Open access • Journal Article • DOI:10.1007/S00244-004-3014-4

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**Institutions:** Flemish Community, Ghent University

**Published on:** 01 Jul 2004 - Archives of Environmental Contamination and Toxicology (Springer-Verlag)

**Topics:** Alluvial plain, Soil quality, Riparian zone, Soil survey and Sediment

Vandecasteele B., Quataert P., De Vos B., Tack F.M.G., 2004. Assessment of the pollution status of alluvial plains: a case study for the dredged sediment-derived soils along the Leie river. Archives of Environmental Contamination and Toxicology 47 , 14-22.

**Article: AECT MS#2003-014 (revised)**

# Assessment of the pollution status of alluvial plains: a case-study for the dredged sediment-derived soils along the Leie river

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## Abstract

The concept of an integrated multifunctional river management is gaining importance. For major rivers, restoring the contact between rivers and alluvial plains is an important goal as riparian areas have a specific role for several riverine processes. However, former and current human activities are an obstruction or a limitation for river restoration. We studied the influence of former dredging activities along the river Leie on the alluvial plain quality. A soil survey and an archive query for reconstructing the history of dredging operations were conducted simultaneously. The geographical impact expressed as topographical changes and covering of the original soil profile and related processes and biota was large. The pollution status of dredged sediment-derived soils was found to be far from negligible: concentrations of Cd, Cr and Zn were, in 10% of the cases, higher than 20, 480 and 2800 mg kg$^{-1}$ DM, respectively.

A clear geographical trend was found, with a clustering of dredged sediment-derived soils in the most downstream part from the river. The oldest sites have the lowest sediment layer thickness and were mainly found in the alluvial area between Deinze and Ghent. Pollution trends as a function of geographical and temporal factors are discussed. The survey on dredged sediment-derived soils reveals the pollution of the Leie alluvial plain as an indirect consequence of the river's shipping function. Both agriculture and nature rehabilitation on dredged sediment-derived soils can only be accepted after profound risk assessment, and management should focus on ecological risk reduction. Results indicate the importance of soil quality assessment in alluvial plains for an integrated river management, rather than *a priori* assuming pristine soil conditions. The collected 'off-line' sediment data can be used as a reconstruction of past sediment pollution, especially when long-term sediment monitoring programs are not available.

*Keywords:* dredged sediment, Heavy metals, landfills, Leie, Scheldt, alluvial

# 1. Introduction

The concept of an integrated multifunctional water management is gaining importance. Restoring the contact between rivers and alluvial plains is an important element in this. Riparian areas have several important functions. They constitute a sink for nutrients (Reddy and D'Angelo 1994), a reserve for water storage during high discharge events and a habitat for organisms. Former and current human activities have affected the alluvial plains of rivers and are a constraint for river restoration projects. On several locations along the rivers, dredged sediments have been disposed. This affected the topography along the river shores and eventually constituted a source of pollution with organic micropollutants and heavy metals.

Sediments act as a sink and a carrier for pollutants and therefore provide time integrated data about geographical and temporal trends in pollutant emission to the river system (Regnier and Wollast 1993, Sternbeck and Östlund 2001). However, these trends (Petersen et al. 1997, Bordas and Bourg 2001) may be discerned with much difficulty from samples taken directly from the river (Mellor 2001). Temporal trends may also be affected by diagenetic processes (Zwolsman et al. 1993). Besides the use of sediment and suspended matter samples taken directly from the river bed (Ollivon et al. 2002, Belzunce et al. 2001), sediment cores from floodplain lakes (Winter et al. 2001), landfilled dredged sediments (Vandecasteele et al. 2002a) and salt marshes (Zwolsman et al. 1993, Christiansen et al. 2002) were used to identify temporal trends in sediment quality.

This research was concerned with the areas affected by dredged sediment disposal along the river Leie in Flanders, Belgium. Their pollution status with respect to heavy metals was assessed. An attempt was made for temporal analysis of sediment quality trends. A comparison of different groups of landfills was based on the dredging history of the river. Based on the results, general recommendations are discussed.

# 2. Materials and methods

## 2.1. Study area

The study area for this research was the Flemish part of the Leie (Fig. 1). The Leie is a major tributary of the Scheldt river, joining the Scheldt at Ghent. It is not subjected to tidal influence. The catchment area of the Leie covers about 2600 km² in north-west France, and 3700 km² in the western part of Belgium. The river is characterized by a low slope, at 11 cm km$^{-1}$. In the downstream part between Deinze and Ghent, the slope decreases to near zero and there is a strong meandering. Water pollution of the river already starts close to the French border, for example by the Deûle river coming from the agglomeration of Lille and Doaui (Vallée et al. 2000).

Since the industrial revolution, the river Leie has been strongly regulated. In the Leie section between the French border and Deinze, the first major canalization works were executed and sluices were built in the 19th century because of the economical importance of coal transport (Defoort and Roggeman 1996). In this period the Leie Diversion Canal was dug for a better drainage of the catchment. Between 1965 and 1985 meanders were cut short and the river profile upstream Deinze was broadened to allow for shipping traffic up to 1350 tons and to prevent cities from floodings. The section downstream Deinze, which is not used for shipping traffic, largely retained the original meandering pattern. The dredged pure sandy or loamy soil materials resulting from the broadening works were used for levelling the lower parts of the alluvial plain (Defoort and Roggeman 1996). For the section between Deinze and Ghent, human influence by infrastructure works on the river bed was minor, especially because this section lost its shipping transport function since 1970.

The dredging history of the river was reconstructed based on the archives of the Flemish Government Administration. Dredged amounts are displayed as function of period and location of the dredging operation by means of a bubbleplot (Fig. 2).

## 2.2. Data of the sampled dredged sediment-derived soils

In this study we sampled the dredged sediment-derived soils (DSDS) in the Leie alluvial plains constructed before 1995. The procedures adopted to identify potentially levelled-up sites (Vandecasteele et al. 2001), the sampling strategy, soil chemical and physical analyses and criteria used to evaluate the pollution level are described in detail elsewhere (Vandecasteele et al. 2002b, Vandecasteele et al. 2003). In the upstream part from Deinze, urbanization and industry execute a large pressure on the open areas, and mostly possible DSDS could not be sampled because they were already used for construction. The low [sampled area of the DSDS /dredged amount] ratio in the upstream part of Deinze is clearly illustrated when comparing Fig. 3b with Fig. 3c. For many of the sampled sites, their former use as a dredged sediment disposal could not be ascertained by historical records. These sites were identified based on field observations, comparative granulometric analyses and chemical analyses as outlined previously (Vandecasteele et al. 2002b). Briefly, criteria were developed, based on a comparison between reference data from soil samples of areas positively identified as affected by dredged sediment disposal and samples from undisturbed alluvial soils along the River Leie and the Upper and Sea Scheldt. In total, 48 sites with a total surface of 125 ha were identified as sites that have been affected by dredged sediment disposal. Observations of these DSDS were used for general pollution assessment and for studying the measured concentrations of heavy metals in relation to location along the river Leie and time of landfilling.

Each DSDS was assigned to one of 4 groups of dredging works (Fig. 2). These groups were discerned based on the dredging history of the Leie river. Group (1) included the DSDS in the upstream part of the Gent-De Panne railway bridge (km 44 from the Flemish border crossing). Group (2) DSDS were constructed between 1960 and 1983 and are located between the Gent-De Panne railway bridge and the Astene barrage (km 52 from the Flemish border crossing). Group (3) comprises DSDS in the same section but constructed after 1983 and group (4) the DSDS in the downstream section from the Astene barrage constructed before 1970. The results from the sampled landfills were clustered according to these groups.

For a better detection of the temporal trend, we additionally sampled the Rabot site, the most recent landfill used for the 1994 dredging operation near Deinze but constructed outside the Leie alluvial plains (Fig. 1, Group 5 in Fig. 2). Group 2-5 all contain landfills constructed with sediments dredged in the most downstream part of the study area, thus comparison is allowed.

The proportion of DSDS and other levelled-up sites in the Leie alluvial plain were calculated based on a GIS-analysis including soil maps, river profile broadenings, constructed and levelled-up areas.

## 2.3. Statistical methodology

Statistical processing started with an explorative principle components analysis (PCA) to detect the major relations between soil parameters. The general characteristics and the degree of pollution of the 4 groups of DSDS were compared with ANOVA. All variables were tested for symmetry and homoscedasticity. No transformation was necessary based on visual inspection of the data. Multiple comparison of means was performed according to the Sidak method with 95% simultaneous confidence intervals (Mathsoft 1999). This is a conservative method which allows for comparison of groups with a different number of elements. The heavy metal concentrations were compared as such but for temporal trend detection data also were compared after normalization for the average clay content. It is important to know if changes in heavy metal concentrations in the sediments are related to varying sediment properties or not. Normalisation of heavy metal concentrations towards the clay content is an appropriate technique for testing the robustness of the data. Statistical analyses were performed by Splus2000 (Mathsoft, Seattle).

# 3. Results

## 3.1. Archive data on dredging history

The bubbleplot (Fig. 2) shows dredged quantities as a function of location and period of the dredging operation. The marked increase in amounts with time near Deinze was caused by the works for straightening and broadening the river. This reduced the length of the Flemish part of the Leie upstream Deinze by 40%. It caused a higher fall and consequently an increased flow rate and a changed sedimentation pattern. Near Deinze, the flow rate decreases and part of the water is entering the Diversion Canal. The downstream part of the Leie has not been affected by broadening works during the last decades and continues its strongly meandering course. In the archive data, it is found that before the river broadening most sedimentation occurred in the section downstream Deinze. Fig. 3a reveals that dredged amounts increased sharply after 1960. The first large peak coincided with the winter floodings between 1965 and 1968, which resulted in a large sedimentation problem in the downstream part. After 1970, regular large dredging operations were necessary, especially around Deinze. At that time several parts of the river upstream were already straightened and canalized. Current sedimentation rates in the Leie catchment are estimated at 140.000 $m^3$ $year^{-1}$ (Flemish Government Administration, personal communication). The most recent dredging works were executed in 1994 and 2001. Between 1994 and 2001 no dredging was possible because of developments in environmental law and regulations.

### 3.2. Pollution assessment

From 125 ha of dredged sediment landfills representing 48 sites, 139 soil samples were collected at 92 sampling points (Fig. 3c). Metal contents and physico-chemical properties are shown in Table 1. Strong correlations of heavy metal contents with clay, loam, organic carbon (OC) and $CaCO_3$ contents are clearly revealed by PCA (Fig. 4). No distinct clusters of samples were observed. Descriptive data for the sampled alluvial plain soils used as a reference data (not influenced by sediment disposal or overbank sedimentation) are given in Table 2. Cd and Zn levels on the DSDS are on an average 10 times higher than in the surrounding alluvial soils. Total heavy metal levels displayed in Table 2 are slightly above normal ranges for soils of similar clay and organic carbon content in this region (Tack et al. 1997), while levels measured in the DSDS are considered to be very high. Values for P, CaCO3 and EC are clearly higher for the DSDS than for the alluvial soils.

From the 92 sampling points (95%) on DSDS, 87 or 95% were found to be polluted with at least one of the measured heavy metals according to the criteria outlined by the Flemish Decree on Soil Sanitation (VLAREBO 1996). Classification of the measured concentrations of heavy metals according to the reference values (Fig. 5) clearly demonstrates severe pollution with Cr, Cd, Zn and Pb. Cu is a minor contaminant, while Ni is of less environmental concern in the area. In 99 of the 139 samples (72%) with soil pollution, Cr, Cd as well as Zn concentrations are above the pollution criterion for agriculture, nature and forestry. Cd pollution is lower than in the Upper Scheldt area (Vandecasteele et al. 2002a) and similar to the Sea Scheldt (Vandecasteele et al. 2003). In comparison with the Upper and Sea Scheldt, Cr levels are lowest while the Zn, Cu and Pb levels are highest for the Leie DSDS.

## 3.3. Geographical impact and morphology of the DSDS

The area of the landfills varied between 0.25 and more than 10 ha and averaged to 2.6 ha. The average area for landfilling was 1.6 ha in the period before 1965, 2 ha between 1965 and 1980 and 6 ha after 1980. For 85% of the sampling points where pollution was found, the polluted sediment was on the surface. The thickness of the polluted layer was lower than 50 cm for 32% of the total area of contaminated sites, and between 50-100 cm for 27% of the area. For 41% of the area designated as contaminated, the thickness of the contaminated layer exceeded 1 meter.

Almost half of the landfill area (45%) was raised between 1965 and 1980, while 25% of the area was raised before 1965, and 30% after 1980. When the cumulative dredged sediment landfill area is plotted against the position downstream along the Leie (Fig. 3c), it is observed that 70% of the landfills are situated in the most downstream 1/3th of the study area. There is a distinct clustering of landfills near the city of Deinze. Several landfills of group 3 were constructed along the Diversion Canal, but were filled with sediments from the Leie and the canal outfall.

## 3.4. Spatial trends in DSDS quality

The differences in sediment quality between the four groups of DSDS (Fig. 2) were tested with ANOVA. For all metals, phosphorus and clay content, differences were highly significant ($p < 0.001$). Differences were still significant for OC ($p < 0.05$) but not for silt content. Highest levels of Cd, Cr, Ni, Zn and clay were found for group 2 and lowest levels for group 1, while Pb was highest for group 4 and lowest for group 3 (Table 3). Cu was highest for both group 2 and group 4 and lowest for group 1. Especially for Cr, the grouped data were highly variable. The low heavy metal concentrations for group 1 can at least partly be related to a lower clay and OC content of the dredged sediment (Table 3). Both sediment properties are important for heavy metal binding. It thus can be concluded that important pollution of the sediment with heavy metals was already going on before 1965. For one site in the most downstream section in the vicinity of Ghent, records exist that the landfill was constructed between 1930 and 1935. Maximum heavy metal contents measured on that site were 16 mg Cd kg$^{-1}$ DM, 290 mg Cr kg$^{-1}$ DM, 960 mg Pb kg$^{-1}$ DM and 2600 mg Zn kg$^{-1}$ DM.

## 4. Discussion

The results of this survey served two purposes. On the one hand, they allowed to reconstruct historical sediment pollution of the River Leie. On the other, this study gives information about the influence of sediment disposal on soil quality in the alluvial plains. Along the Leie river, sediments have mostly been disposed close to the location where they were dredged, this in contrast to the Upper (Vandecasteele et al. 2002a) and Sea Scheldt (Vandecasteele et al. 2003). This greatly facilitates detection of spatial and temporal trends in sediment disposal and sediment quality for the river Leie.

### 4.1. Temporal trends in sediment quality

The collected 'off-line' sediment data (Winter et al. 2001) can be used as a reconstruction of past sediment pollution of the River Leie, especially because long-term sediment monitoring programs are not available. The pre-requisite of metal stabilization in the sediment for temporal comparison of sediment data (Christiansen et al. 2002) is largely met for these calcareous landfilled sediments because of the very low mobility of metals (Vandecasteele et al. 2002a). It is evident from the data that sediment pollution was occurring since long before 1970, especially for the area downstream from Deinze. With respect to the contamination levels encountered, it has to be taken into consideration that sediments were mostly removed from river sections with high accumulation due to a lower flow velocity. Contamination will therefore be concentrated because fine particles with high heavy metal loads preferentially settle in these areas.

The Rabot landfill used for the 1994 dredging operation in the Deinze area was constructed outside the Leie alluvial plains. Comparison of group 4 (before 1970), 2 (1970-1983), 3 (1984-1990) and 5 (1994) reveals a temporal sediment quality trend. Fig. 6a depicts the trend in the raw data, while Fig. 6b shows the data normalized for sediment clay content. No significant trends were found, except for Pb. Pb exhibits a marked decrease since the seventies. This is also observed in sediment studies of other river basins (e.g. (Smit et al. 1997) for the Rhine-Meuse Delta). The lower heavy metal concentrations for group 3 relative to group 2 represents an important sediment quality improvement in a short period.

Differences in pollution levels may also be related to differences in sediment properties between groups. The strong positive correlation between clay content, organic carbon and heavy metal concentrations is clearly illustrated in the biplot (Fig. 4). To correct for the effect of clay content on metal concentration levels, data were normalized with respect to clay (Fig. 6b). This resulted in a decrease in variation in Cr, Cd and Zn, but hardly affected the trend observed for Pb. Clearly, the decrease in sediment Pb can be attributed to a significant decrease of Pb inputs into the river system. Cd contents show some decrease since the seventies, while no trend is observed for Cr and Zn.

## 4.2. Structural changes in river systems and sediment quality

The River Leie is mostly canalized and embanked, especially in the upstream part, and water levels are strongly regulated. Overbank sedimentation therefore is very unlikely to happen. In a natural river system, overbank sedimentation is a natural process by which sediments are removed from the water during high discharge events. For two UK rivers, overbank sedimentation rates were determined to be up to 40% of the total sediment load (Walling et al. 1999). For the River Leie, this process was replaced by dredging operations. Riverine sedimentation leads to a thin sediment layer extended over larger areas in the alluvial plains (Martin 2000), while dredged sediment disposal in the alluvial plains results in discrete landfills scattered over the alluvial plains.

Making rivers navigable locally resulted in levelling up and covering of the original soil and the specific habitat (geographical impact). At the same time, significant contamination with heavy metals and high nutrient levels were introduced. This survey allowed to map the pollution of the terrestrial compartment of the Leie alluvial plain which is connected to pollution of the water body through dredging activities. The data from our survey can be used for ecological risk assessment comparing several rehabilitation and management scenarios for the alluvial plains (Kooistra et al. 2001).

## 4.3. Potential adverse effects

The high $CaCO_3$ contents and the small difference between actual and potential pH of all DSDS suggest a strong buffering capacity against acidification of the substrate. Potential leaching of heavy metals is not expected to be a concern (Singh et al. 2000). However, despite high OC and/or clay contents, bio-availability of heavy metals towards plants and soil dwelling organisms may be enhanced (Singh et al. 1998, Tack et al. 1999, Stephens et al.

2001). Earthworms occupy a key position in the transfer of pollutants towards other trophic levels and have a high potential for Cd accumulation (Hendriks et al. 1995). Bioconcentration of Cd by earthworms was calculated to be a risk for higher trophic levels in the foodweb when concentrations in DSDS exceed 10 mg Cd $kg^{-1}$ DM (Beyer and Stafford 1993). This concentration is exceeded in the superficial layer of the dredged sediment landfills along the Leie in more than half of the sampling points (75 samples from 52 points). On a dredged sediment landfill along the river Leie, elevated Cd and Zn concentrations in leaves of *Salix fragilis* and high Cd concentrations in small mammals were found, indicating potential adverse effects of dredged materials for ecosystems (Mertens et al. 2001). Volunteer willows rooting in polluted dredged sediment landfills showed elevated foliar Cd and Zn concentrations (Vandecasteele et al. 2002c): the Cd concentrations were clearly higher than the 1.14 mg Cd/ kg dry weight threshold value for feedstuffs defined in the EU directive 1999L0029, and in most cases higher than the 6 mg Cd/kg dry weight permissible level in raw material used as fertilizer (VLAREA 1998).

## 4.4. Management of dredged sediment-derived soils

The geographical impact of DSDS can be locally high. Dredged sediments are classified as waste products by European (EU waste catalogue) and regional legislation (VLAREA 1998). We define the volume-to-area ratio (V:A) as an important measure representing the surface use efficiency for risk and management evaluation purposes. On a site where sediments are filled up to 2 meter the available space is used more efficiently, which is shown by a higher V:A. In general 2 groups of DSDS can be distinguished: (1) recent landfills, with special protective measures, sometimes constructed in former sandpits or above waste dumps and with larger surfaces and higher V:A and (2) the older landfills, which are scattered over the alluvial plain and have a very low V:A. For the recent landfills, clearly stated legislative limitations for reuse of the site are delineated and safe land-uses, usually after capping the site, are planned. For the older landfills, no land-use limitations related to the presence of contamination currently exist, as these sites officially are not identified as being a DSDS. Especially for the last group of DSDS, the low V:A must be evaluated adequately. For all sites without a functional capping, save land-use must be guaranteed and future monitoring of soil processes such as acidification rates and turnover of organic matter is necessary.

## 4.5. Nature rehabilitation

Rehabilitation of the alluvial plains in the frame of integrated water management will be confronted with several obstructions, e.g. the destroyed meandering pattern, the levelling-up of the wetter parts during the river broadening works (Defoort and Roggeman 1996), the intensive urbanization pressure on the open areas (upstream from the canal Roeselare-Leie), and both pollution status and geographical distribution of DSDS especially in the vicinity and downstream from Deinze. Landfilling of dredged sediments caused a pollution of the alluvial plains with a more permanent character than the *in situ* sediment pollution itself (Vandecasteele et al. 2002a). River sediment quality is expected to improve gradually once input of pollutants into the river system has been reduced. For example, ongoing sedimentation results in burial of older sediments. Sediment quality improvement in the river can lead to surface sediments becoming non-toxic (Borgmann and Norwood 2002).

In the upstream part from Deinze, impact of polluted DSDS is lowest. However, in this area the effect of the meander cutting-off and the river broadening works were highest. The proportion of DSDS and other levelled-up sites in the Leie alluvial plain is shown in Fig.

7. From an ecological viewpoint, the area downstream from Deinze is most problematic because more strongly polluted dredged sediments were landfilled in this area. At the same time, this is the area that has the highest potential for river wetland restoration because meandering is still relatively intact. The sites all originated before 1980, mainly (80%) before 1965. No protective measures were applied in these periods and these DSDS have since been used as a normal soil, mostly as pasture.

In case of nature restoration projects, more detailed soil survey and research is needed to allow for a correct assessment of the ecological potential of the area. Nature rehabilitation resulting in overbank sedimentation and spreading of polluted sediments must be avoided as long as sediment quality is inappropriate (Smit et al. 1997). When a management objective for nature development on polluted DSDS is proposed, both risks of pollution and feasibility of the selected target must be considered. Three aspects can limit the feasibility: (1) DSDS are levelled-up and thus have a changed hydrology and sometimes another soil texture, (2) DSDS are rich in nutrients and thus can limit the development of certain species and stimulate another vegetation type, and (3) pollution can result in toxicity for target species. First the substrate characteristics and the relative suitability as rooting medium or habitat for plants and soil organisms must be considered. When nature management goals can not be met due to pollution, remediation measures must be considered. Polluted dredged sediment-derived soils in alluvial plains used for nature conservation or agriculture must be properly managed aiming at ecological risk reduction. The presented results warn us that reliable data on soil quality in alluvial areas are necessary, rather than *a priori* assuming pristine soil conditions.

## Acknowledgements

This project was carried out with financial support from the Waterways and Marine Affairs Administration (AWZ) of the Ministry of the Flemish Community. We are grateful to Carine

Buysse, Els Mencke, Anya De Rop, Athanaska Verhelst and Ann Capieau for the accurate soil analyses and to Koen Willems for the help during the field survey.

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Table 1. Summary statistics for the dredged sediment-derived soils (139 soil samples)

| | Mean | Median | Stdev. | Min. | 10th Perc. | 90th Perc. | Max. |
|---|---|---|---|---|---|---|---|
| **Cd (mg kg$^{-1}$ DM)** | 9.7 | 9.9 | 6.4 | 0.3 | 1.6 | 19.7 | 26.4 |
| **Cr (mg kg$^{-1}$ DM)** | 269 | 232 | 209 | 35 | 93 | 484 | 1761 |
| **Cu (mg kg$^{-1}$ DM)** | 190 | 177 | 89 | 18 | 87 | 310 | 512 |
| **Ni (mg kg$^{-1}$ DM)** | 45 | 45 | 18 | 11 | 21 | 67 | 142 |
| **Pb (mg kg$^{-1}$ DM)** | 397 | 344 | 249 | 35 | 140 | 703 | 1139 |
| **Zn (mg kg$^{-1}$ DM)** | 1520 | 1395 | 846 | 77 | 509 | 2796 | 3808 |
| **% clay** | 38 | 39 | 12 | 12 | 24 | 53 | 65 |
| **% silt** | 45 | 45 | 9 | 16 | 34 | 56 | 60 |
| **% sand** | 16 | 12 | 16 | 0 | 1 | 41 | 70 |
| **P (g kg$^{-1}$ DM)** | 2.8 | 2.8 | 1.0 | 0.5 | 1.4 | 4.2 | 5.7 |
| **S (g kg$^{-1}$ DM)** | 3.2 | 2.3 | 2.5 | 0.4 | 1.0 | 6.2 | 13.6 |
| **N (g kg$^{-1}$ DM)** | 3.9 | 3.8 | 1.6 | 1.3 | 2.3 | 5.3 | 12.4 |
| **% $CaCO_3$** | 6.9 | 6.9 | 1.5 | 3.8 | 5.0 | 8.8 | 13.1 |
| **% OC** | 4.1 | 4.0 | 1.3 | 1.8 | 2.3 | 5.8 | 7.4 |
| **pH-$H_2O$** | 7.5 | 7.5 | 0.2 | 6.9 | 7.2 | 7.8 | 8.0 |
| **pH-$CaCl_2$** | 7.1 | 7.1 | 0.2 | 6.5 | 6.9 | 7.4 | 7.6 |
| **EC (µS cm$^{-1}$)** | 767 | 465 | 667 | 113 | 169 | 1844 | 2550 |

Table 2. Summary statistics for the reference soil samples from the A horizon of 28 alluvial soils in the study area

| | **Mean** | **Median** | **Stdev.** | **90th Perc.** | **Max.** |
|---|---|---|---|---|---|
| **Cd (mg kg$^{-1}$ DM)** | 0.9 | 0.9 | 0.5 | 1.5 | 2.3 |
| **Cr (mg kg$^{-1}$ DM)** | 65 | 66 | 29 | 100 | 119 |
| **Cu (mg kg$^{-1}$ DM)** | 27 | 23 | 16 | 47 | 78 |
| **Ni (mg kg$^{-1}$ DM)** | 24 | 26 | 11 | 37 | 46 |
| **Pb (mg kg$^{-1}$ DM)** | 65 | 57 | 38 | 105 | 192 |
| **Zn (mg kg$^{-1}$ DM)** | 157 | 139 | 90 | 257 | 441 |
| **% clay** | 21 | 22 | 8 | 31 | 37 |
| **% silt** | 38 | 39 | 12 | 51 | 54 |
| **% sand** | 41 | 38 | 18 | 73 | 79 |
| **P (g kg$^{-1}$ DM)** | 1.1 | 1.0 | 0.4 | 1.6 | 2.1 |
| **S (g kg$^{-1}$ DM)** | 0.8 | 0.7 | 0.4 | 1.4 | 1.7 |
| **N (g kg$^{-1}$ DM)** | 4.5 | 4.6 | 2.1 | 7.2 | 8.3 |
| **% $CaCO_3$** | 1.1 | 1.0 | 0.6 | 1.8 | 2.2 |
| **% OC** | 3.7 | 3.9 | 1.7 | 5.5 | 6.4 |
| **pH-$H_2O$** | 6.3 | 6.4 | 0.5 | 6.9 | 7.2 |
| **pH-$CaCl_2$** | 5.7 | 5.7 | 0.5 | 6.3 | 6.5 |
| **EC (µS cm$^{-1}$)** | 130 | 142 | 58 | 210 | 234 |

Table 3. Average concentration of heavy metals (mg $kg^{-1}$ dry soil) and descriptive soil properties for the dredged sediment landfills as a function of location (definition of the groups: see Figure 2). Means that are not significantly different are denoted with the same letter (Sidak multiple comparison of means at the 95% level of significance). Background concentration (BC) for heavy metals according to the Flemish Decree related to Soil Sanitation for the standard soil type (1% OC and 10% clay) are displayed too

| | **1** | **2** | **3** | **4** | **BC** |
|---|---|---|---|---|---|
| **Cd** | 5.9 a | 14.0 b | 9.5 a | 8.8 a | 0.8 |
| **Cr** | 145 a | 210 b | 152 ab | 218 b | 37 |
| **Cu** | 154 a | 362 c | 234 ab | 280 b | 17 |
| **Ni** | 38 a | 54 b | 49 ab | 40 a | 9 |
| **Pb** | 300 ab | 350 b | 196 a | 580 c | 40 |
| **Zn** | 1020 a | 1935 c | 1284 ab | 1604 bc | 62 |
| **clay (%)** | 31 a | 46 c | 39 bc | 36 ab | |
| **OC (%)** | 3.4 a | 4.2 ab | 4.1 ab | 4.4 b | |
| **P (g $kg^{-1}$ DS)** | 2.4 a | 3.4 b | 3.2 ab | 2.5 a | |
| **EC (µS $cm^{-1}$)** | 742 ab | 935 b | 1169 b | 445 a | |

(Figure captions)
Figure 1. The Leie and Scheldt river with the study area indicated.

Figure 2. Bubbleplot indicating the dredged amounts as function of both period and distance along the river. The distance is measured downstream from the French border. The circle surface displays the dredged amount ((1) DSDS in the upstream part of the Gent-De Panne railway bridge, (2) DSDS constructed between 1960 and 1983 and located between the Gent-De Panne railway bridge and the Astene barrage, (3) DSDS in the same section but constructed after 1983, (4) DSDS in the downstream section from the Astene barrage constructed before 1970).

Figure 3. (a) Total dredged amounts for all locations as a function of period and (b) total dredged amounts for all periods as a function of location of the dredging operation, and (c) differential and cumulative distribution of the area of sampled sites as a function of position along the Leie.

Figure 4. Biplot with results of a PCA of the heavy metal contents and other soil characteristics for the 139 soil samples from dredged sediment-derived soils, in which 59% of the variation is explained by the first two components.

Figure 5. Classification of the heavy metal concentrations of the samples of the dredged sediment landfills over the sanitation standard values of the Flemish Decree on Soil Recovery (0: < background concentration levels, 1: between background concentration level and pollution criterion, 2: > pollution criterion, 3: > sanitation standard value for nature and agriculture, 4: > sanitation standard value for habitation, 5: > sanitation standard value for recreation and 6: > sanitation standard value for industry). The number of samples in each class is shown on the Y-axis.

Figure 6. Temporal trends in dredged sediment quality for heavy metals expressed relative to the average value in group 4 (DSDS constructed downstream from Deinze before 1970), with (b) or without (a) normalisation towards the clay content.

Figure 7. Relative importance of dredged sediment-derived soils and other levelled-up sites for the upstream en downstream area of Deinze.

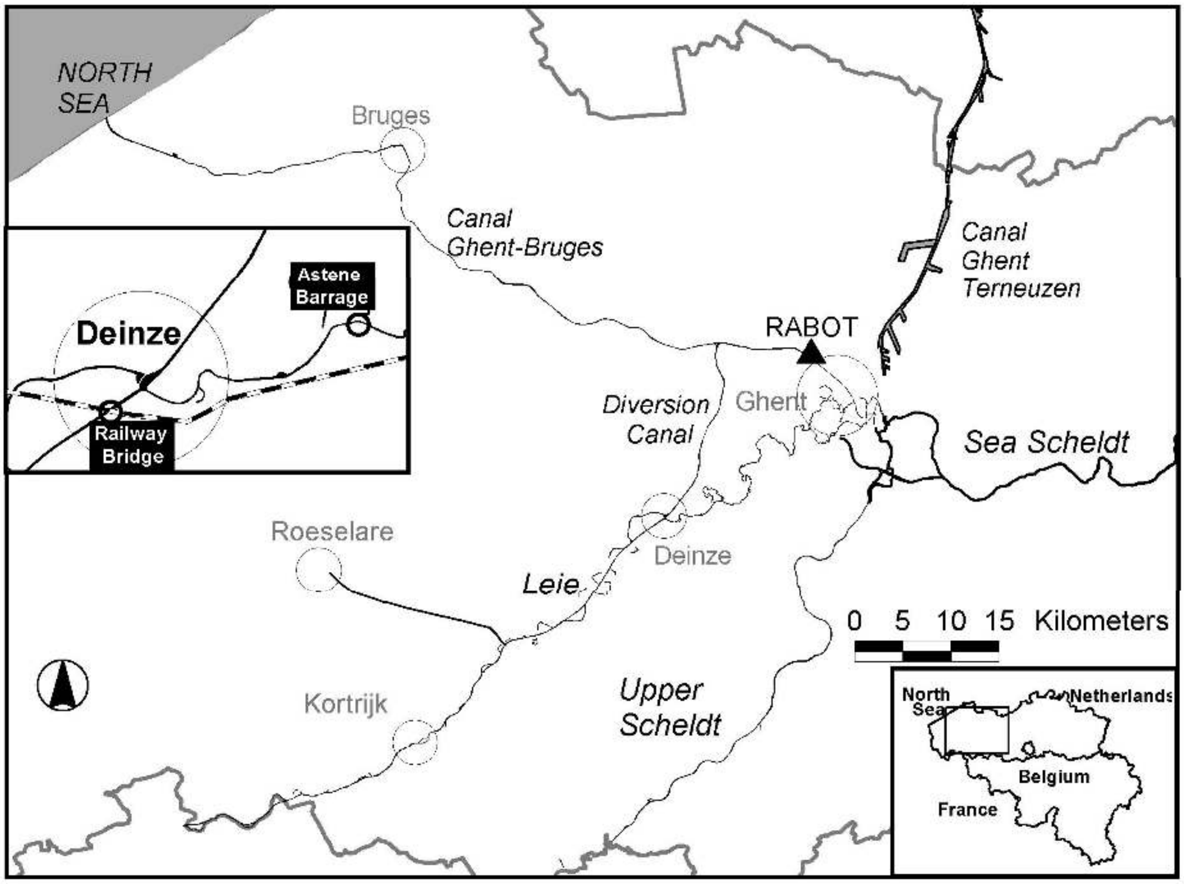
NORTH SEA
Bruges
Canal Ghent-Bruges
Canal Ghent Terneuzen
RABOT
Diversion Canal
Ghent
Sea Scheldt
Deinze
Astene Barrage
Railway Bridge
Roeselare
Deinze
Leie
Kortrijk
Upper Scheldt
0 5 10 15 Kilometers
North Sea
Netherlands
Belgium
France

Figure 1

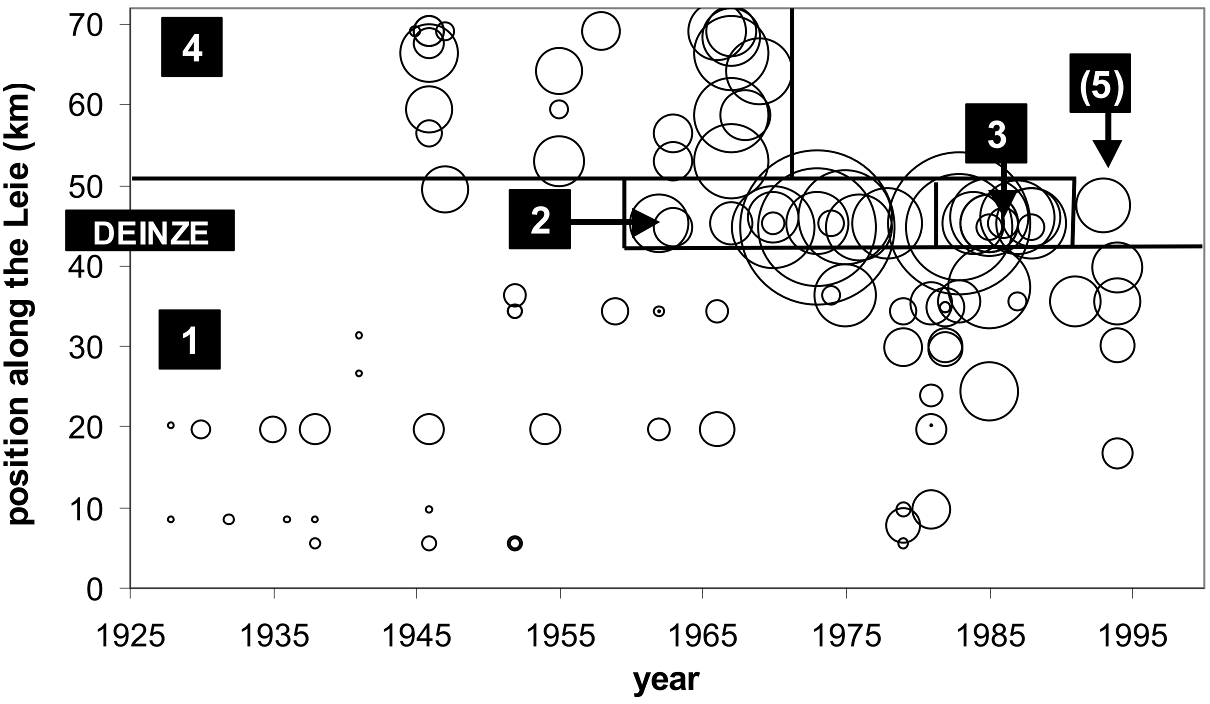
4
1
2
3
(5)
DEINZE
position along the Leie (km)
0
10
20
30
40
50
60
70
1925
1935
1945
1955
1965
1975
1985
1995
year

Figure 2

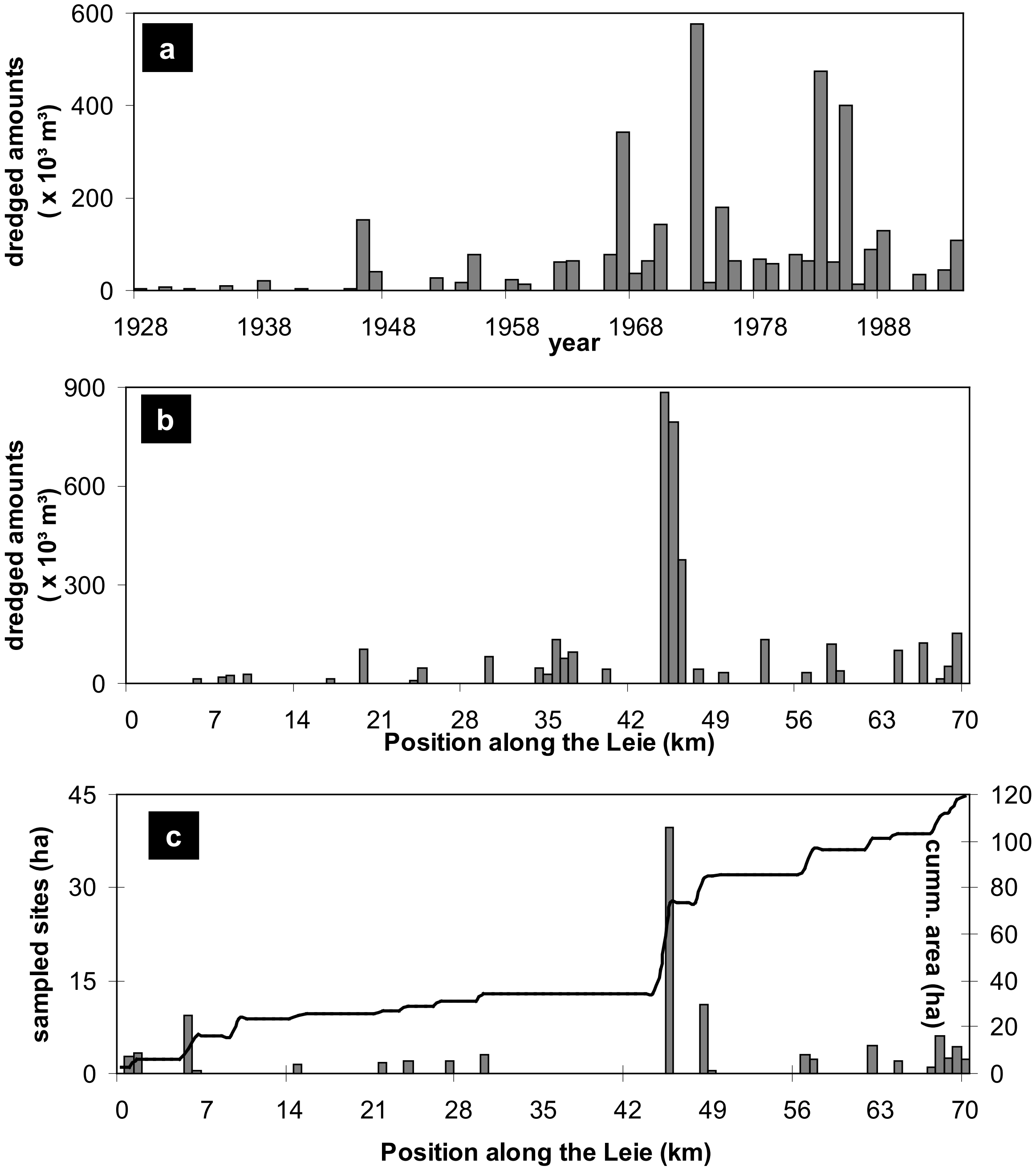
a
dredged amounts ( x 10³ m³)
600
400
200
0
1928
1938
1948
1958
1968
1978
1988
year
b
dredged amounts ( x 10³ m³)
900
600
300
0
0
7
14
21
28
35
42
49
56
63
70
Position along the Leie (km)
c
sampled sites (ha)
45
30
15
0
cumm. area (ha)
120
100
80
60
40
20
0
0
7
14
21
28
35
42
49
56
63
70
Position along the Leie (km)

Figure 3

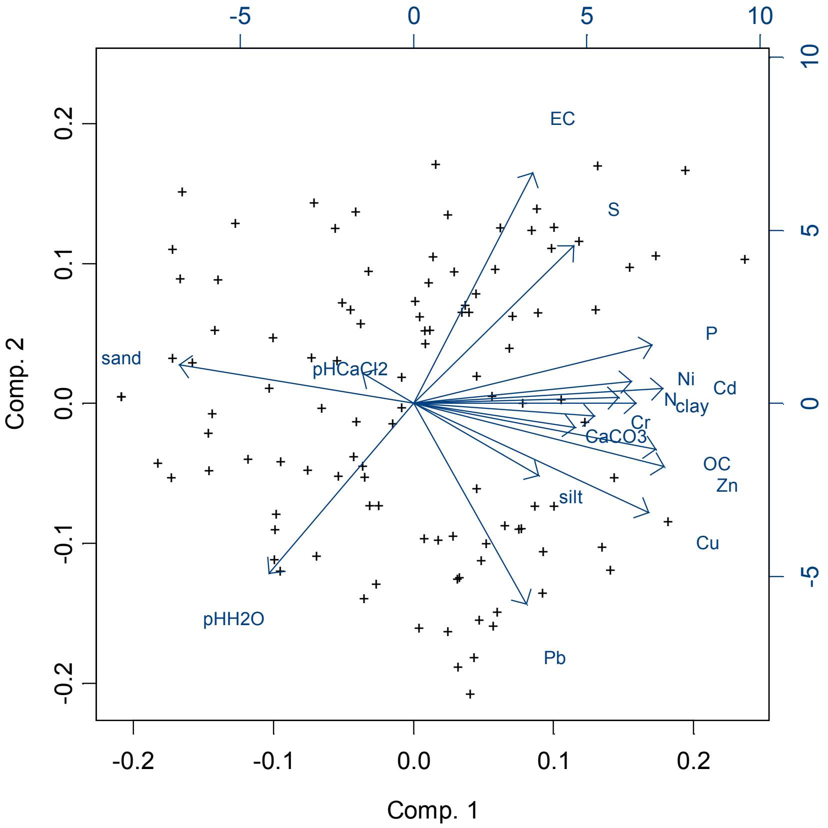
-5
0
5
10
10
5
0
-5
0.2
0.1
0.0
-0.1
-0.2
-0.2
-0.1
0.0
0.1
0.2
Comp. 1
Comp. 2
EC
S
P
Ni
Cd
N
clay
Cr
CaCO3
OC
Zn
silt
Cu
Pb
pHH2O
pHCaCl2
sand

Figure 4

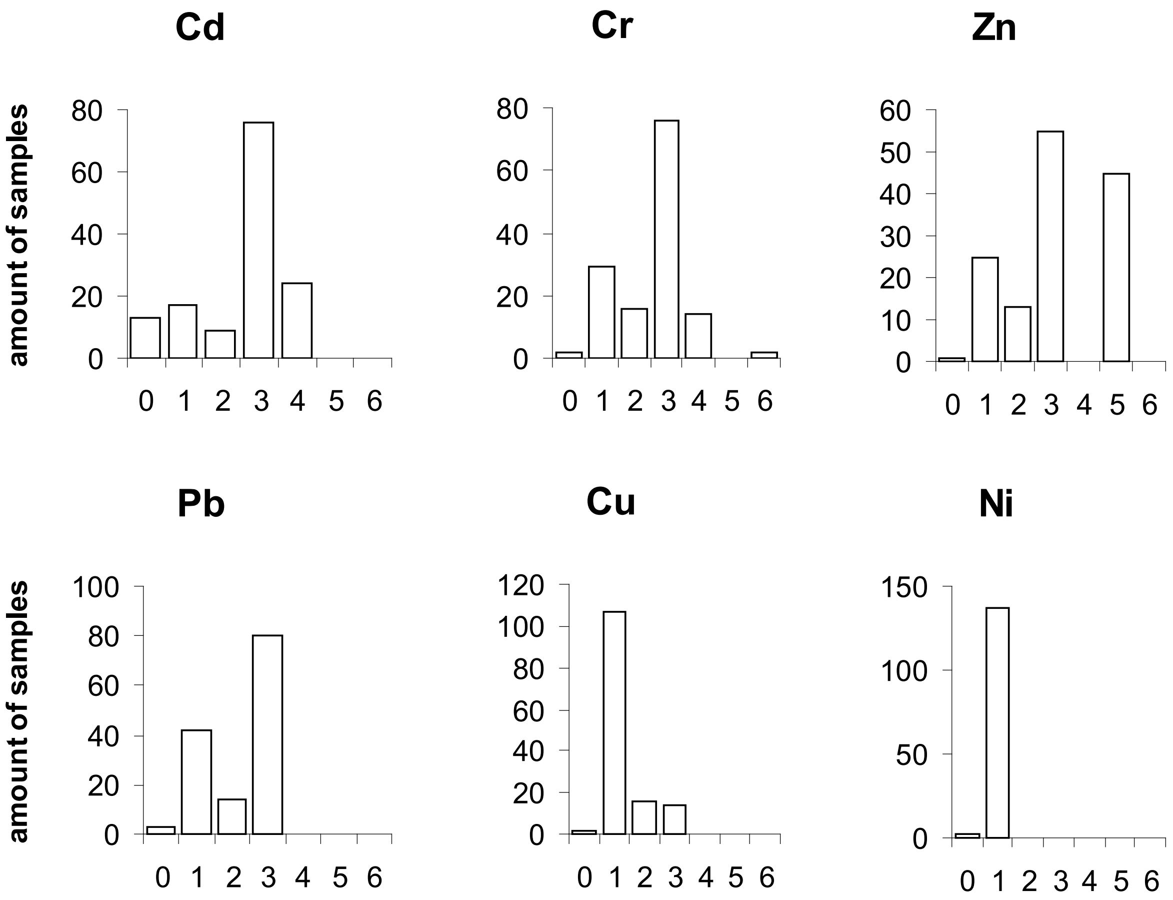
Cd
Cr
Zn
amount of samples
80
60
40
20
0
0 1 2 3 4 5 6
60
50
40
30
20
10
Pb
Cu
Ni
100
120
150
50

Figure 5

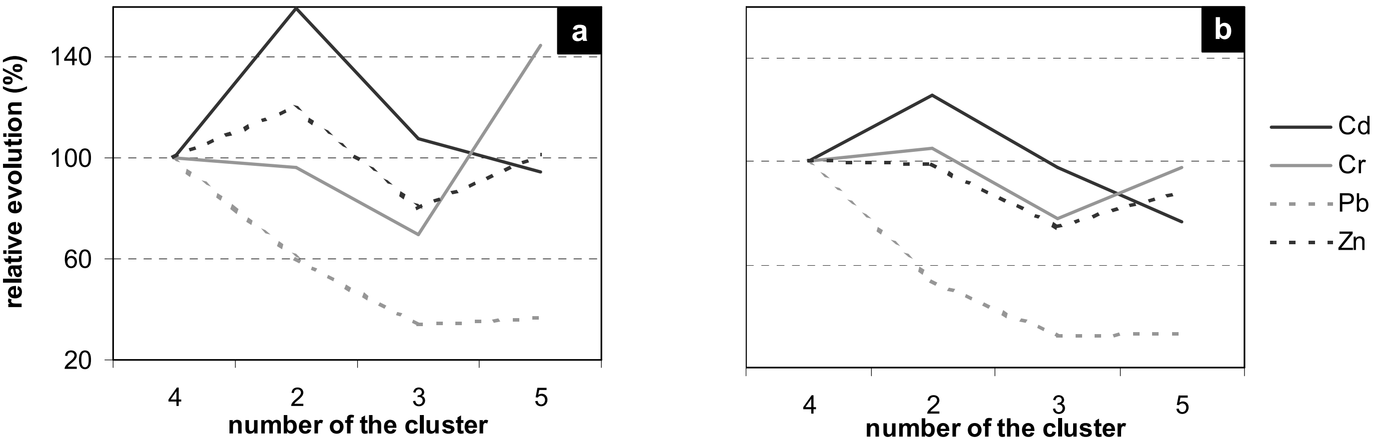
a
b
140
100
60
20
relative evolution (%)
4
2
3
5
number of the cluster
Cd
Cr
Pb
Zn

Figure 6

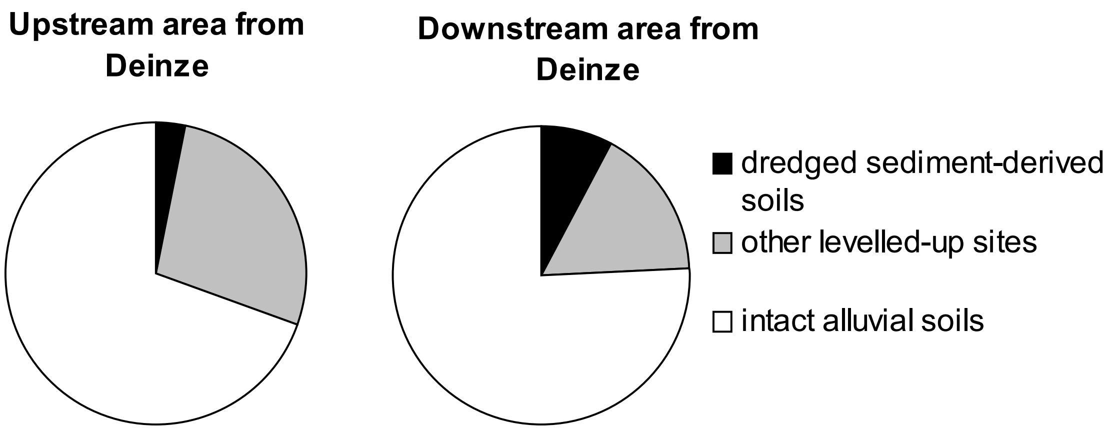
Upstream area from Deinze
Downstream area from Deinze
■ dredged sediment-derived soils
▨ other levelled-up sites
☐ intact alluvial soils

Figure 7