increase erosion of the banks (Peters, 2001).

Figure 6.3: A tree near Ter Gracht that is undercut by the river.
When trees are standing too low above water level to be undercut, the river might erode around them. First a scour hole will develop on the upstream side of the tree (figures 6.6A, 6.7 and 6.8). The scour hole will grow as erosion continues. It will expand (figure 6.6C) until the riverbank is eroded all around the tree. The tree is than standing isolated in the river without any connection to the riverbank (figures 6.6D, 6.9, 6.10, 6.11, and 6.12). Some will fall down, others might stand in the river for a long time.
As the river keeps migrating, the bank behind the tree is further eroded and sedimentation on the opposite bank continues. The trees in the river seem to be moving from one bank to the other, although the banks are migrating, not the trees.

Figure 6.6: Schematic representation of erosion around a tree (the red riverbanks suffer erosion). A: no erosion, B: a scour hole is developing, C: the scour hole is extended behind the tree, D: the scour hole has breached through at the other side of the tree.

Figure 6.7: Two scour holes developing upstream of two willow trees near Epen (picture from Jos de Moor).
Figure 6.8: Scour hole upstream of willow tree near Epen. The river has almost breached through behind the tree (picture from Jos de Moor).

Figure 6.9: The scour hole has breached through behind the willow tree (see picture 6.10). The picture is taken near Ter Gracht.
Figure 6.10: The same scour hole as shown in figure 6.9. Here we can clearly see that the scour hole was breached through. The river has eroded the bank behind the tree. A bit downstream (to the right in the picture) we see a tree that has stood isolated in the river, but has fallen down now.

Figure 6.11: The river is eroding the bank behind this tree near Bommerig (picture from Jos de Moor).
§6.2.4 Flow retardation

Flow retardation is achieved by dams. At the inlet channels of the water mills, they are constructed dams that control the water level. The other dams in the river consist of stacks of boulders from bank to bank on the riverbed (figure 3.1). They are used to slow the water and to limit erosion. We find seven of these in section 2 and they are also present in many straight stretches. Straightened sections 6, 8 and 12 all have these dams.

§6.3 Restoring sinuosity of the Geul River

The straightening of the riverbanks has led to faster transport of the water and therefore to higher peakflows downstream. Together with increasing discharges since the fifties (figure 6.13), this increased the chance of flooding. This was one of the reasons for partly restoring sinuosity of the channel (Bureau voorlichting, 2002). Other factors are the aesthetic and ecological value of meandering rivers. These are important aspects because part of the valley is now nature reserve and the meandering Geul adds extra value to it. Combining water management and nature conservation is now one of the aims of the local waterboard (Waterbeheersplan Roer en Overmaas, 2004-2007). The sinuosity of the Geul is restored in a passive way. Bank stabilization and protection are removed and the Geul is allowed to migrate freely over large stretches. This way it will restore its sinuosity itself, but that will take a long time.
Figure 6.13: Illustration of the changes in river discharge (1950’s and 1980’s) at a given return time. Large flood events, small flood events and the average base flow (3.6 m³/sec; see section on hydrology) are indicated (Dautrebande et al., 2000).
Chapter 7: Conclusions

The banks of the Geul have been straightened and protected for centuries. Therefore, the river has not migrated much during this period. A few decades ago, this situation changed. The need for water retention and the realisation of the aesthetic value of a meandering river led to a change in management policy. Since 1988 large stretches of the Geul are allowed to meander freely.

In spite of the new management policy, river migration is still localized, because trees are protecting much of the riverbanks. This will change in the near future because new trees will not be planted on the banks. Once erosion removes the trees that are currently on the banks, river migration will increase. This can already be seen at locations where trees are absent and bank protection is removed.

The occurrence of erosion is influenced by sinuosity and bank protection. Where sinuosity is high, much of the riverbank length suffers erosion. Stretches with low sinuosity have more stable banks. Erosion rates also show an increase with increasing sinuosity. In the research area, erosion rates can be up to 2 meters per year.

Bank protection is the second influence on erosion. Stretches with little bank protection generally suffer more erosion than stretches with a high degree of bank protection.

Lateral sedimentation rates of the pointbars are assumed to be approximately equal to the erosion rates as erosion of the concave bend is compensated by sedimentation in the convex bend. Therefore, lateral sedimentation rates show an increase with increasing sinuosity.

Vertical aggradation rates of the pointbars range from 0.02 to 0.15 meters per year and the highest rates are found in the youngest pointbars. The vertical aggradation rates are not strongly related to sinuosity.

No clear downstream trend can be found in the grainsize samples.
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Waterbeheersplan waterschap Roer en Overmaas 2004-2007
List of figures

<table>
<thead>
<tr>
<th>Chapter</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chapter 2</td>
<td></td>
</tr>
<tr>
<td>Figure 2.1: The Geul river catchment.</td>
<td>6</td>
</tr>
<tr>
<td>Figure 2.2: Topographical map of the research area</td>
<td>9</td>
</tr>
<tr>
<td>Chapter 3</td>
<td></td>
</tr>
<tr>
<td>Figure 3.1: Erosive riverbanks near Ter Graat.</td>
<td>10</td>
</tr>
<tr>
<td>Figure 3.2: Stable and unstable riverbank near Gulpen.</td>
<td>11</td>
</tr>
<tr>
<td>Figure 3.3: Active, vegetated active and inactive pointbars near Partij.</td>
<td>12</td>
</tr>
<tr>
<td>Figure 3.4: Walls replacing natural riverbanks near the town of Mechelen.</td>
<td>12</td>
</tr>
<tr>
<td>Figure 3.5: Trees planted on a riverbank near Ter Graat to stabilise the bank (picture from Jos de Moor).</td>
<td>13</td>
</tr>
<tr>
<td>Figure 3.6: Bank toe protection with boulders near Mechelen.</td>
<td>13</td>
</tr>
<tr>
<td>Chapter 4</td>
<td></td>
</tr>
<tr>
<td>Figure 4.1: Thirteen sections of the research area based on sinuosity.</td>
<td>15</td>
</tr>
<tr>
<td>Figure 4.2: Section 1.</td>
<td>17</td>
</tr>
<tr>
<td>Figure 4.3: Section 2.</td>
<td>17</td>
</tr>
<tr>
<td>Figure 4.4: Section 3.</td>
<td>18</td>
</tr>
<tr>
<td>Figure 4.5: Section 4.</td>
<td>19</td>
</tr>
<tr>
<td>Figure 4.6: Comparison of the riverbank locations in 1965, 1983 and 1965 for A4.1 and A4.2 in section 4.</td>
<td>20</td>
</tr>
<tr>
<td>Figure 4.7: Section 5.</td>
<td>21</td>
</tr>
<tr>
<td>Figure 4.8: Section 6</td>
<td>22</td>
</tr>
<tr>
<td>Figure 4.9: Section 7.</td>
<td>22</td>
</tr>
<tr>
<td>Figure 4.10: Channel migration from 1935 to 1995 in section 7 (from: Stam, 2002)</td>
<td>23</td>
</tr>
<tr>
<td>Figure 4.11: Section 8.</td>
<td>24</td>
</tr>
<tr>
<td>Figure 4.12: Section 9.</td>
<td>24</td>
</tr>
<tr>
<td>Figure 4.13: Comparison of riverbank locations in section 9 in 1983 and 2003.</td>
<td>25</td>
</tr>
<tr>
<td>Figure 4.14: Section 10.</td>
<td>25</td>
</tr>
<tr>
<td>Figure 4.15: Section 11.</td>
<td>26</td>
</tr>
<tr>
<td>Figure 4.16: Section 12.</td>
<td>26</td>
</tr>
<tr>
<td>Figure 4.17: Section 13.</td>
<td>27</td>
</tr>
<tr>
<td>Figure 4.18: Comparison of riverbank locations in 1993 and 2003 in section 13.</td>
<td>28</td>
</tr>
<tr>
<td>Figure 4.19: The percentage of stable bank length in the different sections, plotted against sinuosity.</td>
<td>29</td>
</tr>
<tr>
<td>Figure 4.20: The percentages of stable and protected bank length plotted against sinuosity.</td>
<td>29</td>
</tr>
<tr>
<td>Figure 4.21: The influence of bank protection on stable bank percentage.</td>
<td>30</td>
</tr>
<tr>
<td>Figure 4.22: Length profile of the Geul.</td>
<td>31</td>
</tr>
<tr>
<td>Figure 4.23: Erosion rates, derived by the tree method, plotted against sinuosity.</td>
<td>32</td>
</tr>
<tr>
<td>Chapter 5</td>
<td></td>
</tr>
<tr>
<td>Figure 5.1: Pointbar area class plotted against sinuosity.</td>
<td>34</td>
</tr>
<tr>
<td>Figure 5.2: Example of a bimodal grainsize distribution in a sample from the Geul.</td>
<td>34</td>
</tr>
<tr>
<td>Figure 5.3: Depth profile of pointbar sampling point P1.</td>
<td>35</td>
</tr>
<tr>
<td>Figure 5.4: Pointbar transect with the location of the individual sampling points.</td>
<td>35</td>
</tr>
<tr>
<td>Figure 5.5: Depth profile of pointbar sampling point P7.</td>
<td>36</td>
</tr>
<tr>
<td>Figure 5.6: Depth profile of pointbar sampling point P6.</td>
<td>36</td>
</tr>
<tr>
<td>Figure 5.7: Depth profile of pointbar sampling point P5.</td>
<td>37</td>
</tr>
<tr>
<td>Figure 5.8: Depth profile of pointbar sampling point P4.</td>
<td>37</td>
</tr>
<tr>
<td>Figure 5.9: Depth profile of pointbar sampling point P3.</td>
<td>37</td>
</tr>
<tr>
<td>Figure 5.10: The location of sampling points P8 and P9.</td>
<td>38</td>
</tr>
</tbody>
</table>
Figure 5.11: Depth profile of pointbar sampling point P9.
Figure 5.12: Depth profile of pointbar sampling point P8
Figure 5.13: The location of sampling points P10 and P11.
Figure 5.14: Depth profile of pointbar sampling point P11.
Figure 5.15: Depth profile of pointbar sampling point P10.
Figure 5.16: Depth profile of pointbar sampling point P12.
Figure 5.17: The location of sampling points P13, P14 and P15.
Figure 5.18: Depth profile of pointbar sampling point P15.
Figure 5.19: Depth profile of pointbar sampling point P16.
Figure 5.20: Pointbar-transect through P3, P4, P5, P6 and P7, scale
Figure 5.21: The average coarse modal values of the grainsize samples plotted against distance downstream from the Belgian-Dutch border.

Chapter 6
Figure 6.1: River erosion behind wooden wattle near Mechelen.
Figure 6.2: Boulders protecting the riverbank from the bottom to the top of the bank (half a kilometre south of Epen).
Figure 6.3: Undercut tree near Ter Graat.
Figure 6.4: Undercut tree, tipping over (near Ter Graat).
Figure 6.5: This tree near Ter Graat has fallen down into the river after it was undercut.
Figure 6.6: Schematic representation of erosion around a tree
Figure 6.7: Two scour holes developing upstream of two willow trees near Epen (picture from Jos de Moor).
Figure 6.8: Scour hole upstream of willow tree near Epen. The river has almost breached through behind the tree (picture from Jos de Moor).
Figure 6.9: The scour hole has breached through behind the willow tree near Ter Gracht.
Figure 6.10: Same scour hole as shown in figure 6.9.
Figure 6.11: Bank erosion behind tree near Bommerig (picture from Jos de Moor).
Figure 6.12: Trees in the Geul river near Bommerig (picture from Jos de Moor).
Figure 6.13: Changes in river discharge in the 1950’s and 1980’s (Dautrebande et al., 2000).
List of tables

Chapter 4
Table 4.1: The sinuosity and the percentage of erosive, unstable, stable and protected riverbank for the different sections. 16

Chapter 5
Table 5.1: Classification of the sections into six pointbar area classes. Class 6 has the largest pointbar area per unit river length, class 1 the lowest. 33