Modeling and prediction of the natural decontamination of the mining-impacted Geul River floodplain

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Abstract

Heavy metal contamination due to historical metal mining is an important problem in many rivers around the world. The contamination is very persistent and it is accumulated and spread in the floodplain sediments. This paper presents a study of the mining-impacted Geul River in The Netherlands. The Geul is a meandering river which has been contaminated since Roman times due to metal mining. Especially during the 19^{th} and 20^{th} century zinc and lead mining in Belgium caused contaminated sediments to be deposited on the floodplains of the Geul River.

This study aims to investigate and predict the temporal dimensions of the natural decontamination of zinc and lead at the Geul River floodplain between Cottessen and Meerssen.

The area of study is the floodplain of the Geul River between Cottessen situated at the Dutch-Belgian border and Meerssen located close to its confluence with the Meuse River, approximately the total channel length of the area of study is 20 km. Nine transects along the catchment were chosen out to cover the 20 km. The transects were separately every 4 km in the downstream direction. Sediment cores were taken along each transect every 10 cm in a vertical profile of an average of 1.5 meters depth. The soil samples were later on analyzed to obtain the concentration of zinc and lead with the use of a hand-held X-Ray fluorescence spectrometer. Results from the soil sample analysis were used in a regression analysis to provide information of the actual situation of contamination.

CAESAR model (Cellular Automaton Evolutionary Slope and River Model) was used to simulate two scenarios in which erosion, deposition and remobilization of sediments occur. Two different case scenarios were used to predict the decontamination of 70% of the total excess of contamination of the floodplain. First case scenario used results from regression analysis and sediment output from CAESAR model simulation. Second case scenario used a map of total excess of contamination and an output map of elevation differences from CAESAR model simulation. By the use of an exponential decay formula prediction of the natural decontamination of 70% of the total excess contamination was calculated and compared with the persistence of the metal contamination of a study at River Swale, Northern England.

Results of fieldwork and regression analysis show that upstream floodplain areas contain higher contamination in lead and zinc than downstream areas. Nevertheless, although upstream sediments are more contaminated downstream sediments also show a noticeable content in lead and zinc contamination indicating that the contamination has been already highly widespread along the sediments of the Geul. According with the first case scenario in order to decontaminate 70% of the actual heavy metal contamination of the Geul floodplain will take 1241 years for lead and 1095 years for zinc. The results from the second case scenario are 2140 years for lead and 1745 years for zinc. Therefore, both results show that for the Geul reach to be higher than 70% decontaminated it will take more than thousands years, indicating the environmental problem which causes metal mining at the banks of the river.

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1. Introduction

1.1 Problem definition

Heavy metal contamination of sediments is an important environmental problem on many river systems around the world. The contamination is very persistent and highly widespread causing large areas of floodplains to be polluted during long periods of time. Since the contamination affects large floodplain areas studies to determine the total inventory of pollutants and the patterns that the contaminants show along the floodplain are very difficult to investigate precisely.

Several investigations have shown the large scale effects of the contamination due to extraction and processing of metal ores as well as the high persistence of these contaminants. Modeling studies at River Swale, Northern England have shown that more than 70% of the deposited contaminants remain within the river system for more than 200 years after the mining activities are finished (Coulthard and Macklin 2003). It is also stated by previous investigations that contaminants from historical metal mining can contaminate areas up to several hundred meters from the source where they remain for hundreds or thousand years (Coulthard and Macklin 2003).

The large scale contamination that metal mining causes on many river systems around the world shows the relevance of this study. In this case the mining-impacted Geul River floodplain in The Netherlands is studied. The Geul is a 60 km meandering river situated in an area which has been impacted by active mining since the Roman times, especially during the 19th, and 20th century zinc and lead mining in Belgium caused contaminated sediments to be deposited on the floodplains of the Geul River. The dynamics of meandering rivers cause the dispersal of contaminated sediments along the fluvial system due to high erosion and lateral migration rates.

1.2 Research objective

This study aims to investigate and predict the temporal dimensions of the natural decontamination of zinc and lead at the Geul River floodplain between Cottessen and Meerssen due to remobilization of polluted floodplain sediments due to dynamics of the meandering river.

In order to achieve this goal field samples taken from the Geul floodplain are analyzed in terms of lead and zinc contamination. CAESAR model (Cellular Automaton Evolutionary Slope And River model) developed by Dr. T.J Coulthard (University of Hull, UK) was used to simulate scenarios in which erosion, deposition of sediments due to the meandering and remobilization processes occur. Maps and sediment output of the model were further studied in terms of its relation with heavy metal remobilization and the actual metal inventory of the Geul River. Finally exponential decay functions were used to estimate the natural decontamination of the area of study.

2. Study Area

2.1 Description of the area

The area of study is the floodplain of the Geul River situated in the South of Limburg, The Netherlands. It is a small meandering river which originates at the border between eastern Belgium and Germany and it flows towards the Meuse River (figure 1) located a few Kilometers further from the north of the city of Maastricht, The Netherlands (De Moor et al., 2008). The total channel length is around 56 km, which 36 km belong to The Netherlands and 22 km to Belgium (Leenaers, H., 1989).

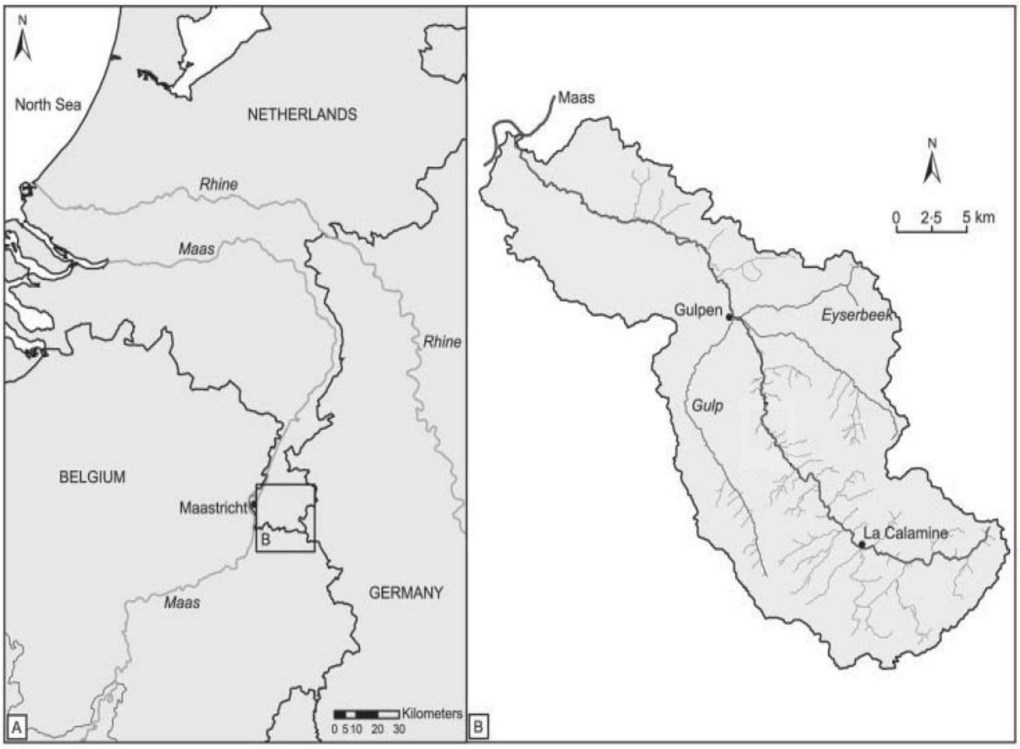

Figure 1: Location of the Geul River cathment (a) and a more detailed map of the Geul River cathment(b)(De Moor et al., 2007).

The Geul River Catchment has an area of 380 km². About 240 km² of the total area is located in The Netherlands (De Moor et al., 2008). The altitude of the catchment varies from 50 to 400 m asl at the confluence with the Meuse River and in the headwaters respectively. The valley gradient varies within the range of 0.02 m m^{-1} to 0.0015 m m^{-1}. The average discharge is 3.4 m^3s^{-1} which fluctuates due to occasional peak discharges larger than 40 m^3s^{-1}. Infrequent high peak discharges can be produce as a result of heavy thunderstorms causing local floods (De Moor et al., 2007).

The actual catchment of the Geul is characterized by large irregular river valleys and flat plateaus that are locally and partly covered by alluvial fans. The area of research in this study is the floodplain which is flat varying in width from 200 m near the Belgian-Dutch border to 700 m near the union to the Meuse River. The river channel width varies from 8 to more than 15 meters (De Moor et al., 2007).The Geul River is considered to be a fast flowing river with maximum lateral migration rates of 2 m yr^{-1} (De Moor et al., 2008).

The geology of the river is characterized by Devonian and Carboniferous limestones, sandstones and shales in the Belgian and southern part of The Netherlands. Soils can be classified as silty loam Luvisols (De Moor et al., 2008).

The land use of the area is mainly farmland (pasture) and the landscape is mainly characterized by the presence of grassland in the river valley. Villages are situated on the hills of the valley as well as camp sites giving Geul valley an important facet as recreational area (Leenaers, H., 1989).

The Geul River is considered to be one of the few partly meandering rivers in The Netherlands. In the last decades, most of the rivers have been straightened and channelized, but due to the high ecological value of the Geul catchment local authorities allow its natural meandering (De Moor et al., 2007).

2.2 Mining activities and metal dispersal in the Geul catchment

Mining activities have played an important role in the Geul basin during centuries. The main sites of mining and ore treatment are located in the Belgian part of the catchment. The most important mining centers were La Calamine, Plombières and Schamlgraf (figure 2). The exploitation of zinc and lead had its origin around the thirteenth century but it was during the nineteenth and twentieth centuries when the mining area started working on a commercial scale (Leenaers, 1989). Industrial operations started at La Calamine orebody in 1806 consisting mainly of Zn oxides. Industrial mining at Plombières and Schmalgraf began in 1844 and 1868 respectively dominating the Pb-Zn sulfides in both of them (Swennen et al., 1994). The last mine closed in 1938 but until 1950s the treatment of the metal ores continued (Leenaers, 1989). Due to the inefficient techniques used and the dumping of tailings in large heaps, pollutants were released directly into the river and accumulated on the river sediments.

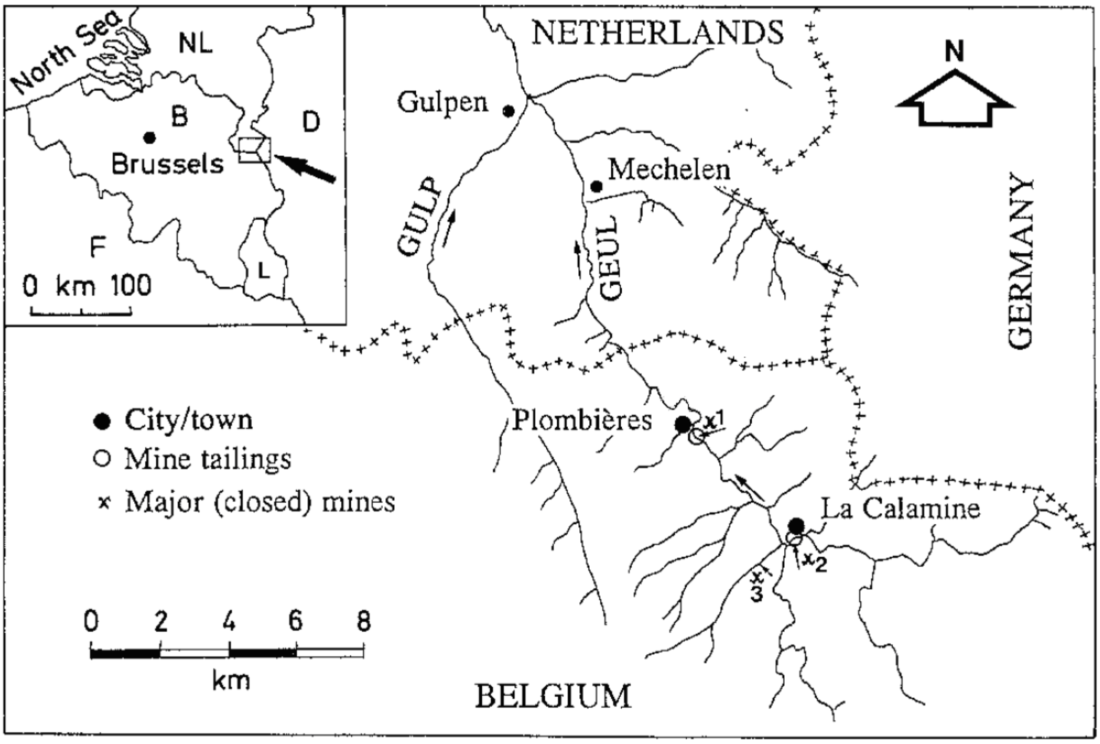

Figure 2: Location of the three mining centres: 1. Plombières; 2. La Calamine; 3 Schmalgraf. (Swennen et al., 1994).

Between 1845 and 1882 the peak of mining activities took place. The metals that were introduced into the river system came from the mine water pumping and ore treatment effluent. This provided the river with high concentrations of suspended solids that made the river water more acid due to the oxidation of sulfides. As a result of this, the river water experienced an increase in its dissolved metal carrying capacity (Stam, 1999).

The meandering character of the Geul River implies that processes as erosion, transport and deposition processes play an important role on the downstream migration of sediments. This migration process can also be influenced by changes in discharge of the river as for example peak discharges and consequent inundation of the floodplains. All these factors can have an effect on the contents of heavy metals of the sediments of the Geul River.

The contamination of the sediments by zinc and lead provided the necessary habitat conditions for the zinc flora (*Viola calaminaria*) to live in. Recently a registered a decrease in the zinc flora populations have been registered. This could have happened partly as a result of the meandering of the river as the lateral erosion produces the dilution of the contaminated sediments (De Moor et al., 2007).

Floodplains play an important role on the storage of metal-rich sediments. During overbank floods these sediments can be remobilized and re-deposited. The frequency of flood events makes an influence on the remobilization-re-deposition rate (Dennis et al., 2008).

Previous studies (Leenaers et al., 1989) performed by in the Geul River found a decrease of metal concentrations on the downstream direction. This was explained as a result of dilution processes with clean bed, bank and hillslope material (Leenaers et al., 1989). According to this study, discharge and distance to the source and floodplain geometry are important factors to consider when studying the metal dispersal in the catchment area. Total metal concentrations experience an exponential reduction with distance to the source by dilution processes. The geometry of the floodplain was found to make a large influence on the distribution of the pollutants at local scale (Leenaers et al., 1989).

3. Methodology

3.1 Fieldwork and sampling collection

With the purpose of studying the metal dispersal over the Dutch floodplain of the Geul catchment the heavy metal inventory was calculated. For that issue, fieldwork was done along the river valley to carry out sample collection. Therefore, several locations were chosen over the catchment of the Geul River to take sediment cores from the floodplain. Nine cross-sections distributed approximately each 4 Km on the upstream direction were performed.

The distribution of the drilling locations, numbered by transects along the river valley (figure 3), looks as follows:

1. Meerssen.
2. Strabeek.
3. Schin op Geul.
4. Keutenberg.
5. North Gulpen.
6. Partij.
7. Mechelen.
8. Terpoorten.
9. Cottessen.

The coordinates of the exact location of each coring is provided at Appendix 3.

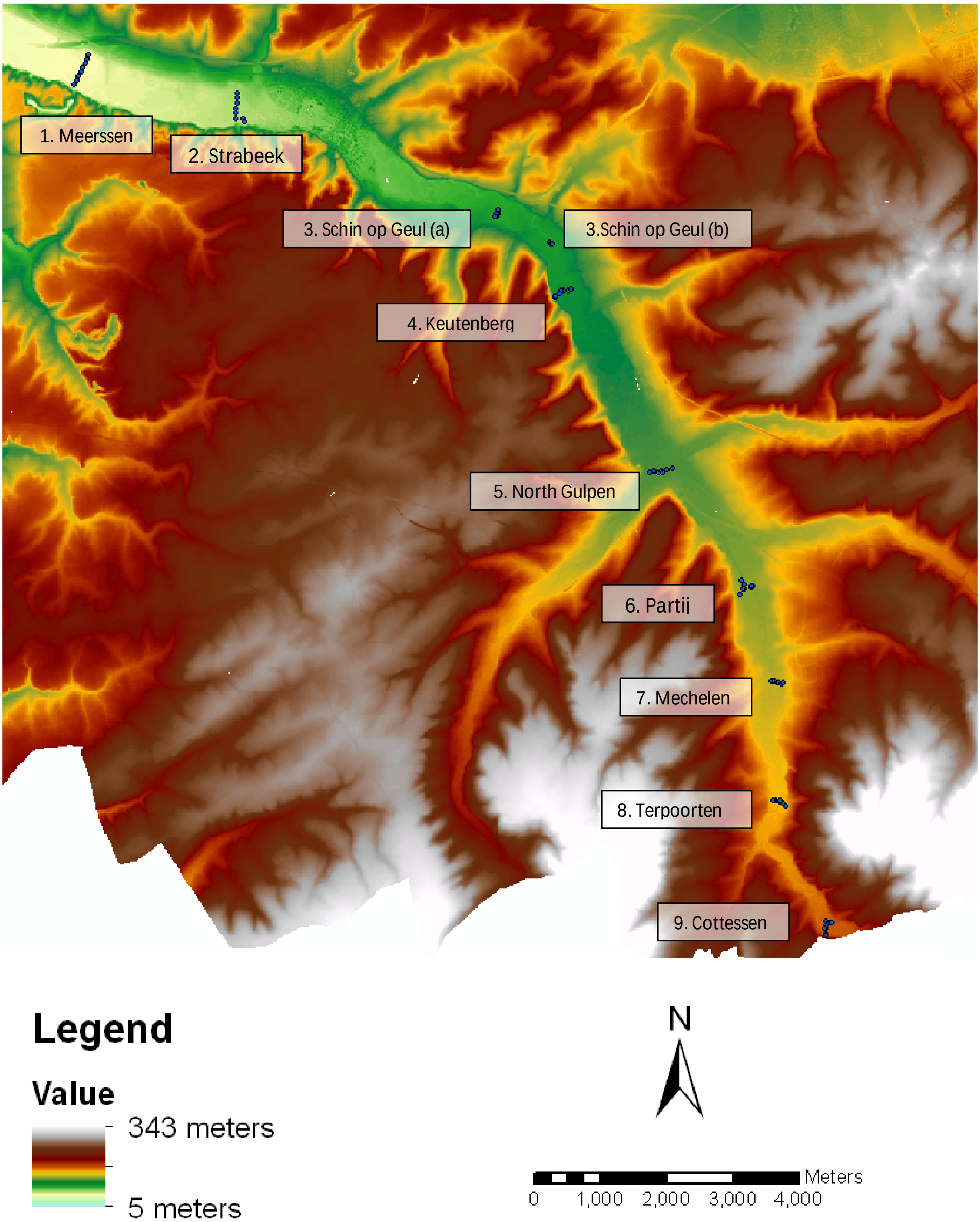

Figure 3: Location of the coring transects along the area of study.

In transect 3, Schin op Geul, two locations were chosen (a and b) due to the impossibility of performing the whole transect in location a as it was a private property.

The cross-sections were done perpendicular to the direction of the valley. In each transect up to 11 corings were performed distributed in both sides of the river according to the width of the valley and the morphological units present in it. Samples were taken each 10 cm deep in every coring reaching in occasions a maximum depth of 2.5 m was reached. The total number of collected samples is 1238. All the samples were stored in plastic bags and labeled according to the location and depth they were taken from.

3.2 Sampling analysis

Due to the large number of samples collected for the analysis of heavy metal contaminants a portable X-ray fluorescence analyzer was used for detecting and quantifying zinc and lead concentrations in sediments in a fast, easy and accurate way.

With the purpose of assessing the heavy metal concentrations of the samples collected in the Geul catchment CSO Adviesbureau voor Milieu-Onderzoek (B.V., P.O. Box 1323, 6201 BH Maastricht, The Netherland) kindly provided us with Thermo Fisher Scientific Niton® XL3t-600 handheld XRF analyser with which the measurements were performed (figure 4).

Figure 4: Fisher Scientific Niton® XL3t-600 handheld XRF analyser (Learn XRF com, 2011).

Studies have demonstrate that soil moisture content of the samples measured directly in the field leads to lower values of lead concentrations than the samples measured after being homogenized and dried in the laboratory (Hürkamp et al., 2009). If the samples have more than 20% of water content the accuracy of the XRF analyzer measurements is no longer assured (Learn XRF com,. 2011).

Therefore, the collected samples of the Geul catchment were fully dried during two weeks at room temperature (25°C).They were afterwards manually homogenized by the use of a mortar in order to obtain more representative average values of the locations where they were collected.

The concentrations of zinc and lead for each sample obtained using a Fisher Scientific Niton® XL3t-600 handheld XRF are expressed in ppm.

3.3 Preparation of the data for spatial analysis

After visual examination of the whole heavy metal concentration data set obtained from the measurements taken with Fisher Scientific Niton® XL3t-600 handheld XRF, the natural background values for lead and zinc were assessed. Transect 1, located at Meerssen, is the furthest located from the mining source and has the lowest heavy metal concentrations. Therefore, average minimum values from this transect were set as standard background values of lead and zinc in soil for the Geul catchment. These are 10 ppm and 40 ppm for lead and zinc respectively.

By subtracting the background values to the lead and zinc concentration values obtained with the handheld XRF the excess concentration values that every sample contained were calculated.

After taking into consideration the bulk density of a soil profile of (1.33 g/cm^3) and an average depth value for every sample of 0.10 m the heavy metal concentrations in ppm were transformed into g/m^2. All sample values per coring until 1.70 meters depth were summed up to obtain the total amount of lead and zinc per coring.

With the goal of evaluating the total inventory and the spatial distribution of heavy metal concentration along the floodplain the statistical method of regression analysis was used. With this method two different cases were performed. The first one describes the relation of the heavy metal concentration with the distance to the Belgian border. The second case describes the relation of the content of heavy metal per coring with distance of each coring to the river.

In order to obtain a linear relationship between the 2 studied variables, the amount of heavy metal in g/m^2 was Ln-transformed.

With the aim of study the distribution of contaminants at the geomorphologic units within the Geul catchment three mayor units were differentiated: abandoned channel, point bar and floodplain. After the fieldwork performed in this study the results of every coring were sorted within one of the three geomorphologic units according to its characteristics. The summation of the amount of total heavy metals for every single geomorphologic unit was assessed and divided by the number of samples per geomorphologic unit. Therefore, an average value of the metal concentration of each geomorphologic unit was calculated.

4. Results of the spatial distribution of heavy metal contaminants

4.1 Statistical analysis

The statistical analysis presented in this study was developed in further detail in the thesis called "Heavy Metal contamination in the Geul River: Assessment of the metal inventory in and export from the river valley" (Miguel Ayala., L. 2011). Graphs and tables of the calculations and results can be found in the mentioned study.

4.1.1 Regression analysis of contamination and distance to the Belgian border

The amount of heavy metal represents the dependent variable Y while the independent variable X is the distance from each transect to the Belgian border. Next graphs show the linear regression analysis of lead and zinc with distance to the Belgian border.

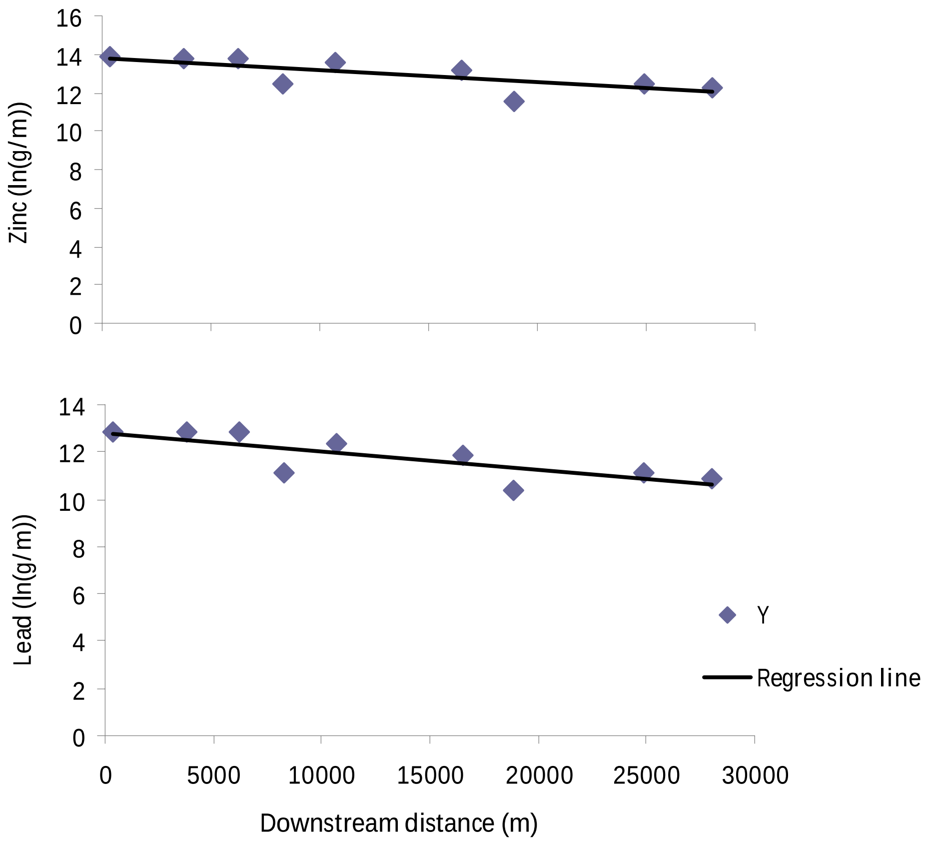

Figure 5: Linear regression analysis graphs of lead and zinc with downstream distance (0 m is situated at the Belgian border)

Table 1: Statistical parameters of linear regression analysis graphs of lead and zinc with distance to the Belgian border.

Regression Statistics	Zinc	Lead
Determination coefficient R^2	0.53	0.60
P value	0.025	0.014
Standard Error	0.61	0.65
b (slope)	-6.4E-05	-7.85E-05
a (intercept)	13.82	12.83

The results showed an expected decrease in heavy metal concentrations when increasing distance to the river since the source of contamination is located in the upstream part of the river. Therefore, higher contamination values remaining upstream are transported downstream within the sediments by processes of erosion and deposition.

In some cases, like transects 4 and 7, lower heavy metal contents than the predicted values in the regression analysis are found. Some of the corings at transect 4 are located at a campsite therefore a mixing up of soil layers could have influenced the decrease in heavy metal content in this area. At transect 7 the reason may be the influence of an alluvial fan where clean sediment from the hill slopes is deposited.

4.1.2 Regression analysis of contamination and distance to the river

The natural logarithms of the heavy metal amounts of the corings g/m^2 per transect represent the dependent variable Y while the independent variable X is the distance from each coring to the river. Since this regression analysis is qualitatively but not numerically used in this study graphs and tables can be found at appendix 1.

From this analysis it can be inferred that amounts of zinc as well as lead diminishes when the distance from the river increases.

4.2 Geomorphologic analysis

The summation of the amount of total heavy metals for every single geomorphologic unit was assessed and plotted in a graph as follows (figure 6):

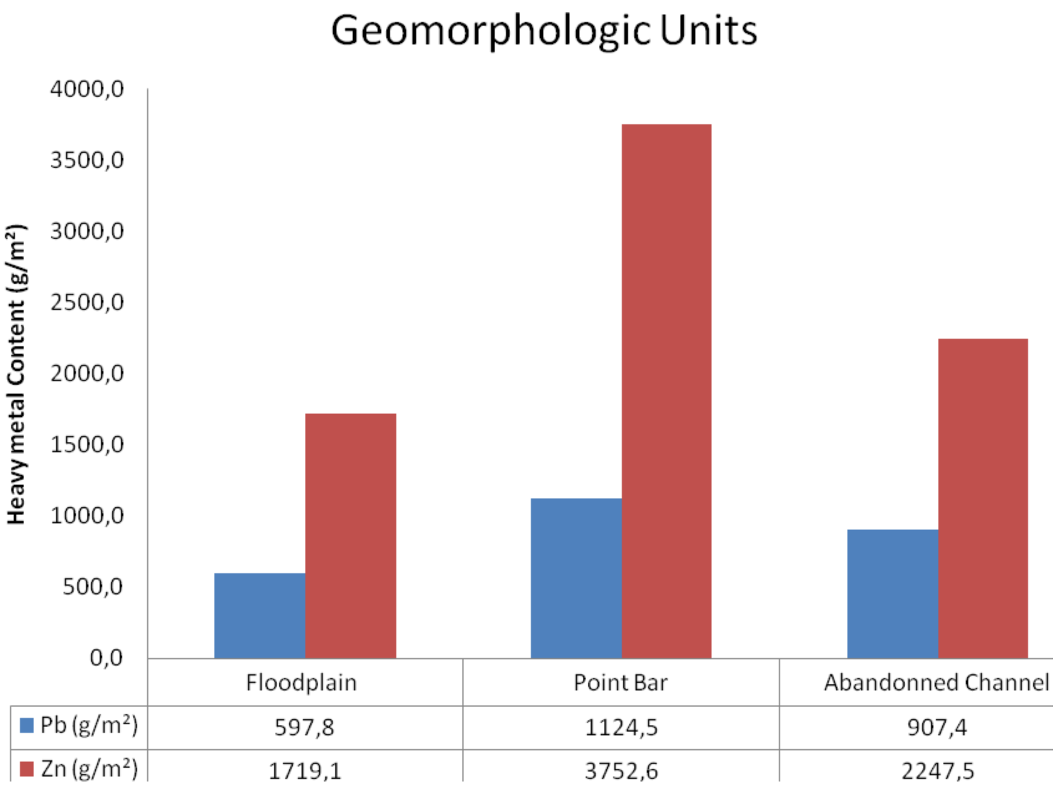

Figure 6. Heavy metal content corresponding with each geomorphologic unit.

As it can be seen in the previous graph the highest content of heavy metals are accumulated in the point bars followed by abandoned channels. Floodplain areas are the ones with less heavy metal concentration due to the low frequency of inundation. The further from the river channel the lower heavy metal concentration is. The abandoned channels are areas where water does not normally flow anymore (but for in occasional high discharges) and therefore dilution processes cannot take place. Highest heavy metal concentrations are found in point bars. Point bars are the places where contaminants are more active due to erosion-deposition processes and where they first get accumulated before being remobilized due to these processes.

6. CAESAR model: Cellular Automaton Evolutionary Slope and River model

CAESAR is a two dimensional flow and sediment transport model which can simulate morphological changes in river catchments or reaches. Initially this model was part of a PhD project from Coulthard (1999). Since then the model has been further developed in sophistication and application. It has been used in over 100 reaches and catchments over the world on catchment scales ranging from 1 km^2 to 1000 km^2 and reaches up to 40 km in length. For the simulation it has been also used to various timescales, from individual floods to 10 000 years (Coulthard and Van De Wiel, 2011).

Initially CAESAR was applied on the catchment scale; however due to its capability of simulating erosion and deposition over river reaches it led to a development of a 'reach mode version'. In reach mode water can be added as input at a point within the model and erosion and deposition observed in a more detailed view over the reach (Coulthard and Van De Wiel, 2011).

Further developments of the model include the possibility to simulate river meandering. Lateral erosion is added using a novel edge counting algorithm that counts the number of wet and dry cells next to the river bank and then uses this to calculate whether it is on the inside or outside of a bend (Coulthard and Van De Wiel, 2011).

6.1 Model structure

CAESAR model is a catchment cellular model or cellular automata (CA) which represents processes on a two dimensional framework or mesh of grid cells. The concept of the model can seem easy, however, the interaction between cells and its operation can be quite complex and lead to non linear behavior.

In order to provide a general scheme of how CA models work next figure shows a diagram of key processes involve:

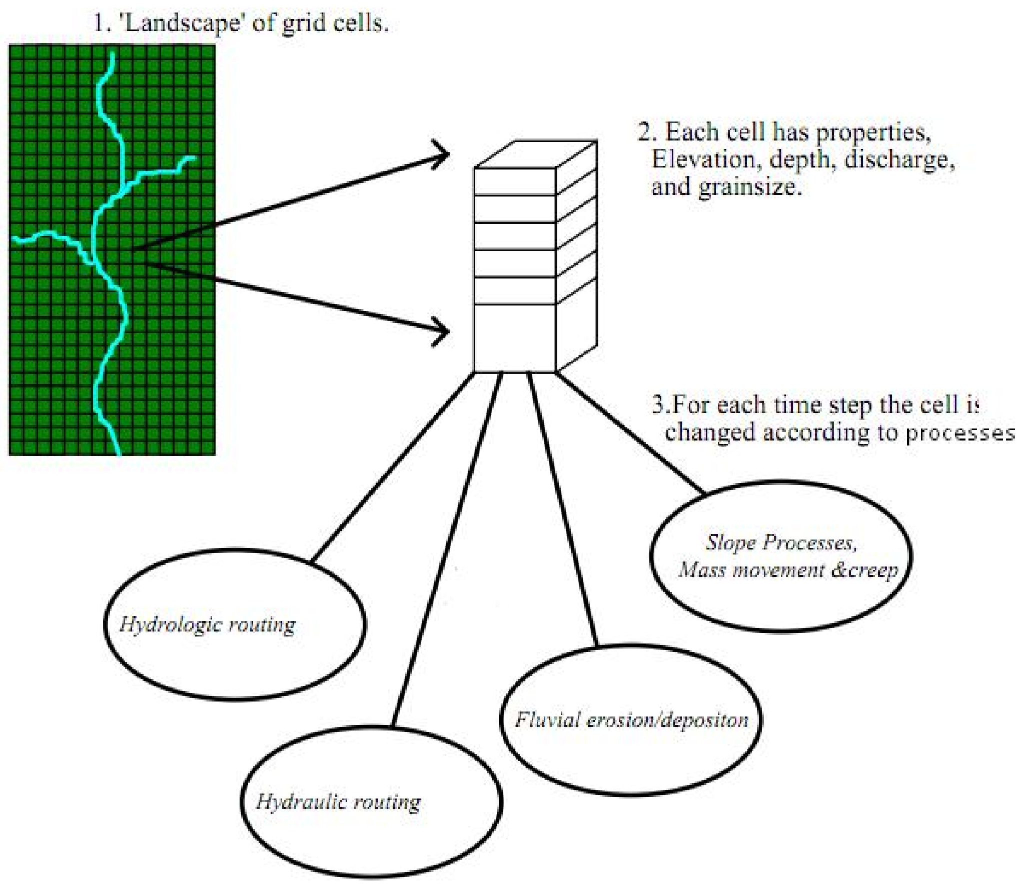

Figure 7: Schematic diagram of the key processes operating in the CA model. (Coulthard, T. J., 1999)

CAESAR represents the catchment as a domain composed of uniform square grid cells, each of them contain initial properties of the domain as elevation, water depth, discharge, vegetation cover and grain sizes fractions. According with the different processes descriptions that apply in the model which will be explained in further detail in the next section, the values of each cell are updated with respect to the neighboring cells each time step. As an example, erosion in a cell depends on the depth of water in the cell and the slope between that cell and its neighbours (Coulthard, 1999).

CAESAR model can run in two different modes: catchment mode and reach mode. Catchment mode uses as input an hourly rain data set while reach mode uses one or more points where discharge is inputted to the system (Coulthard, 1999).

As in this study only the reach will be used the structure and requirements of this mode will be explained below.

6.2 Reach mode

Reach mode of CAESAR uses a DEM file of the zone of study. DEM should be prepared in the way that any sink or pit are removed and taking into account that the exit point of the DEM should be on the right hand edge of the map, so the drainage network follows a descent path towards the exit point. It is also necessary to introduce a bedrock file which indicates the depth at which the bedrock is situated (Coulthard and Van De Wiel, 2011).

Reach mode requires a point or series of points were discharge and sediment data is introduced in the system. The file has the text format, first column corresponding to time steps, water discharge (m^3/s) in the second column and inputs for the different grain size fractions (m^3 corresponding to each time step) in the 6th to 14th column. Consequently, output file has the same format as it will explained later (Coulthard and Van De Wiel, 2011).

6.2.1 Flow routing

Discharge is inputted at one or different points of the river system and then it is routed using a scanning multiple flow algorithm. CAESAR uses a "flow-sweeping" algorithm. During a sweep water discharge is routed to a range of cells in front and distributed according to differences in water elevation of the donor cell and bed elevations in the receiving cell. In case an obstruction on the channel no donor cells can be identified in the sweep direction and the discharge remains in the donor cells to be distributed in following sweeps in different directions (Van De Wiel et al., 2007)

Manning's equation is used to calculate flow depth and flow velocity as the following formula shows:

$$Q\ [m^3 s^{-1}] = UA = \frac{1}{n} h^{2/3} \sqrt{SA}$$

where *Q,U,* and *h* are respectively discharge, flow velocity and flow depth, A is the cross-sectional area of the flow ($A = h\ c_w$), *S* is the average downstream slope, n is Manning's coefficient and c_w is cell width (Van De Wiel et al,. 2007).

6.2.2 Sediment transport

Erosion and deposition are caused by movement of beadload and suspended sediment within the alluvial channels. Flow which is not removed from the basin remains for the following iteration and consequently hollows are filled up and flow trapped in meanders remains leading to simulation of meandering and braiding processes.

Wilcock and Crowe equation is used to model fluvial erosion and deposition for all cells with a flow depth (Coulthard and Van De Wiel, 2011). Therefore, sediment transport is driven by this equation which calculates transport rates qi, for each sediment fraction i (Van De Wiel et al,. 2007):

q_i [m^{3}s^{-1}] = $\frac{F_i U_*^3 W_i^*}{(s-1)g}$

where F_i denotes the fractional volume of the i-th sediment in the active layer, U_* is the shear velocity, s is the ratio of sediment to water density, g denotes gravity and W^*_i is a complex function that relates the fractional transport rate to the total transport rate (Van De Wiel et al., 2007).

Rates of transport can be converted into volumes, V_i, by multiplying transport rate q_i with the time step of the iteration:

V_i [m^3] $= q_i d_t$

Neighbours cells with lower bed elevations are considered to transport bed load (figure 8 a). On the other hand, transport of suspended load is routed to cells where water elevation is lower than in the cell considered (figure 8 b) (Van De Wiel et al., 2007).

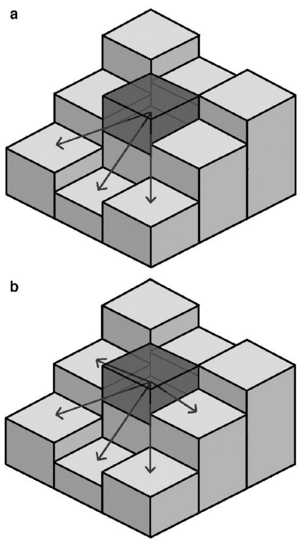

Figure 8: Routing directions for bed load (a) and suspended load (b)(Van De Wiel et al,. 2007).

6.2.3 Lateral erosion

In order to calculate lateral erosion at the model an algorithm composed by three parts is used. First it determines the local channel curvature then calculates the lateral erosion and afterwards distributes the eroded sediments across the channel (Van De Wiel et al,. 2007)

The difference between CAESAR model and linearized meander models is that CAESAR calculates depositions along the inside banks from the model's automaton rules instead of assuming a fixed channel width. In order to develop inside bends the model uses the hydraulic conditions within the channel to deposit sediments (Van De Wiel et al., 2007).

6.3 Operation and outputs

As it is explained before every cell has properties of elevation, water discharge, depth and vegetation cover, depth to bedrock and grain sizes. During each iteration the rules governing the model determine the behavior of the system and cells properties are updated.

As consequence, CAESAR provides result outputs in two formats. The spatial data as elevation, water depth and grainsizes comes in tables of ascii data that can be imported into ARC-GIS. Water and sediments outputs at the right hand downstream edge of the DEM are in a text format output file.

The spatial data can be analyzed by subtracting a DEM created for one certain time from a DEM from another and then observe the spatial patterns differences in erosion and deposition.

Water and sediments output come in the same format as the input file, containing discharge values at the outlet in the second column and the sediment discharges of the nice grainsizes in the following columns (Coulthard and Van De Wiel, 2011).

6.4 Validation and uncertainty

CAESAR is designed as a tool for scientific research and hypothesis testing. The accuracy of the physical processes which represents is largely unknown as well as the effect of the physical processes represented as 2D. This limitation is due to difficulties when validating some of the results. Validation of the model can be complex since the model generates data that cannot be measured directly in the field.

As an example, the flow can be compared against measured flood levels, however erosion and deposition are more difficult to compare since normally there are not field data related with these processes. In general, not only for CAESAR but for fluvial models the limitations are due to the heterogeneity of the natural environments and the difficulty to measure it and represent it in a numerical model (Coulthard and Van De Wiel, 2011).

7. Application of CAESAR model to the Geul River using reach mode

7.1 Model inputs

7.1.1 Digital elevation map, DEM

In order for the model to perform the simulations the input data needs to be previously modified to fulfill the model requirements.

The elevation map used is the one of The Netherlands (AHN) with a resolution of 25 meters. According to this cell width, the area for each cell is 625 meters. The catchment of the river Geul was cut out from the AHN map. In order to select the floodplain from the whole catchment area of the river Geul the scale was modified leaving out values over 125 meters. The main channel line was manually drawn in some parts and lowered 2 meters. Sinks were removed and some walls were added in the input and output cells to force the water to properly flow in and out of the channel.

A bedrock file was created subtracting 2 meters from the final DEM of the Geul catchment.

CAESAR model is designed such that the main channel flows from left to right. This requirement implied some more changes in the original DEM. To obtain a flow direction from left to right, the catchment had to be rotated 180° as figure 9 shows. In this case, the outlet of the River Geul points south. Therefore, the DEM was clipped on the right side as it can be seen in figure 9.

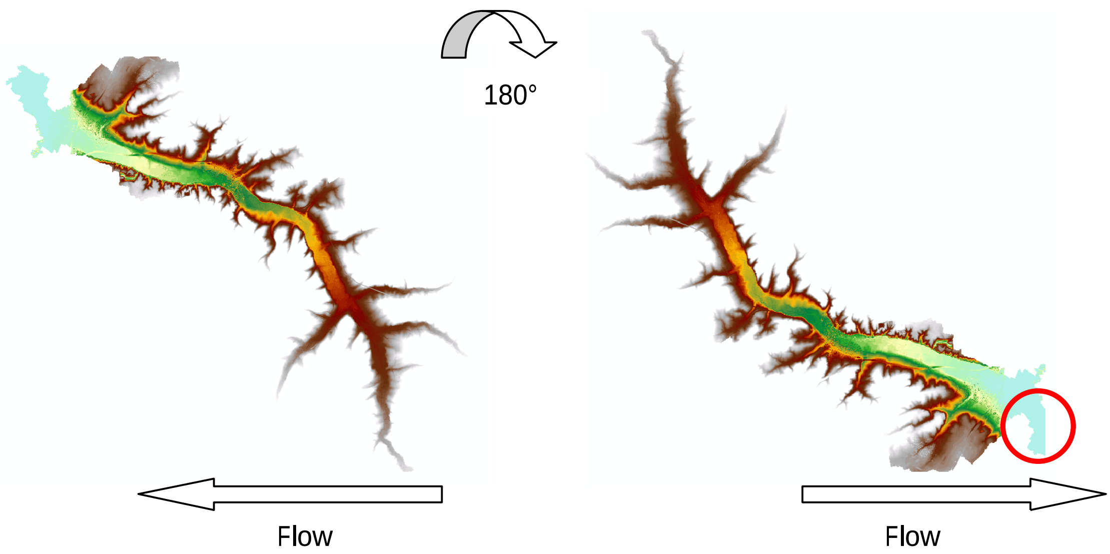

Figure 9: Original map (left) and clipped map (right).

After these modifications the final DEM resulted in a file with 514386 cells. Among this total, the number of active cells is 96306. The surface elevation varies within the range of 37-131 meters a.s.l.

7.1.2 Discharge

There are two different types of simulations in this study. One of the simulations contains only hourly discharge values in m^3/s corresponding with each time step and no suspended sediment data was introduced. The other one contains as input suspended sediment data corresponding from the rating curves calculated together with hourly discharge data.

Locations of input discharges in the model correspond with the locations of the meteorological stations where discharges of the Geul River and its tributaries are measured. (See appendix 4 for exact coordinates of the locations.)

Due to the lack of discharge information at the lowest half part of the Geul catchment two extra discharge inputs, Downstream 1 and 2, were added along the main channel. The locations of the discharge locations introduced in Caesar reach mode are shown in the following map:

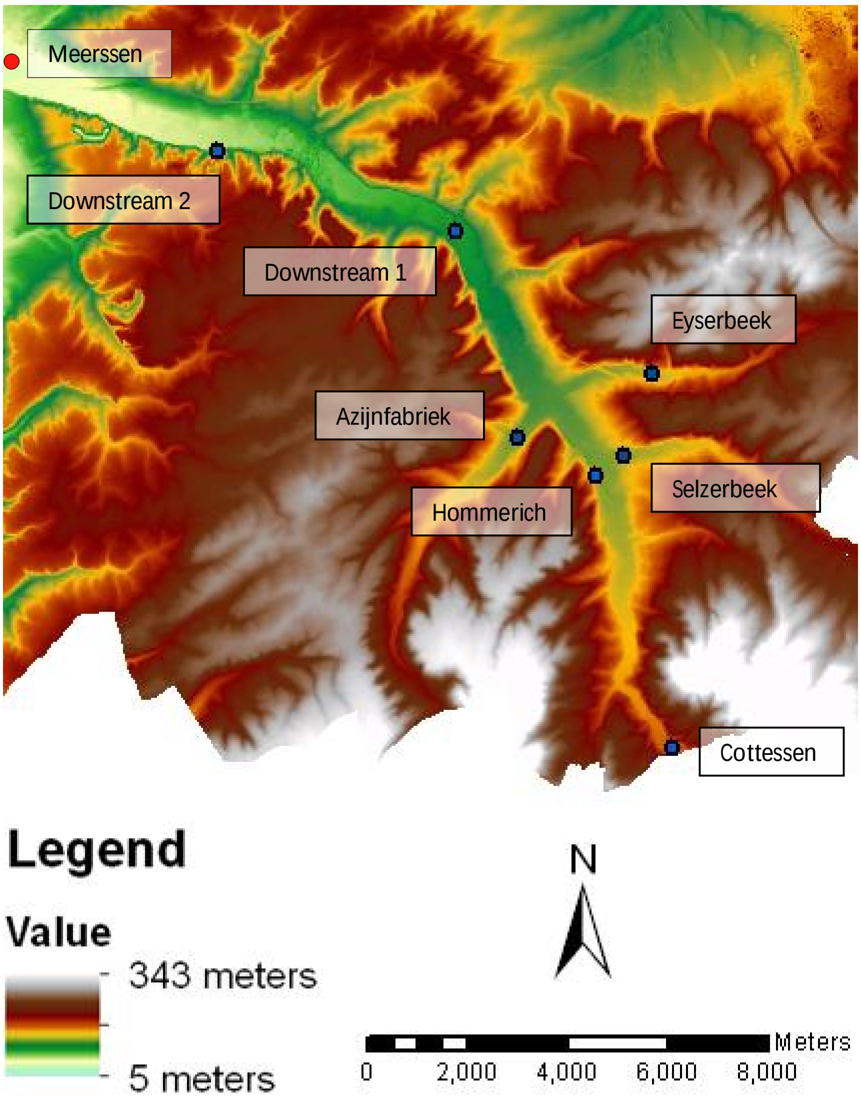

Figure 10: Locations of Caesar input discharges along the Geul catchment (blue dots). Downstream discharge station at Meerssen (red dot). See appendix 4 for exact coordinates of the locations.

Due to the fact that both Cottessen and Hommerich are located at the main channel some calculations were needed to get the set of discharge data values corresponding at Hommerich location avoiding adding double discharge values to the model. Assuming an average flow velocity of 1m/s (Wiggers et al., 2006) and measuring the distance from Cottessen to Hommerich measure stations (8200 meters) it was possible to calculate the time delay at which discharges at Cottessen reach Hommerich. Therefore, hourly discharge data set of Cottessen was subtracted from hourly Hommerich data set at two hours shift and the resulting data set introduced at Hommerich.

In order to calculate the last two input discharge locations, Downstream 1 and 2, several calculations were necessary to approach the corresponded discharge values to realistic values. Using available data from a discharge station at Meerssen (located downstream the Geul catchment next to its confluence with the Meuse river) the discharges for the two downstream locations 1 and 2 were calculated.

Considering a flow velocity of 1 m/s (Wiggers, et al., 2006) and a distance of approximately 22 km from the location at where all the upstream discharges merge (Azijnfabriek, Eyserbeek, Hommerich, Selzerbeek and Cottessen) result in 6 hours of travel time from this mentioned location to Meerssen station.

Therefore, subtracting upstream discharge values where water merges to Meerssen discharge values at 6 hours shift it is possible to calculate the remaining discharge values corresponding to an input at the downstream part. However, in order to make it more equally spatial distributed the calculated discharge values were divided by two and two downstream inputs set of values were introduced in the model.

Downstream 1 is separated from the merging point of the upstream inputs at 7 km, therefore corresponding to a 2 hours shift in discharges. Downstream 2 is located 7 km further down than the location of downstream 1 with another 2 hours shift in discharge values. In this way and taking into consideration a flow velocity of 1m/s a peak discharge value occurring at downstream 1 appears at downstream 2 location 2 hours later. Consequently, the former peak discharge value will appear at Meerssen discharge station 4 hours later.

7.1.3 Suspended sediment

For the modeling of scenario 1 carried out in this study, suspended sediment data was introduced in the model as an input. Discharges and suspended sediment data were put together in a text file in columns 2nd and 6th respectively, for every input location. To assess the amount of suspended sediment to be introduced into the model rating curves were used.

A database of suspended sediment (Roer en Overmaas Water Authority) of the Geul catchment was used. The values of suspended sediment from Cottessen, Hommerich, Azijnfabriek and Selzerbeek that corresponded with the discharge input locations for the current study was used.

Only the values from years 1994, 1997 and 2000 were selected as they were the most complete and recent ones matching with the available discharge data.

Due to the fact that the values of suspended sediment were expressed in mg/l, these values were transformed to kg/m^3 and later multiplied by the corresponding discharge in place and time (m^3/s). Obtained suspended sediment values were finally expressed in m^3/s, after being divided by bulk density, which is 1600 kg/m^3 for suspended sediment.

Suspended sediment values (m^3/s) and their correspondent discharge values (m^3/s) were plotted as the following graphs show.

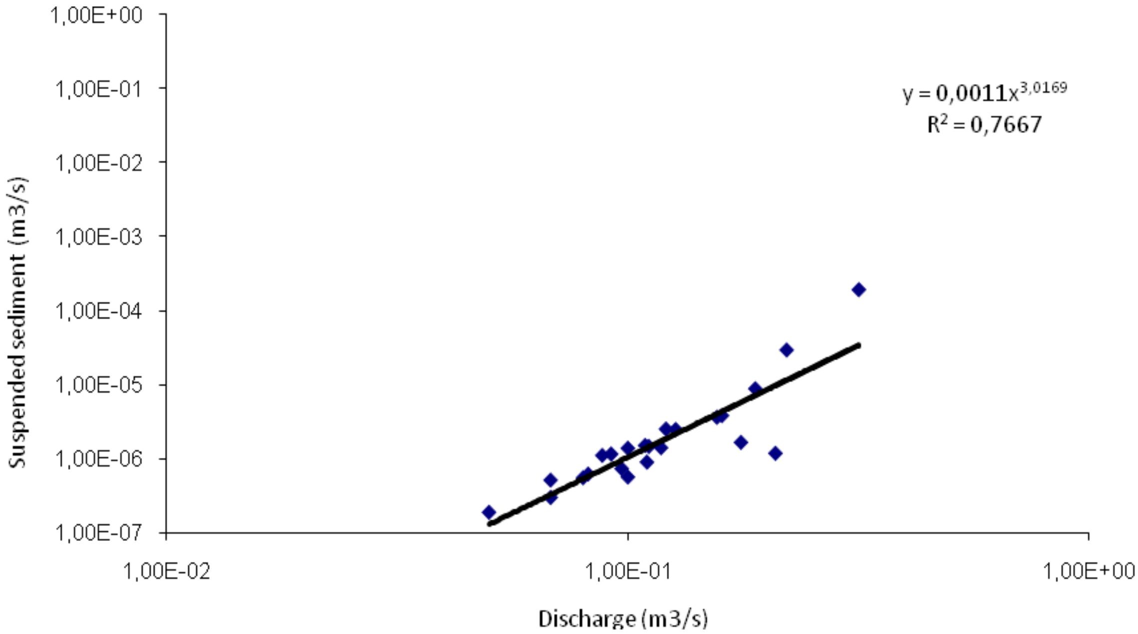

Figure 11. Sediment rating curve at Eyserbeek.

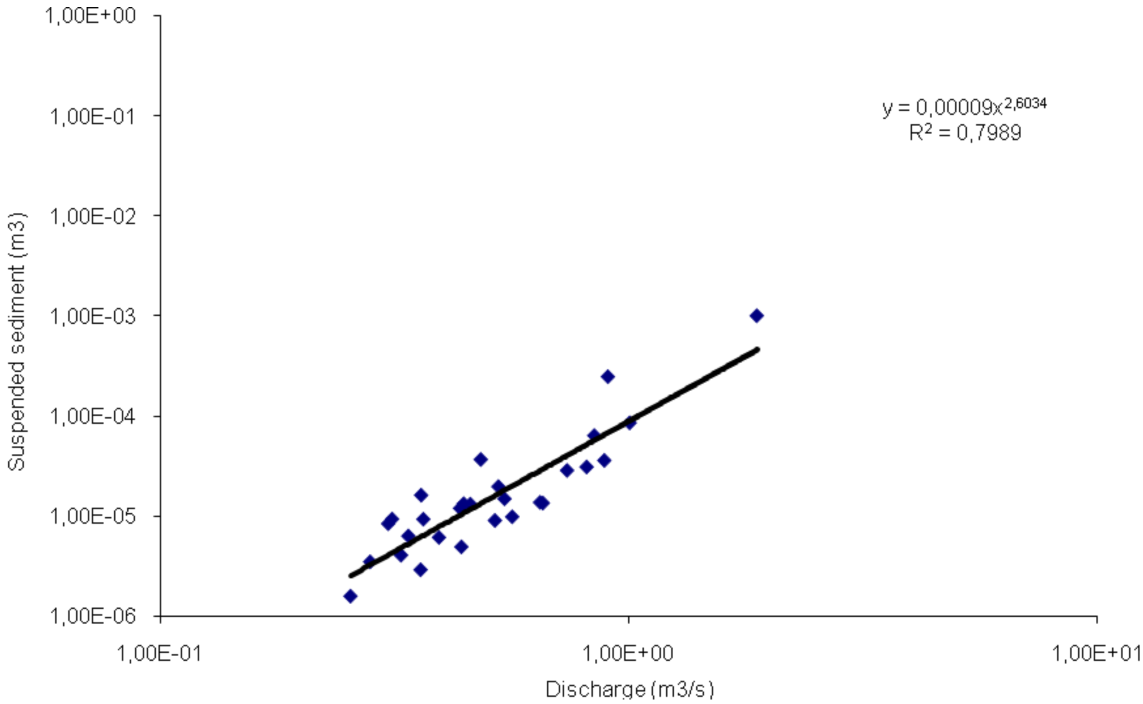

Figure 12. Sediment rating curve at Azijnfabriek.

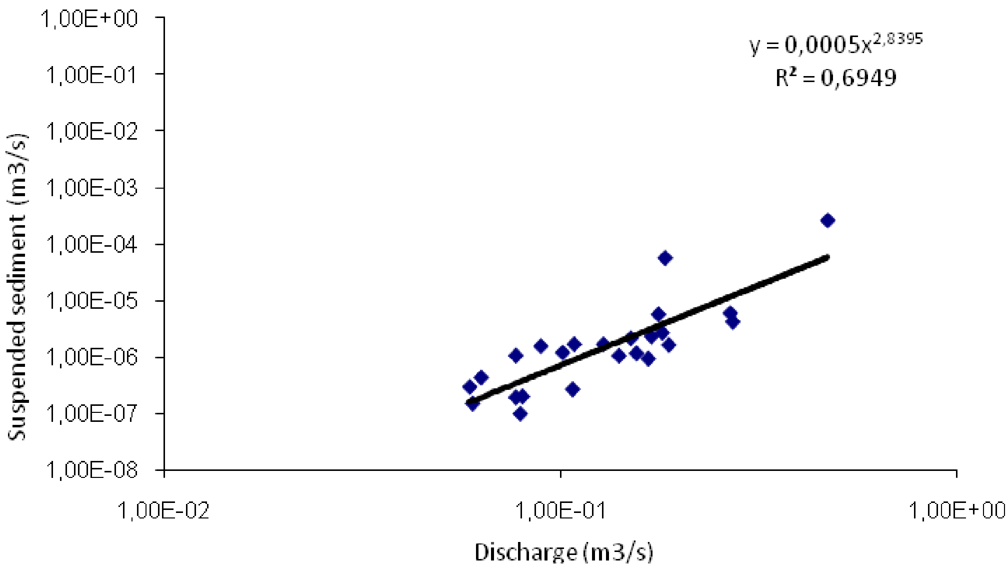

Figure 13. Sediment rating curve at Selzerbeek.

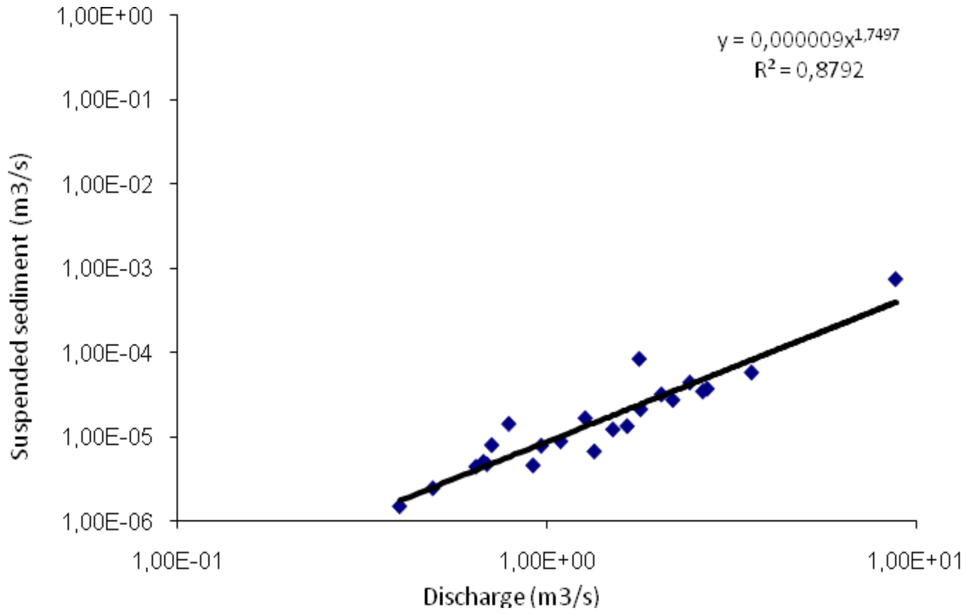

Figure 14. Sediment rating curve at Cottessen.

The formulas of each of the rating curves presented next to the previous graphs were used to introduce suspended sediment at their respective discharge station. Input locations “downstream 1” and “downstream 2” were introduced without suspended sediment as they are not real discharge stations and consequently there is not suspended sediment data associated with the discharge.

7.1.4 .Model parameters

The version of CAESAR model used for carrying out this study is 6.2g. The input parameters used for this version can be classified in different types based on the way their values were set. A summary of the main parameters is listed in table 5.

Some of the parameters are standard model parameters as for example parameters involving vegetation, while some others were set after several runs of the model and comparison of results for each of them. Finally the rest of the parameters were set after calculations with real data and/or by comparison to parameter values found in literature.

Table 2. List of the main parameters.

Parameter	Value
Lateral erosion (m/year)	0,5
Min Q for depth Calc (m)	0,25
Water depth threshold above which erosion will happen (m)	0,005
Initial discharge (m3/s)	1
Max erode limit (m)	0,1
Memory limit	3
Init# of scans	50
Max velocity used to calculate Tau (Pa)	5
Vegetation (critical shear stress) (Pa)	100
Vegetation (grass maturity)	1

Next some of the most important parameters are explained in further detail.

Lateral erosion rate was set as 0,5 m/year after running the model with several values within the range of 0.3-2 m/year according to lateral erosion values found in the study carried out by De Moor (2006).

Among the two methods to calculate lateral erosion method 1 was chosen where lateral erosion includes vertical erosion as the follows expression shows:

Lateral erosion [m/year] = (vertical erosion * lat rate) / grain size

The initial discharge was set as 1 m^3/s (Wiggers et al., 2006).

Four grain sizes were differentiated according to the Diameter limits (mm) USDA Classification and based on fieldwork data obtained by Van Heemskerk, Van Rijnsoever, (2005) included in the appendix 8 (drilling sites) of the mentioned study. The proportion of each grain size (as a fraction of 1) was set as the following table shows:

Table 3. Grain sizes and proportions of each of them.

		Grain size (µm)	Proportion
Size 1	Suspended Sediment (clay + silt)	<50	0.64
Size 2	Fine sand	50-150	0.18
Size 3	Sand	150-300	0.07
Size 4	Coarse sand	300-1200	0.11

The fall velocity for the suspended sediments was set at the default value of 0.0033 m/s.

Min Q for depth Calc (minimum discharge for depth calculation) is the threshold above which the model will calculate a flow depth. It is dependent on grid cell size, being 0.1 meter per meter cell size, for example a DTM with 10m cell size will have a Min Q of 0.1, and a DTM with 50m cell size will have a Min Q of 0.5. In this case, the cell size is 25 meters. Therefore, Min Q for depth calculation was set as 0.25. (Coulthard, 2010).

The max erode limit (m) determines the maximum amount of material that can be eroded within a cell (Coulthard, 2010). In this study the erode limit is 0.1 m.

The ini# of scans refers to the number of scans required to establish the zone around the channel where the model concentrates (Coulthard, 2010). It uses a scanning multiple-flow algorithm that sweeps the area in four directions (north to south, east to west, west to east and south to north) (Coulthard and Macklin, 2003). This parameter was set to 50.

For the model to assess the amount of erosion, the shear stress (Tau) is calculated based on flow velocity. In this way, it determines the amount of sediment eroded and moves it according to the discharge in different directions (Coulthard, 2010). This was set as a default value of 5 N m^{-2}.

Vegetation is also included in the model by the critical shear stress and grass maturity (range of 0 to 1) parameters. As it was considered natural vegetation (grass), according to literature the values set for these two parameters were 100 and 1 respectively (Coulthard, 2010).

7.2 Case scenarios

Two different case scenarios were carried out using the CAESAR model reach mode in order to model the sediment transport and dynamics of the meandering of the River Geul.

7.2.1 Scenario 1- 14 years simulation with no suspended sediment input

The input data was taken from discharge data in Meerssen for 14 years, from 1995 to 2008 (Roer en Overmaas Water Authority). No sediment input was introduced in the model. The next map represents the elevation differences between the model output elevation and the input digital elevation map of the study area.

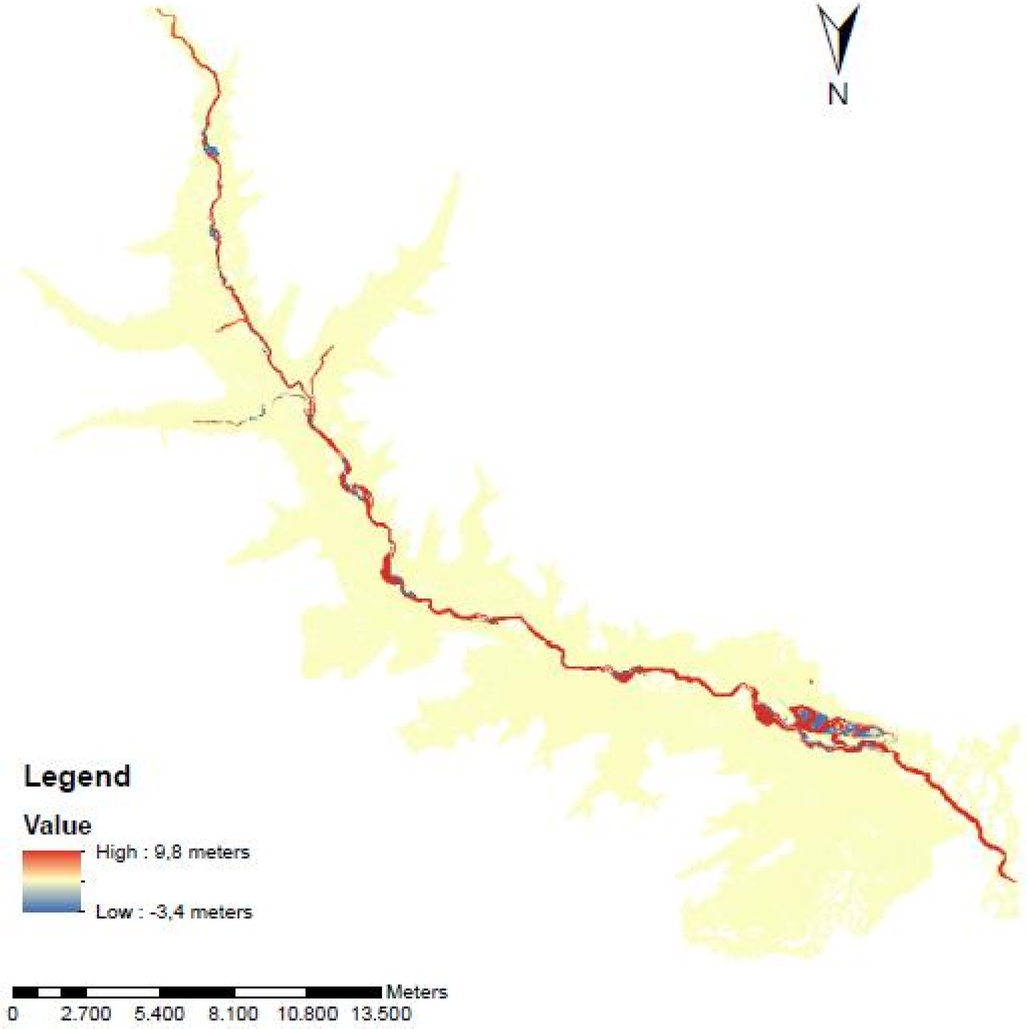

Figure 15: Erosion and deposition of sediment along the catchment of the Geul River. Positive values in red correspond with erosion and negative values in blue correspond with deposition.

It is important to mention that the average value of the map is 0.009 m and the standard deviation is 0.172, meaning that the higher value reached of almost 10 meters of erosion it is an exceptional value over the whole catchment. This positive value also indicates that the erosion is higher than the deposition as expected.

7.2.2 Scenario 2- 14 years simulation with suspended sediment input

Discharge data from Meerssen for the years 1995 to 2008 (Roer en Overmaas Water Board) was inputted in the model. Suspended sediment was introduced corresponding with four of the seven discharge inputs. Next map shows the elevation difference between the model output elevation map and the elevation map introduced as input in the model.

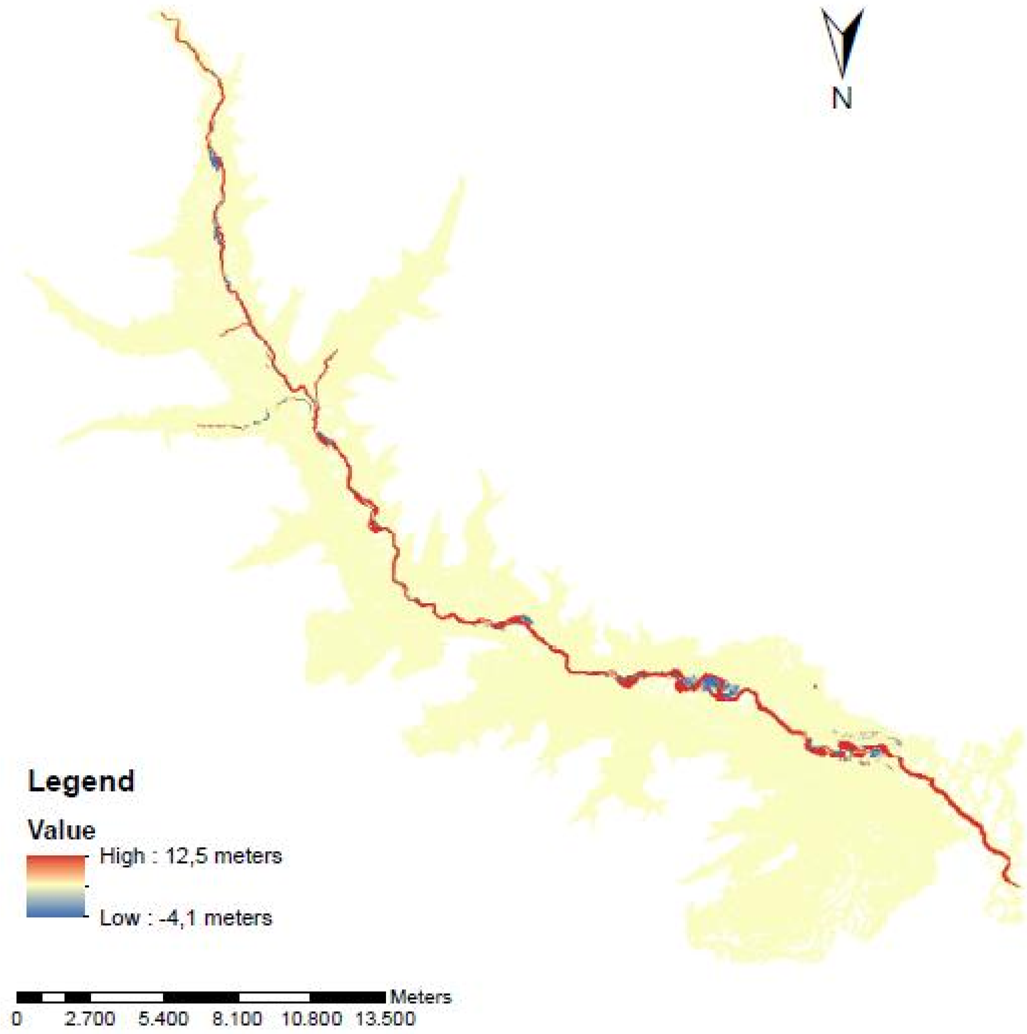

Figure 16: Erosion and deposition of sediment along the catchment of the Geul River. Positive values in red correspond with erosion and negative values in blue correspond with deposition.

The average value of the map is 0.0082 m and the standard deviation of 0.166, consequently the higher value reached of 12.5 meters erosion is an exceptional value over the whole catchment. As expected during the simulation erosion is higher than deposition.

7.2.3 Sediment results of the two scenarios.

Next table shows the output of the total sediment per year and per simulation corresponding with each scenario. The amount of sediment at the output is given in m^3.

Table 4: Total sediment output per year of simulation of scenario 1 and scenario 2.

	Sediment output per year of Simulation- Scenario 1 (m^3)	Sediment output per year of Simulation- Scenario 2 (m^3)
Year 1	$5,04 \times 10^5$	$5,48 \times 10^5$
Year 2	$2,77 \times 10^5$	$1,83 \times 10^5$
Year 3	$1,63 \times 10^5$	$4,31 \times 10^5$
Year 4	$5,03 \times 10^5$	$3,04 \times 10^5$
Year 5	$2,30 \times 10^5$	$1,86 \times 10^5$
Year 6	$2,71 \times 10^5$	$1,23 \times 10^5$
Year 7	$1,87 \times 10^5$	$1,62 \times 10^5$
Year 8	$1,20 \times 10^5$	$1,09 \times 10^5$
Year 9	$6,97 \times 10^4$	$1,15 \times 10^5$
Year 10	$7,63 \times 10^4$	$6,36 \times 10^4$
Year 11	$5,34 \times 10^4$	$3,31 \times 10^4$
Year 12	$5,90 \times 10^4$	$4,49 \times 10^4$
Year 13	$4,09 \times 10^4$	$3,74 \times 10^4$
Year 14	$3,00 \times 10^4$	$2,02 \times 10^4$
Total	2.58×10^6	2.36×10^6

As explained previously, scenario 1 has no suspended sediment data at the input while scenario 2 contains suspended sediment input at 4 of the 7 discharge locations at the model. It can be seen from table 3 that when using suspended sediment at the input the total amount of sediment decreases slightly but both results are of the same order of magnitude. The decrease in total amount of sediment in scenario 2 is an unexpected result. Since suspended sediment is introduced in the system an increase in total amount of sediment at the output would be expected, therefore the reason behind to explain this decrease is unknown.

Moreover, during the first years of simulation CAESAR creates a spin up process during which the model generates higher sediment values as it can be seen at the previous table. Therefore, introducing suspended sediment in the system can lead to higher error during the first years of simulation.

Due to the small difference found at the output, the unknown error introduced at scenario 2 due to the lack of data of suspended sediment corresponding with the years used for the simulation and the spin up process, predictions calculated in the next section use the results from the first scenario .

8. Predictions of decontamination of the Geul River

Two different procedures will be use to predict how long it will take for the river to decontaminate 70% of the actual contamination. This percentage was chosen to be able to compare results from this study with previous studies that shows that more than 70% of the deposited contaminants remain within the river system for more than 200 years after the mining activities are finished (Coulthard and Macklin 2003).

First case uses the results obtained from regression analysis of contamination and distance to the Belgian border and sediment output of scenario 1. Second case consists in overlapping the map of total excess contamination with elevation difference output map of scenario 1.

For both cases an exponential decay formula is used to calculate the predictions. Exponential decay in decontamination is expected since areas contaminated with high concentration in heavy metals erode first; these areas are closer to the river. Areas situated further from the river in the floodplain are less contaminated and it also takes longer time for these sediments to be eroded. Therefore, the decontamination approximate to an exponential decay function.

8.1 Case 1-Prediction using regression analysis and sediment output of scenario 1.

In order to calculate how long would take the dynamics of the river to decontaminate the floodplain a procedure will be used based on the comparison of the total sediment obtained by CAESAR model after 14 years simulation and the total excess metal inventory of contaminants after regression predictions.

The graphs of the regression analysis of zinc and lead values of the Geul catchment with respect to the distance to Belgian border (figure 5) were used to make the calculations.

The integral of each of the regressions lines for zinc and lead result in the total amount of these contaminants in the study area.

8.1.1 Predictions for the removal of 70% of total lead contamination

In case of calculations for assessing lead:

$$y = e^{-8 \cdot 10^{-5} x + 12,83}$$

$$\int (y) = \frac{1}{-8 \cdot 10^{-5}} \cdot e^{-8 \cdot 10^{-5} x + 12,83}$$

$\int_{0}^{28000} (y) = 4.1$ tons of lead in the Geul catchment.

As explained before, the model results after 14 years simulation were used for these calculations. In order to avoid spin up process that generates very high sediment values during the first years of the simulation, as it can be observed at table 4, the following calculations will be based on the sediment value obtained for the last year of the 14 years simulation which is equal to 29980 m^3.

To transform 29980 m^3 of sediment into kg to be comparable to the amount of sediment calculated by the regression analysis, it was multiplied by the bulk density (1330 kg/m^3) resulting in 39.9 tons of total sediment.

Multiplying 39.9 tons of total sediment by the average values of 100 ppm (100 mg/kg) of lead and 400 ppm (400 mg/kg) of zinc found in the Geul catchment the amount of lead leaving the catchment in one year is results in 3990 kg of lead per year.

To predict a total decontamination of the river it is important to consider that the decontamination process follows an exponential decrease, expressed by the following formula:

N(t) = N (0) * e^(-t*τ)

where,

N(t) = 4100000 kg Pb- 3990 kg Pb = 4096010 kg Pb remain at the catchment after 1 year.

N (0)= 4100000 kg of total Pb in the catchment. Obtained by regression analysis.

t = time (1 year)

τ =decay constant ($years^{-1}$)

By substituting with the previous values the decay constant for lead can be calculated:

τ =- 0.00097 $years^{-1}$

With the use of this constant and N(0) the time it will take for the river to remove 70% of the whole amount of lead is approximately 1241.2 years as the following calculation shows:

N(t) = N (0) * e^(-t*τ)

1230000 = 4100000 * e^(-t*-0.00097) = 1241.2 years to remove 70% of total lead contamination

8.1.2 Predictions for the removal of 70% of total zinc contamination

Calculations for zinc were carried out with the same procedure resulting in 13.7 tons of zinc by integrating the formula of the regression line of Zinc (figure 5). The amount of zinc that leaves the Geul in one year is 15600 kg according with the sediment output of the last year simulation.

The calculated decay constant in the same way as done for lead results in:

N(t) = N (0) * e^(-t*τ)

where,

N(t) = 13700000 kg Zn - 15600 kg Zn = 13684400 kg Zn remain at the catchment after 1 year.

N (0)= 13700000 kg Zn in the catchment.

t = time (1 year)

τ =decay constant = -0.0011 years^{-1}

With the use of this constant and N(0) the time it will take for the river to remove 70% of the whole amount of zinc is approximately 1094.52 years .

Tabla 5: Summary of predictions to achieve 70% of contaminant removal in the Geul catchment using a decay formula.

Contaminant	Prediction 70% of contaminant removal
Lead (Pb)	1241 years
Zinc (Zn)	1095 years

8.2 Case 2- Prediction overlapping map of total excess contamination with elevation difference output map of scenario 1.

In order to assess how long the river would take to carry out a decontamination process, one of the ways would be by assessing the amount of contamination of the sediment at the outlet of the Geul river after a 14 years simulation of CAESAR model and calculating how long it would take the river to remove 70% of the current amount of contamination.

As explained before results from scenario 2 may bring a high uncertainty so results obtained from scenario 1 without introducing suspended sediment data in the input were used for the following calculations here explained.

As first step for these calculations, a map of the total excess of lead and zinc (g/m2) up to 1.7 meters deep (Van der Perk et al., 2011) was overlapped to the elevation difference map of scenario 1 where it can be seen where erosion and deposition take place over the catchment.

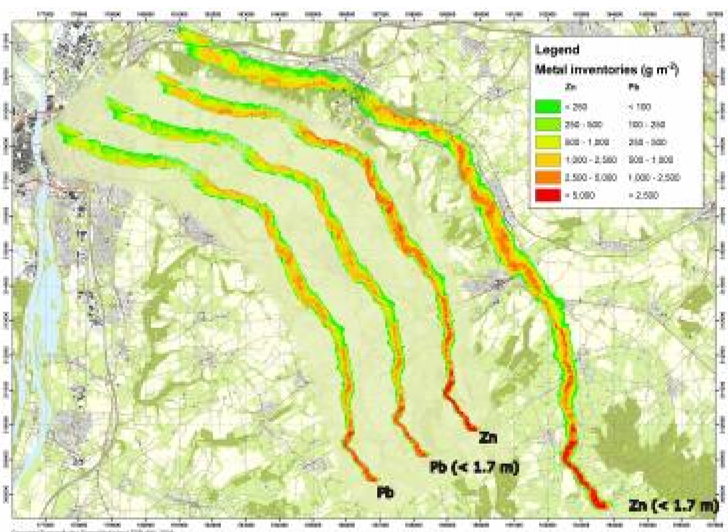

Figure 17: Predicted metal inventories in the Geul valley (Van der Perk et al., 2011)

Once these 2 maps were overlapped, every cell contains information of elevation difference with respect to the former DEM and concentration of lead and zinc. By multiplying, elevation difference of the area of each cell by metal concentration the total amount of lead and zinc of eroded and deposited sediment can be calculated. The results are the following:

- Content of lead in deposited sediments: 482 kg
- Content of lead in eroded sediments: 3236 kg
- Content of zinc in deposited sediments: 2007 kg
- Content of zinc in eroded sediments: 13664 kg

Considering the following balance the amount of lead and zinc that leaves the catchment can be calculated:

Content of metal eroded – Content of metal deposited = Content of metal at the outlet

- Content of lead at the outlet=2754 kg
- Content of zinc at the outlet= 11657 kg

According to the total excess metal inventory map, total amounts of metals in the Geul valley are 4986 tons and 16678 tons of lead and zinc respectively (Van der Perk et al., 2011). The corresponding values of lead and zinc content at the output maps are 2754 kg and 11657 kg.

8.2.1 Predictions for the removal of 70% of total zinc contamination

Next the calculations for the decontamination of zinc with time will be shown. As explained at the previous section an exponential decay formula for the decontamination of the river with time is used:

$N(t) = N(0) * e^{(-t*\tau)}$

where,

N (0)= 16678000 kg of total Zn

N(t) = 16678000 kg of total Zn- 11657 kg of Zn after 14 years of simulation = 16666343 kg Zn

t = 14 years

τ =decay constant = -0.000049 years^{-1}

With the use of this constant the time it will take for the river to remove 70% of the whole amount of zinc is 24570.9 years

It is clearly seen that the time to remove zinc from the catchment when overlapping the maps is much higher than the method used in section 8.1. As it was explained before and stated at the output sediment from scenario 1 (table 3), it is obvious that the model removes more sediment the first years of simulation compare with the last years. Therefore, a new decay constant will be calculated taking into account that almost 40% of the sediment removal from the map used for overlapping is occurring during the first three years.

With the use of this constant (τ = -0.00023 $years^{-1}$)the time it will take for the river to remove 70% of the whole amount of zinc is 5234.66.88 years.

Predictions have been done also considering that the sediment leaving the catchment during the scenario corresponds only to the last year of modeling. Calculating the corresponding decay constant for one year (τ = -0.00069 $years^{-1}$) it will take 1744.88 years to remove 70% of zinc from the catchment.

8.2.2 Predictions for the removal of 70% of total lead contamination

Calculations for the removal of lead are showed below:

$N(t) = N(0) * e^{(-t*\tau)}$

where,

N (0)= 4986000 kg total lead

N(t) = 4986000 kg total lead - 2754 kg lead after 14 years simulation = 4983196.14 kg lead remaining in the catchment.

t = 14 years

τ =decay constant = -0.000040 $years^{-1}$

With the use of this constant the time it will take for the river to remove 70% of the whole amount of lead is 30099.32 years.

Using the same reason as when calculating the decontamination of zinc when overlapping the maps the time needed for the removal of 70% of lead contamination will be calculated using a new decay constant. This constant considers that the amount of sediment leaving the catchment during scenario 1 is mainly due to the first years of modeling (40% of sediment output is due to the first three years). With the use of the new constant calculated (τ = -0.00018 $years^{-1}$) the time it will take for the river to remove 70% of the whole amount of zinc is 6688.74 years.

Predictions have been done also considering that the sediment leaving the catchment during the simulation corresponds only to the last year of modeling. Calculating the corresponding decay constant for one year (τ = -0.00056) it will take 2140.37 years to remove 70% of lead from the catchment.

Table 6: Summary of predictions to achieve 70% of contaminant removal in the Geul catchment using a decay formula.

Contaminant	Prediction 70% of contaminant removal
Lead (Pb)	2140 years
Zinc (Zn)	1745 years

9. Discussion of results

Results of fieldwork and regression analysis show that upstream floodplain areas contain higher contamination in lead and zinc than downstream areas. This result is expected since the main sites of the mining activities which lead to the contamination of sediments are at the Belgian part of the Geul River. Nevertheless although upstream sediments are more contaminated downstream sediments also show a noticeable content in lead and zinc contamination. This is due to processes taking place at the floodplain as erosion, transport and deposition which play an important role on the migration of sediments downstream, especially during high peak discharges and inundation of the floodplains.

The geomorphologic units which characterize the area (point bar, abandoned channel and floodplain) (figure6) contain different concentration of heavy metal contamination. With respect to the geomorphologic units point bars and abandoned channel will be eroded first while furthest locations along the floodplain will be only affected with high discharges causing the inundation of the floodplain. In addition, contamination content also decreases vertically (see appendix 2). All these processes are complex to model in reality; therefore a simplification is used and the decontamination is approximated to an exponential decay function due to the reasons explained above.

Simulations of the Geul reach using CAESAR model provide a file with sediment data at the output and a map of the difference in elevation between the input DEM and a certain time. From the maps obtained after 14 years simulation it is clearly seen the areas where erosion and deposition take place. Erosion of sediments occurs at the outer part of a meander an accumulation of sediments in the inner part of the meander as figure 15 and 16 show.

Two different cases were used to predict the decontamination of the river. First case uses results of statistical analysis and sediment output of CAESAR model (simulation 1) to predict the decontamination of the river. From the integral of the regressions the actual total lead and zinc content at the Geul floodplain is calculated being 4.1 tons of lead and 13.7 tons of zinc. After applying an exponential decrease as explained previously in order to decontaminate 70% of actual heavy metal contamination of the Geul floodplain will take 1241 years for lead and 1095 years for zinc.

The second case uses results from overlapping map of the total excess contamination with elevation difference output map of CAESAR simulation to predict the decontamination of 70% of the total amount of heavy mental in the Geul floodplain. Calculations show that only in the case of considering that erosion and deposition output of CAESAR model map is due to one year simulation results are of the same order of magnitude than results from the technique previously used for the first case. Making this assumption the time to reach 70% of decontamination will be 2140 years for lead and 1745 years for zinc.

Due to the uncertainty created from the difference of results obtained when they are calculated with different years representing the output map of CAESAR model it is considered more trustable results obtained when using regression analysis and sediment output of CAESAR model to calculate the decontamination of the river (case 1).

Moreover, the maps used for the second case have different resolutions. Consequently it causes errors when overlapping both maps, since locations at these two maps do not precisely coincide.

It is also important to mention and consider that the input DEM used for the simulations with CAESAR model has a resolution of 25 meters. Thus, the size of the river is overestimated since the river has a length varying from 8 to 15 meters. In addition, at some locations of the DEM two cells shape the width of the river increasing even more the overestimation of the output sediment eroded created by CAESAR model simulations.

The results of this study are in accordance with the long persistent of heavy metals in river systems however, as explained before, the high resolution needed as input for the model may lead to an overestimation of sediments output of the model used for the calculations. Thus causing an overestimation of the time needed for the dynamics of the river to decontaminate the Geul catchment.

10. Conclusions and recommendations

The aim of the this study was to investigate and predict the temporal dimensions of the natural decontamination of the Geul River between Cottessen and Meerssen due to remobilization of polluted sediments along the catchment and the dynamics of the meandering river. The main sites of the mining activities which lead to the contamination of sediments are at the Belgian part of the Geul River. Upstream zones contain higher contamination in lead and zinc than downstream areas. However, downstream areas are also high polluted indicating that the contamination has been already highly widespread along the sediments of the Geul as previous studies (Coulthard and Macklin, 2003) developed along UK contaminated catchment have also shown.

Both of the methods used for this study show that for the Geul reach to be higher than 70% decontaminated it will take more than thousands years, indicating the environmental problem which causes metal mining at the banks of the river. Prior studies have shown the long term contamination in river systems affected by historical metal mining.

Due to the fact that the dynamics of the meandering river play a big role in the decontamination of the river, it is essential to consider that future changes in the discharge regime and effects of climate change can lead to a shorter or longer time to reach the total natural decontamination. However, the temporal dimension of the values found show high persistence of these contaminants in the river system long after the mining activities are finished since the floodplain is already polluted.

Results on this study show the magnitude of the heavy metal contamination of the Geul catchment due to historical metal mining and the persistence of these contaminants in the fluvial system. Nevertheless, a closer research should be done in this area to study in more detail the actual situation of the contaminated sediment distribution. In addition, further investigations are needed to develop models which directly use as input heavy metal contents in the sediments related with each location in order to determine directly the remobilization of these contaminants in the systems and be able to formulate more accurate predictions.

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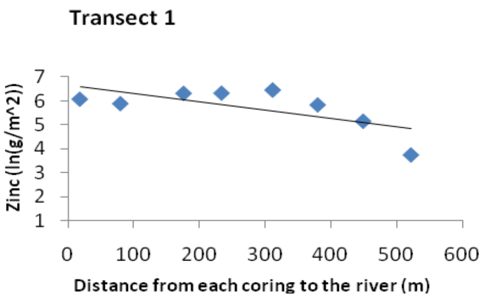
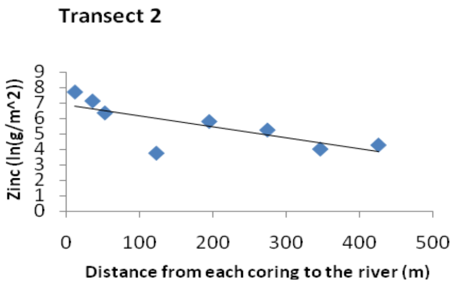
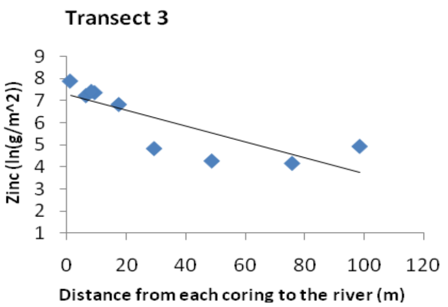
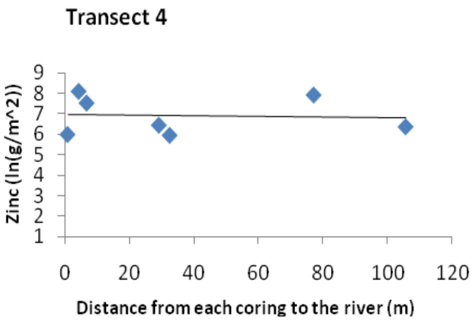
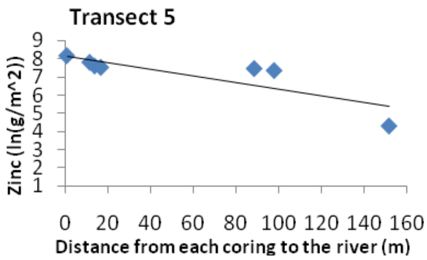
Appendix 1

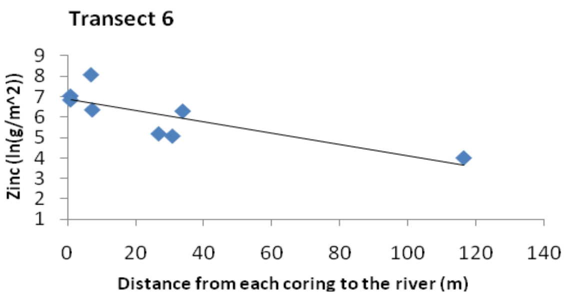


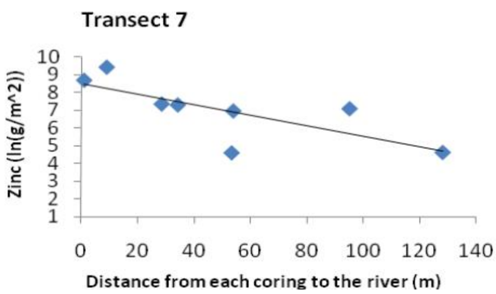


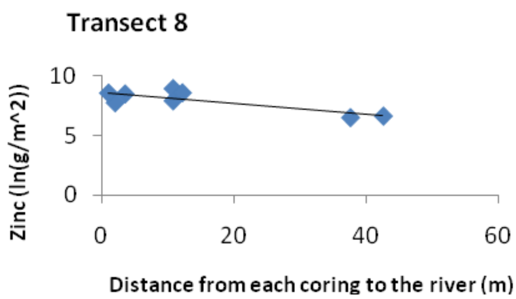












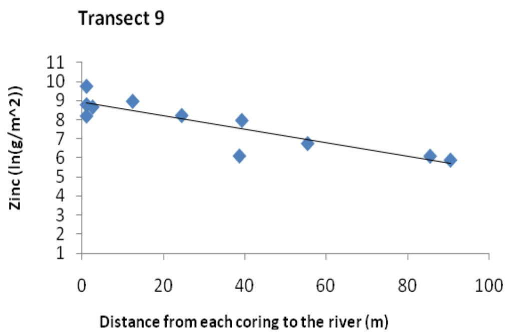


Figure 1. Linear regression analysis graphs of Zinc ($ln(g/m^2)$) per transect with distance from each coring to the river (m).

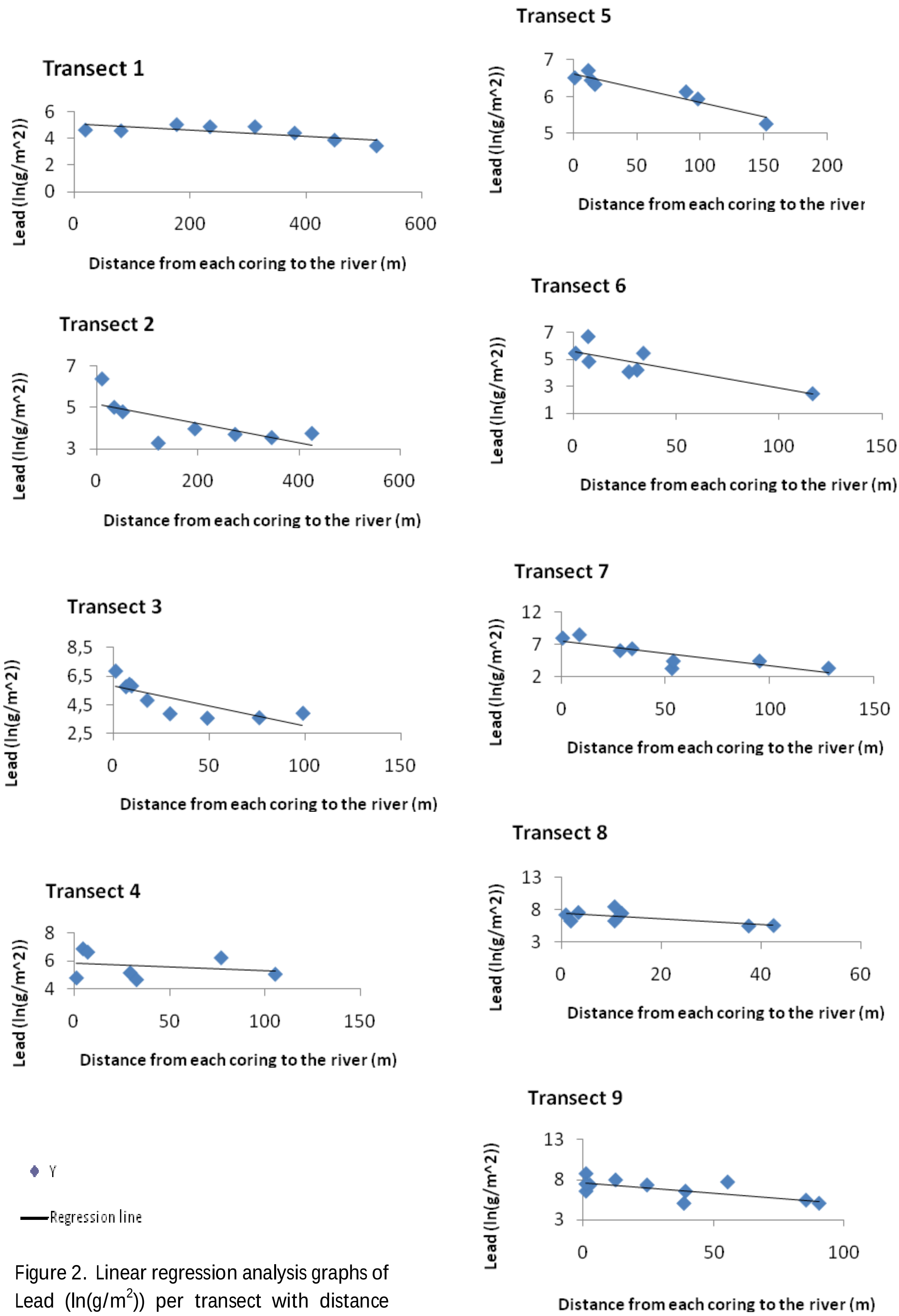


Figure 2. Linear regression analysis graphs of Lead ($ln(g/m^2)$) per transect with distance from each coring to the river (m).

Table 1. Regression analysis results of zinc with respect to distance to the river.

Regression Statistics	Zinc								
Transect number	1	2	3	4	5	6	7	8	9
Determination coefficient R2	0.46	0.55	0.67	0.003	0.68	0.65	0.60	0.71	0.78
P value	0.0643	0.0335	0.0064	0.9	0.0221	0.0159	0.0327	0.0088	0.0003
Standard Error	0.71	1.05	0.91	1.01	0.79	0.84	1.23	0.53	0.66
b	-0.004	-0.007	-0.036	-0.002	-0.018	-0.028	-0.030	-0.049	-0.035
a	6.66	6,83	7,28	6,97	8,16	6.87	8.49	8.65	8.90

Table 2. Regression analysis results of lead with respect to distance to the river.

Regression Statistics	Lead								
Transect number	1	2	3	4	5	6	7	8	9
Determination coefficient R2	0.56	0.49	0.63	0.05	0.89	0.68	0.68	0.43	0.48
P value	0.0330	0.0529	0.0102	0.6419	0.002	0.0112	0.0112	0.0764	0.0183
Standard Error	0.40	0.80	0.78	0.99	0.17	0.76	1.22	0.86	0.53
b	-0.023	-0.047	-0.028	-0.005	-0.008	-0.027	-0.039	-0.043	-0.023
a	5.07	5.16	8.82	5.84	6.63	5.59	7.52	7,43	7.62

Appendix 2

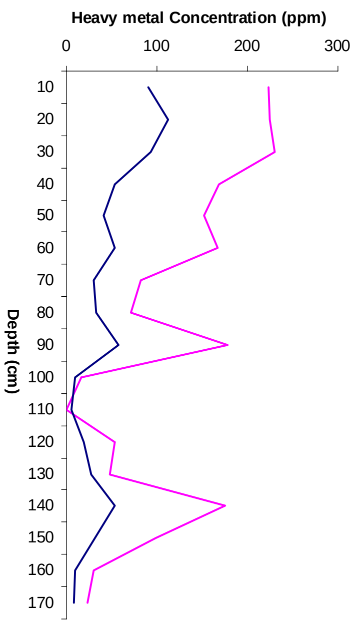


Figure 1: Soil concentration profile

Transect 5 coring 1

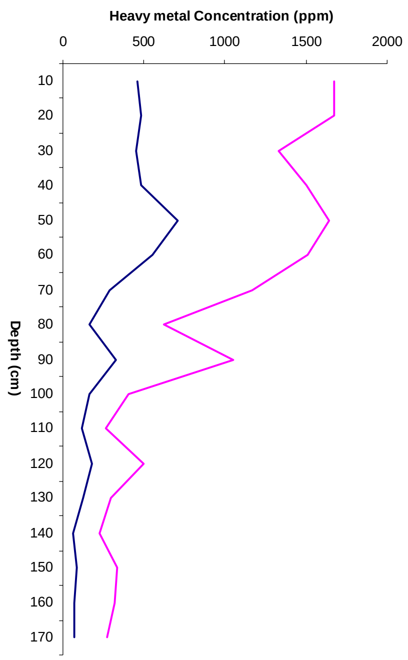


Figure 3: Soil concentration profile

Transect 5 coring 3

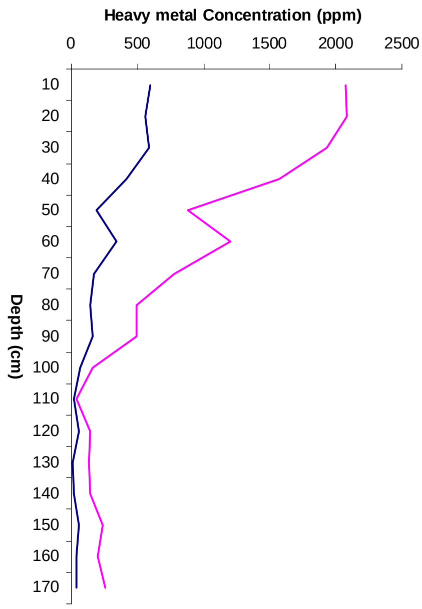


Figure 2: Soil concentration profile

Transect 5 coring 2

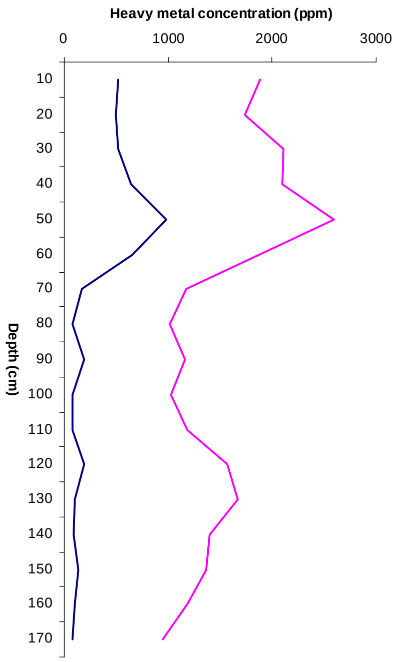


Figure 4: Soil concentration profile

Transect 5 coring 4

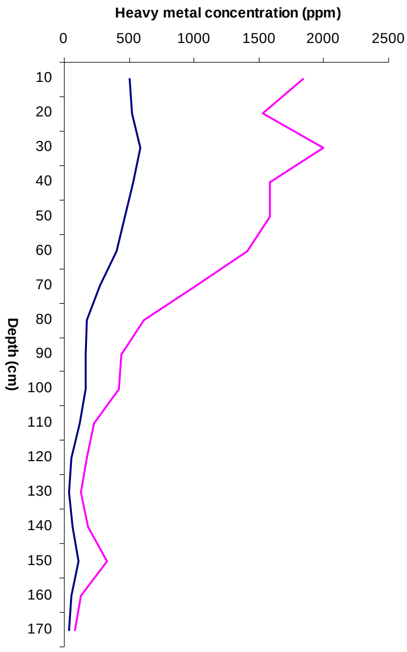


Figure 5: Soil concentration profile

Transect 5 coring 5

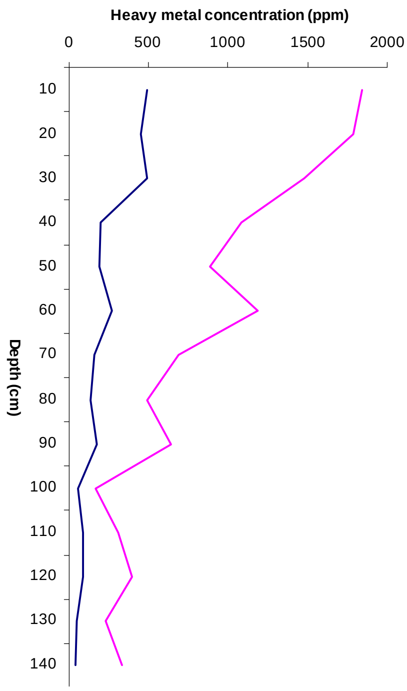


Figure 7: Soil concentration profile

Transect 5 coring 7

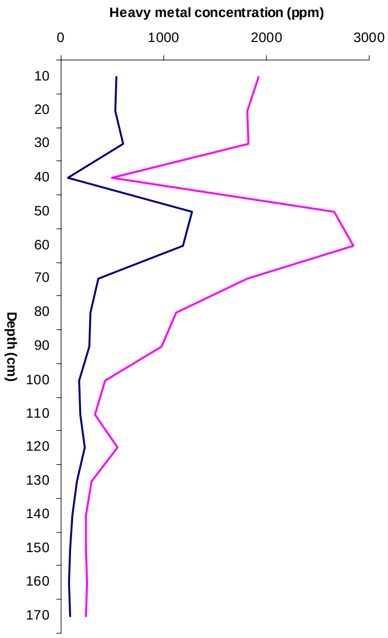


Figure 6: Soil concentration profile

Transect 5 coring 6

Appendix 3

Transect	Coring	X	Y
1	1	182551	320736
1	2	182531	320660
1	3	182503	320603
1	4	182476	320541
1	5	182443	320473
1	6	182418	320418
1	7	182382	320359
1	8	182335	320283
2	1	184749	320170
2	2	184753	320090
2	3	184748	320016
2	4	184745	319937
2	5	184736	319864
2	6	184740	319779
2	7	184842	319780
2	8	184861	319744
3	1	188610	318402
3	2	188602	318371
3	3	188593	318352
3	4	188582	318330
3	5	188570	318310
3	6	188612	318427
3	7	189379	317932
3	8	189395	317923
3	9	189412	317925
4	1	189584	317219
4	2	189657	317225
4	3	189682	317247
4	4	189544	317216
4	5	189528	317172
4	6	189459	317107
4	7	189464	317130
5	1	190856	314510
5	2	190921	314523
5	3	190989	314517
5	4	191015	314525
5	5	191048	314503
5	6	191115	314547

5	7	191197	314581
Transect	Coring	X	Y
6	1	192381	312824
6	2	192361	312797
6	3	192364	312806
6	4	192218	312910
6	5	192258	312766
6	6	192226	312783
6	7	192247	312828
6	8	19218	312697
7	1	192642	311402
7	2	192661	311401
7	3	192690	311384
7	4	192704	311388
7	5	192733	311382
7	6	192764	311370
7	7	192799	311365
7	8	192832	311379
8	1	192842	309557
8	2	192827	309582
8	3	192780	309600
8	4	192874	309540
8	5	192770	309611
8	6	192722	309618
8	7	192703	309621
8	8	192672	309628
9	1	193536	307809
9	2	193489	307807
9	3	193460	307830
9	4	193468	307789
9	5	193448	307749
9	6	193450	307722
9	7	193462	307763
9	8	193443	307715
9	9	193437	307679
9	10	193459	307621
9	11	193459	307619

Appendix 4

Location	X	Y
Cottessen	193609	307708
Hommerich	192116	313154
Meerssen	178825	322436
Eyserbeek	193211	315195
Selzerbeek	192668	313552
Azijnfabriek	190542	313924