THE IMPACT OF BIOTURBATION BY SMALL MAMMALS ON HEAVY METAL REDISTRIBUTION IN AN EMBANKED FLOODPLAIN OF THE RIVER RHINE

SANDER WIJNHOVEN[1], IVO THONON[2], GERARD VAN DER VELDE[3], ROB LEUVEN[4], MATHILDE ZORN[5], HERMAN EIJSACKERS[6] and TOINE SMITS[7]

[1]*Centre for Water and Society, Faculty of Science, Radboud University Nijmegen, P.O. Box 9010, NL-6500 GL Nijmegen, The Netherlands; Participant of the Netherlands Centre for River Studies (NCR);* [2]*Department of Physical Geography, Faculty of Geosciences, Utrecht University, P.O. Box 80.115, NL-3508 TC Utrecht, The Netherlands; Participant of the Netherlands Centre for River Studies (NCR);* [3]*Department of Animal Ecology and Ecophysiology, Institute for Wetland and Water Research, Radboud University Nijmegen, P.O. Box 9010, NL-6500 GL Nijmegen, The Netherlands; Participant of the Netherlands Centre for River Studies (NCR);* [4]*Department of Environmental Science, Institute for Wetland and Water Research, Radboud University Nijmegen, P.O. Box 9010, NL-6500 GL Nijmegen, The Netherlands; Participant of the Netherlands Centre for River Studies (NCR);* [5]*Institute of Ecological Science, Vrije Universiteit Amsterdam, De Boelelaan 1085, NL-1081 HV Amsterdam, The Netherlands;* [6]*Institute of Ecological Science, Vrije Universiteit Amsterdam, De Boelelaan 1085, NL-1081 HV Amsterdam, The Netherlands; Wageningen University and Research Centre, P.O. Box 9101, NL-6700 HB Wageningen, The Netherlands; Participant of the Netherlands Centre for River Studies (NCR);* [7]*Centre for Water and Society, Faculty of Science, Radboud University Nijmegen, P.O. Box 9010, NL-6500 GL Nijmegen, The Netherlands; Water Management and Sustainability, Faculty of Social Sciences, Erasmus University Rotterdam, P.O. Box 1738, NL-3000 DR Rotterdam, The Netherlands; Participant of the Netherlands Centre for River Studies (NCR)*

*(*author for correspondence, e-mail: S.Wijnhoven@science.ru.nl)*

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Abstract. Floodplains along large European rivers are diffusely polluted with heavy metals due to emissions in the past. Because of low mobility of heavy metals in floodplain soils and improvements of water quality, these pollutants will remain in place, and can gradually become covered with less contaminated sediments. Bioturbators, especially earthworms, can play an important role in the mixing and surfacing of contaminated substrate. Surfaced substrate can be redistributed by recurrent flooding events, even to areas outside the floodplain. The question remained to what extent bioturbation by small mammals contributes to the redistribution of heavy metals from river sediments in floodplains. Extensive fieldwork on bioturbators such as voles, moles and earthworms and their distribution patterns, as well as on sediment deposition and bioturbation, was conducted at the 'Afferdensche en Deestsche Waarden' floodplain over the years 2001–2003. Field data were combined with data of experiments in field enclosures and substrate columns to calculate the amounts of sediment and heavy metals (Zn, Cu, Pb and Cd) redistributed during the floods as well as on an annual basis. Moles and voles surfaced considerable amounts of substrate and heavy metals, but not as much as earthworms which contribute a substantial proportion of the total deposition and redistribution during floods. Although the impact of moles and voles on the redistribution during floods was only locally important, on an annual basis the bioturbation activity of especially moles in floodplains cannot be neglected. The annual amounts of substrate and heavy metals surfaced by all investigated bioturbators were even larger than the total amounts of substrate and heavy metals deposited during floods.

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1. Introduction

Many floodplains along large rivers in Europe are contaminated with pollutants, including a range of heavy metals (e.g. Cd, Cr, Cu, Hg, Ni, Pb and Zn), due to the deposition of contaminated sediments during flooding events in the past (Schröder, 2005). The sediments were especially contaminated in the 1960s and 1970s, due to unbridled emissions and a lack of integrated water pollution control (Vink *et al.*, 1999; Middelkoop, 2000). Especially Zn, Cu, Pb and Cd are present in levels posing risks towards floodplain ecosystems (Kooistra *et al.*, 2001, 2005; Leuven *et al.*, 2005; Van Vliet *et al.*, 2005). As retention, mobility and ecological implications of heavy metal contaminants in floodplain soils under changing environmental conditions are poorly understood, there are currently restrictions on digging activities, excavations and hydraulic engineering works in floodplains. This often interferes with ecological rehabilitation plans intended to reduce toxicological risks by removing contaminated soils. This may result in increased costs, delays and even cancellation of ecological rehabilitation activities.

Since the water quality of several large rivers has improved over the last decades, recently deposited soil layers are often less polluted than older layers in the subsoil (Vink *et al.*, 1999; Ciszewski, 2002; Middelkoop, 2002). However, quite a number of animal species dig, root, grub or burrow through these soil layers, as they live partly or permanently underground, create nests, tunnels or hillocks, or search for food in the soil (Mitchell, 1988; Robinson *et al.*, 2002). These soil dwellers can therefore mix the more polluted subsoil with the less polluted topsoil. In addition, they bring the subsoil to the surface, where the soil contaminants can be redistributed. The impact of these so-called bioturbators on the redistribution of heavy metals in floodplains remained largely unclear (Wijnhoven *et al.*, 2006a). Some studies suggest that the impact of certain species on soil redistribution can be substantial. Earthworm and ant species are assumed to be important bioturbators when they are numerous (Scheu, 1987; Müller-Lemans, 1996; Tyler *et al.*, 2001), which is the case in a large variety of ecotopes. Also several small mammal species could potentially have a strong impact on soil horizoning (Mitchell, 1988; Edwards *et al.*, 1999). Examples are the European mole (*Talpa europaea*), which is known to create tunnels up to several hundreds of metres in length (Godfrey and Crowcroft, 1969; Haeck, 1969) and the common vole (*Microtus arvalis*), a good burrower that is sometimes present in densities of up to 1000 individuals per ha (Lange *et al.*, 1994). The burrowing activities of both species are accompanied by the creation of hillocks of excavated substrate. Since this substrate originates from tunnels in the more contaminated subsoil (Verbeke, 1997; Witte, 1997), heavy metals will be exposed at the surface, where weathering of the soil redistributes them with the substrate to the immediate vicinity of the former hillock. Floods can erode the soil hillocks and redistribute the soil and the associated contaminants over larger distances, not only within but also outside the floodplain. At the same time, floods also influence the spatial and temporal distribution of the bioturbators and have a strong impact on their population size (Andersen *et al*., 2000; Wijnhoven *et al*., 2005, 2006b) and burrowing activities.

The aim of this study was to estimate the contribution of bioturbation by small mammals to the distribution of the metals Zn, Cu, Pb and Cd in floodplains. In this paper the following research questions are addressed:

a) What amounts of substrate and heavy metals are surfaced by common voles and European moles in a moderately polluted floodplain?
b) How do the amounts surfaced by small mammals compare to bioturbation by earthworms?
c) What is the share of bioturbation in the deposition of substrate and heavy metals during a flood?
d) What is the importance of bioturbation in the redistribution of substrate and heavy metals compared to the annual deposition during floods?

To answer these questions, we estimated vole- and molehill densities. Amounts of soil and heavy metal concentrations in vole- and molehills were estimated and related to soil concentrations. Further vole- and molehill turnover was monitored in an enclosure and in the open field. The heavy metal loads surfaced by voles and moles were compared to the loads surfaced by bioturbation by earthworms as established in column experiments, and the loads of heavy metals deposited during two floods in 2002.

2. Materials and methods

2.1. Research area

The 'Afferdensche en Deestsche Waarden' (ADW) (longitude 51°54′N, latitude 5°39′E) is a floodplain with an area of 280 ha, situated along the river Waal, the main distributary of the river Rhine in the Netherlands (Figure 1). The research area (160 ha) is embanked by a summer dike (lower embankment near the river to prevent the area from flooding during most of the high waters), and a winter dike (major embankment at its southern border to prevent the hinterland from flooding). The ADW floodplain is a typical moderately polluted floodplain of a large lowland river in the Netherlands (Van Vliet *et al*., 2005), which has been the subject of an ecological rehabilitation programme since 1995 (Zandberg, 1999). It consists of natural and agricultural areas, including some elevated areas, clay excavations, small water bodies and side channels. The research area predominantly consists of grassland and ruderal vegetation types with low grazing intensity (Wijnhoven

Figure 1. Location of the 'Afferdensche en Deestsche Waarden' floodplain (ADW) along the river Waal in The Netherlands.

et al., 2005). The top soil consists of loamy clay deposited by the rivers with an average organic matter content of 7.3 ± 3.3%, a clay/silt content of 51.7 ± 19.1%, and a pH_{CaCl2} of 7.3 ± 0.2. Where excavations have take place, sandy soils can be found near the surface.

The area is subject to periodical inundations, at water discharges of the Rhine $\geq$6300 m^3/s at Lobith (Figure 1). Between 1901 and 2004, the ADW floodplain flooded 77 times. During the last ten years (1995–2004) it flooded 10 times (http://www.waterbase.nl/). The water level in the river rises above the summer dike 4 days per year on average (http://www.waterbase.nl/). During floods, water levels rise to more than 3 m in the lower parts of the floodplain (about three quarters of the total area). The experiments and monitoring activities were executed in the period, between a flood in March 2001 and a flood in January 2004. During this period the area flooded 3 times (i.e. in February 2002, November 2002 and January 2003), of which a flood in February 2002 was preceded by a partial inundation in January. As the research area is bordered by embankments, water leaves the floodplain after flooding mainly by seepage towards the river channel. Once flooded, it takes about two to three weeks for the floodplain to fall dry entirely after the water level in the river has dropped below the height of the summer embankments.

Average annual rainfall is 750 mm, and average annual air temperature is 9.6 °C for this region (as measured between 1971 and 2000; http://www.knmi.nl/).

2.2. Density estimations

To estimate the total bioturbation in the ADW different methods were used. Hillocks from moles are easier to investigate in larger areas than hillocks from voles, due to their size. Vole populations, however, are easier to monitor by live trapping than mole populations due to differences in home range sizes and trappability. Therefore calculations of bioturbation by common voles are based on density estimations of the animals and bioturbation activity in field enclosures. Bioturbation by moles is calculated from density estimations of molehills (Table I).

Wijnhoven *et al.* (2005) described the recolonisation of the ADW by small mammals after flooding events. In this study the research area was subdivided into four zones with similar numbers of monitoring sites: the non-flooded areas and zones at distances of 0–30, 30–120 and more than 120 m from these non-flooded parts. The calculations of bioturbation by voles and moles are therefore based on this subdivision. Earlier observations showed that the densities of small mammals significantly differ between the various zones. We focus on the three periodically flooded zones, as indicated in Figure 2a for the embanked part of the ADW floodplain, as we want to estimate the share of bioturbation within the total sediment deposition. Wijnhoven *et al.* (2005) distinguished 21 small mammal ecotopes based on vegetation structure, soil characteristics and management regime. Based on trapping results these ecotopes were classified into suitable, marginal or unsuitable areas for small mammal species. The habitat suitability of our research area for common voles is presented in Figure 2b. Wijnhoven *et al.* (2006b) calculated the densities of *M. arvalis* during the years 2001 and 2002 in the different zones, during nine trapping sessions. For each session an average density was calculated for each habitat suitability class in each zone. To calculate the amount of surfaced substrate by common voles, the average density just before a flood and the average annual density per zone is calculated (Table I). The average density is multiplied with the average amount of substrate surfaced by a vole as calculated from enclosure experiments.

Throughout 2001 to 2003, large areas of the ADW, including the zones at variable distances to non-flooded terrains described above, were checked for the presence of molehills. The position of each molehill, was determined using a GARMIN GPS 12 Personal Navigator, after which the positions were plotted on maps of the floodplain using ArcMap 8.0. As surface runs with an elevated ridge contribute to the total amount of surfaced soil, each half metre was also recorded. In November 2003, just before a flooding event, the number of molehills was counted over an area of 564000 m^2 (35.0% of the total research area; Figure 2c). The data from this inventory were used to calculate the amount of substrate redistributed during flooding. To calculate the amount of substrate surfaced annually, we assessed the

TABLE I

Input parameters, values and equations with their units and origin, used for the estimations and calculations

Variable	Symbol	Units	Subdivision	Method	Average	Variation	n	Data from
- area	a	ha	0–30 m	ArcMap 8.0	18.24	n.a.	1	[g]
	a	ha	30–120 m	ArcMap 8.0	51.22	n.a.	1	[g]
	a	ha	>120 m	ArcMap 8.0	91.08	n.a.	1	[g]
	a	ha	ADW	ArcMap 8.0	160.45	n.a.	1	[g]
- flood recurrence period	y	weeks	ADW	2001/2002[a]	45	n.a.	1	[g]
- metal concentration 10 cm topsoil	$[Zn]_{0-10}$	mg/kgDW	0–30 m	[a]	357	169[e]	10	[g]
	$[Zn]_{0-10}$	mg/kgDW	30–120 m	[a]	570	409[e]	11	[g]
	$[Zn]_{0-10}$	mg/kgDW	>120 m	[a]	428	216[e]	13	[g]
	$[Cu]_{0-10}$	mg/kgDW	0–30 m	[a]	53.7	24.6[e]	10	[g]
	$[Cu]_{0-10}$	mg/kgDW	30–120 m	[a]	77.2	50.5[e]	11	[g]
	$[Cu]_{0-10}$	mg/kgDW	>120 m	[a]	61.0	29.5[e]	13	[g]
	$[Pb]_{0-10}$	mg/kgDW	0–30 m	[a]	109	48[e]	10	[g]
	$[Pb]_{0-10}$	mg/kgDW	30–120 m	[a]	175	122[e]	11	[g]
	$[Pb]_{0-10}$	mg/kgDW	>120 m	[a]	131	69[e]	13	[g]
	$[Cd]_{0-10}$	mg/kgDW	0–30 m	[a]	1.62	1.32[e]	10	[g]
	$[Cd]_{0-10}$	mg/kgDW	30–120 m	[a]	2.73	2.31[e]	11	[g]
	$[Cd]_{0-10}$	mg/kgDW	>120 m	[a]	2.32	1.42[e]	13	[g]
- metal concentration in enclosure	$[Zn_{en}]_{0-10}$	mg/kgDW		[b]	722	27[e]	6	[g]
	$[Zn_{en}]_{0-5}$	mg/kgDW		[b]	607	38[e]	6	[g]
	$[Zn_{en}]_{0-35}$	mg/kgDW		[b]	674	64[e]	6	[g]
	$[Cu_{en}]_{0-10}$	mg/kgDW		[b]	96.5	4.1[e]	6	[g]
	$[Cu_{en}]_{0-5}$	mg/kgDW		[b]	81.7	3.4[e]	6	[g]
	$[Cu_{en}]_{0-35}$	mg/kgDW		[b]	77.6	6.7[e]	6	[g]

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TABLE I
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Variable	Symbol	Units	Subdivision	Method	Average	Variation	n	Data from
	$[Pb_{en}]_{0-10}$	mg/kgDW		[b]	203	12^e	6	[g]
	$[Pb_{en}]_{0-5}$	mg/kgDW		[b]	173	10^e	6	[g]
	$[Pb_{en}]_{0-35}$	mg/kgDW		[b]	210	15^e	6	[g]
	$[Cd_{en}]_{0-10}$	mg/kgDW		[b]	4.26	0.41^e	6	[g]
	$[Cd_{en}]_{0-5}$	mg/kgDW		[b]	3.52	0.56^e	6	[g]
	$[Cd_{en}]_{0-35}$	mg/kgDW		[b]	3.50	0.97^e	6	[g]
Voles:								
- vole density before flood	DVf	n/ha	0–30 m	$(DVf_{Dec01} + DVf_{Oct02})/2$	6.37	3^e	2	[h]
	DVf	n/ha	30–120 m	$(DVf_{Dec01} + DVf_{Oct02})/2$	3.49	4.6^e	2	[h]
	DVf	n/ha	>120 m	$(DVf_{Dec01} + DVf_{Oct02})/2$	1.01	1.5^e	2	[h]
- vole density in week w	DVw	n/ha	0–30 m	$DVw = 0.0006(w)^2 + 0.167(w)$		0.618^f	9	[h]
	DVw	n/ha	30–120 m	$DVw = -0.0007(w)^2 + 0.0928(w)$		0.186^f	9	[h]
	DVw	n/ha	>120 m	$DVw = -0.0044(w)^2 + 0.1895(w)$		0.307^f	9	[h]
- average annual vole density	DVa	n/ha	0–30 m	$DVa = ({}_0\int^y (-0.0006(w)^2 + 0.167(w)))/y$	4.19	n.a.	1	[g]
	DVa	n/ha	30–120 m	$DVa = ({}_0\int^y (-0.0007(w)^2 + 0.0928(w)))/y$	1.59	n.a.	1	[g]
	DVa	n/ha	>120 m	$DVa = ({}_0\int^y (-0.0044(w)^2 + 0.1895(w)))/y$	0.75	n.a.	1	[g]
- substrate at surface per vole	SVf	kgDW/ind	After 13 w	[b]	6.111	n.a.	5	[g]
- weekly increase number of volehills		%		[b]	9.56	n.a.	2	[g]
- weekly decrease number of volehills		%		[b]	6.49	n.a.	2	[g]

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Variable	Symbol	Units	Subdivision	Method	Average	Variation	n	Data from
- increase of substrate at surface per vole			5 to 13 w	volehill and hole counts [b]	linear	n.a.	2	[g]
- substrate at surface per vole in week w	SVw	kgDW/ind	after initial 5 w	SVw = 0.344(w) + 3.131 [b]		n.a.	5	[g]
- weekly surfaced substrate per vole	SSVw	kgDW/ind*w		(344/1.0307) * 1.0956	0.366	n.a.	5	[g]
- substrate at surface by voles before flood	SSVf	kgDW	0–30 m	SSVf = DVf * a * SVf	710	n.a.	1	[g]
	SSVf	kgDW	30–120 m	SSVf = DVf * a * SVf	1090	n.a.	1	[g]
	SSVf	kgDW	>120 m	SSVf = DVf * a * SVf	593	n.a.	1	[g]
- annually surfaced substrate by voles	SSVa	kgDW	0–30 m	SSVa = DVa * y * a * SSVw	1250	n.a.	1	[g]
	SSVa	kgDW	30–120 m	SSVa = DVa * y * a * SSVw	1360	n.a.	1	[g]
	SSVa	kgDW	>120 m	SSVa = DVa * y * a * SSVw	1180	n.a.	1	[g]
- metal in volehill related to 10 cm topsoil			Zn	$[Zn]_{vh} = 0.98 * [Zn]_{0-10}$ [b]		0.95[f]	78	[g]
			Cu	$[Cu]_{vh} = 0.98 * [Cu]_{0-10}$ [b]		0.95[f]	78	[g]
			Pb	$[Pb]_{vh} = 1.01 * [Pb]_{0-10}$ [b]		0.96[f]	78	[g]
			Cd	$[Cd]_{vh} = 0.94 * [Cd]_{0-10}$ [b]		0.83[f]	78	[g]
- metal at surface by voles before flood	ZnSVf	kg		$ZnSVf = SSVf * (0.98 * [Zn]_{0-10})$		n.a.	1	[g]
	CuSVf	kg		$CuSVf = SSVf * (0.98 * [Cu]_{0-10})$		n.a.	1	[g]
	PbSVf	kg		$PbSVf = SSVf * (1.01 * [Pb]_{0-10})$		n.a.	1	[g]
	CdSVf	kg		$CdSVf = SSVf * (0.94 * [Cd]_{0-10})$		n.a.	1	[g]

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Variable	Symbol	Units	Subdivision	Method	Average	Variation	n	Data from
- annually surfaced metals by voles	ZnSVa	kg		$ZnSVa = SSVa * (0.98 * [Zn]_{0-10})$		n.a.	1	[g]
	CuSVa	kg		$CuSVa = SSVa * (0.98 * [Cu]_{0-10})$		n.a.	1	[g]
	PbSVa	kg		$PbSVa = SSVa * (1.01 * [Pb]_{0-10})$		n.a.	1	[g]
	CdSVa	kg		$CdSVa = SSVa * (0.94 * [Cd]_{0-10})$		n.a.	1	[g]
Moles:								
- molehill density before flood	DMf	n/ha	0–30 m	inventory of 1.4 ha (Nov03) [a]	1209	n.a.	1	[g]
	DMf	n/ha	30–120 m	inventory of 12.2 ha (Nov03) [a]	174	n.a.	1	[g]
	DMf	n/ha	>120 m	inventory of 42.8 ha (Nov03) [a]	27.7	n.a.	1	[g]
- molehill density in week w	DMw	n/ha	0–30 m	$DMw = 0.00008(w)^2 - 0.0007(w)$ [a]		0.982^f	9	[g]
	DMw	n/ha	30–120 m	$DMw = 0.00001(w)^2 + 0.0002(w)$ [a]		0.551^f	9	[g]
	DMw	n/ha	>120 m	$DMw = 0.000005(w)^2 - 0.00007(w)$ [a]		0.731^f	9	[g]
- weight molehill	WM	kgDW	ADW	measured 10 hillocks at 12 localities [a]	0.948	0.630^e	120	[g]
- height molehill	HM	cm		existing and newly built hillocks [c]	6.7	3.15^e	132	[g]
- weekly decrease molehill height		cm		monitored for 66 days [c]	0.43	0.323^e	132	[g]
- weekly decrease molehill height		% HM		[c]	6.42	5.33^e		[g]
- annual number of molehills	DMa	n/ha	0–30 m	$DMa = (y)^{1.064} * (0.00008(y)^2 - 0.0007(y))$	21400	n.a.	1	[g]
	DMa	n/ha	30–120 m	$DMa = (y)^{1.064} * (0.00001(y)^2 - 0.0002(y))$	47900	n.a.	1	[g]
	DMa	n/ha	>120 m	$DMa = (y)^{1.064} * (0.000005(y)^2 - 0.00007(y))$	11400	n.a.	1	[g]

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Variable	Symbol	Units	Subdivision	Method	Average	Variation	n	Data from
- substrate at surface by moles before flood	SSMf	kgDW	0–30 m	SSMf = DMf * a * WM	20900	n.a.	1	[g]
	SSMf	kgDW	30–120 m	SSMf = DMf * a * WM	8430	n.a.	1	[g]
	SSMf	kgDW	>120 m	SSMf = DMf * a * WM	2390	n.a.	1	[g]
- annually surfaced substrate by moles	SSMa	kgDW	0–30 m	SSMa = DMa * a * WM	370000	n.a.	1	[g]
	SSMa	kgDW	30–120 m	SSMa = DMa * a * WM	233000	n.a.	1	[g]
	SSMa	kgDW	>120 m	SSMa = DMa * a * WM	98700	n.a.	1	[g]
- metal in molehill related to 10 cm topsoil			Zn	$[Zn]_{mh} = 0.26 * [Zn]_{0-10} + 120$ [a]		0.44^f	90	[g]
			Cu	$[Cu]_{mh} = 0.26 * [Cu]_{0-10} + 16.3$ [a]		0.39^f	90	[g]
			Pb	$[Zn]_{mh} = 0.26 * [Zn]_{0-10} + 33.5$ [a]		0.47^f	90	[g]
			Cd	$[Zn]_{mh} = 0.18 * [Zn]_{0-10} + 0.76$ [a]		0.15^f	90	[g]
- metal at surface by moles before flood	ZnSMf	kg		$ZnSMf = SSMf * (0.26 * [Zn]_{0-10} + 120)$		n.a.	1	[g]
	CuSMf	kg		$CuSMf = SSMf * (0.26 * [Cu]_{0-10} + 16.3)$		n.a.	1	[g]
	PbSMf	kg		$PbSMf = SSMf * (0.26 * [Zn]_{0-10} + 33.5)$		n.a.	1	[g]
	CdSMf	kg		$CdSMf = SSMf * (0.18 * [Zn]_{0-10} + 0.76)$		n.a.	1	[g]
- annually surfaced metals by moles	ZnSMa	kg		$ZnSMa = SSMa * (0.26 * [Zn]_{0-10} + 120)$		n.a.	1	[g]
	CuSMa	kg		$CuSMa = SSMa * (0.26 * [Cu]_{0-10} + 16.3)$		n.a.	1	[g]
	PbSMa	kg		$PbSMa = SSMa * (0.26 * [Zn]_{0-10} + 33.5)$		n.a.	1	[g]
	CdSMa	kg		$CdSMa = SSMa * (0.18 * [Zn]_{0-10} + 0.76)$		n.a.	1	[g]
Earthworms:								

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Variable	Symbol	Units	Subdivision	Method	Average	Variation	n	Data from
- earthworm density	DE	gFW/m^2	*A. caliginosa*	12 monitoring sessions in 3 years [a]	78	26[e]	12	[i,j]
	DE	gFW/m^2	*L. rubellus*	12 monitoring sessions in 3 years [a]	34	22[e]	12	[i,j]
	DE	gFW/m^2	*L. terrestris*	Lowest estimation during flooding [a]	200	n.a.	2	[i,j]
- activity zone		cm	*A. chlorotica*		0–10	n.a.		[i]
		cm	*A. caliginosa*		0–10	n.a.		[i]
		cm	*L. rubellus*	(might be between 0–3)	0–5	n.a.		[i]
		cm	*L. terrestris*	(could be deeper; 0 up to 300)	0–35	n.a.		[i]
- cast turnover		weeks		[c]	1–2	n.a.		[g]
- cast at surface by earthworms before flood	SEf	gDWs/gFWe	*A. chlorotica*	10 days [d]	1.41	1.65[e]	4	[i]
	SEf	gDWs/gFWe	*A. caliginosa*	10 days [d]	2.88	1.94[e]	4	[i]
	SEf	gDWs/gFWe	*L. rubellus*	10 days [d]	2.18	0.59[e]	4	[i]
	SEf	gDWs/gFWe	*L. terrestris*	10 days [d]	2.01	0.56[e]	4	[i]
- cast surfaced by earthworms before flood	SSEf	kg	*A. chlorotica*	SSEf = SEf * a * DE * 10	40700	n.a.	1	[g]
	SSEf	kg	*A. caliginosa*	SSEf = SEf * a * DE * 10	361000	n.a.	1	[g]
	SSEf	kg	*L. rubellus*	SSEf = SEf * a * DE * 10	119000	n.a.	1	[g]
	SSEf	kg	*L. terrestris*	SSEf = SEf * a * DE * 10	645000	n.a.	1	[g]
- cast production by earthworms		increases linear after 40 days (data from 10, 20, 40 and 80 days available)					4	[g,i]
- annual cast production by earthworms	SEa	gDWs/gFWe	*A. chlorotica*	SEa = 0.0082 * ((y * 7) − 40) + 3.5	5.84	n.a.	1	[g]
	SEa	gDWs/gFWe	*A. caliginosa*	SEa = 0.028 * ((y * 7) − 40) + 5.97	13.95	n.a.	1	[g]
	SEa	gDWs/gFWe	*L. rubellus*	SEa = 0.101 * ((y * 7) − 40) + 6.95	35.74	n.a.	1	[g]
	SEa	gDWs/gFWe	*L. terrestris*	SEa = 0.026 * ((y * 7) − 40) + 3.98	11.39	n.a.	1	[g]

(*Continued on next page*)

TABLE I
(*Continued*)

Variable	Symbol	Units	Subdivision	Method	Average	Variation	n	Data from
- annully surfaced	SSEa	kg	*A. chlorotica*	SSEa = SEa * a * DE * 10	169000	n.a.	1	[g]
cast by	SSEa	kg	*A. caliginosa*	SSEa = SEa * a * DE * 10	1750000	n.a.	1	[g]
earthworms								
	SSEa	kg	*L. rubellus*	SSEa = SEa * a * DE * 10	1950000	n.a.	1	[g]
	SSEa	kg	*L. terrestris*	SSEa = SEa * a * DE * 10	3660000	n.a.	1	[g]
- metal in worm			*A. chlorotica*	$[Me]_{wc} = [Me]_{0-10}$ [b]		n.a.	6	[g]
cast related to 10			*A. caliginosa*	$[Me]_{wc} = [Me]_{0-10}$ [b]		n.a.	6	[g]
cm topsoil			*L. rubellus*	$[Me]_{wc} = ([Me_{en}]_{0-5} * [Me_{0-10}])/[Me_{en}]_{0-10}$ [b]		n.a.	6	[g]
			L. terrestris	$[Me]_{wc} = ([Me_{en}]_{0-35} * [Me_{0-10}])/[Me_{en}]_{0-10}$ [b]		n.a.	6	[g]
- metal at surface by	MeSEf	kg	*A. chlorotica*	$MeSEf = SSEf * [Me]_{0-10}$		n.a.	1	[g]
earthworms before	MeSEf	kg	*A. caliginosa*	$MeSEf = SSEf * [Me]_{0-10}$		n.a.	1	[g]
flood	MeSEf	kg	*L. rubellus*	$MeSEf = SSEf * (([Me_{en}]_{0-5} * [Me_{0-10}])/[Me_{en}]_{0-10})$		n.a.	1	[g]
	MeSEf	kg	*L. terrestris*	$MeSEf = SSEf * (([Me_{en}]_{0-35} * [Me_{0-10}])/[Me_{en}]_{0-10})$		n.a.	1	[g]
- annually surfaced	MeSEa	kg	*A. chlorotica*	$MeSEa = SSEa * [Me]_{0-10}$		n.a.	1	[g]
metal by								
earthworms	MeSEa	kg	*A. caliginosa*	$MeSEa = SSEa * [Me]_{0-10}$		n.a.	1	[g]
	MeSEa	kg	*L. rubellus*	$MeSEa = SSEa * (([Me_{en}]_{0-5} * [Me_{0-10}]) / [Me_{en}]_{0-10})$		n.a.	1	[g]
	MeSEa	kg	*L. terrestris*	$MeSEa = SSEa * (([Me_{en}]_{0-35} * [Me_{0-10}])/[Me_{en}]_{0-10})$		n.a.	1	[g]

$_{0-10}$ = 10 cm topsoil; $_{0-5}$ = 0–5 cm topsoil; $_{0-35}$ = 0–35 cm topsoil; $_{en}$ = enclosure; w = time after flood in weeks; $_{Dec01}$ = December 2001; $_{Oct02}$ = October 2002; $_{vh}$ = volehill; $_{mh}$ = molehill; $_{wc}$ = earthworm cast; Me = metal; distr. = distribution; [Me] = metal concentration; [a] = field measurement; [b] = enclosure; [c] = field experiment; [d] = laboratory experiment; [e] = standard deviation; [f] = R^2; [g] = this study; [h] = Wijnhoven *et al*.. (2006b); [i] = Zorn *et al*. (2004); [j] = Zorn *et al*. (2005). 0–35 cm topsoil; $_{en}$ = enclosure; w = time after flood in weeks; $_{Dec01}$ = December 2001; $_{Oct02}$ = October 2002; $_{vh}$ = volehill; $_{mh}$ = molehill; $_{wc}$ = earthworm cast; Me = metal; distr. = distribution; [Me] = metal concentration; [a] = field measurement; [b] = enclosure; [c] = field experiment; [d] = laboratory experiment; [e] = standard deviation; [f] = R^2; [g] = this study; [h] = Wijnhoven *et al*. (2006b); [i] = Zorn *et al*. (2004); [j] = Zorn *et al*. (2005).

recolonisation by moles by their molehill distribution within the same area, during the first four months after a flood in January 2003 (six counts at regular intervals). A count was also undertaken in large areas of the ADW in January 2002 (16.0% of the total research area) and in June 2002 (13.2% of the total research area), which were periods before and after a flooding event respectively.

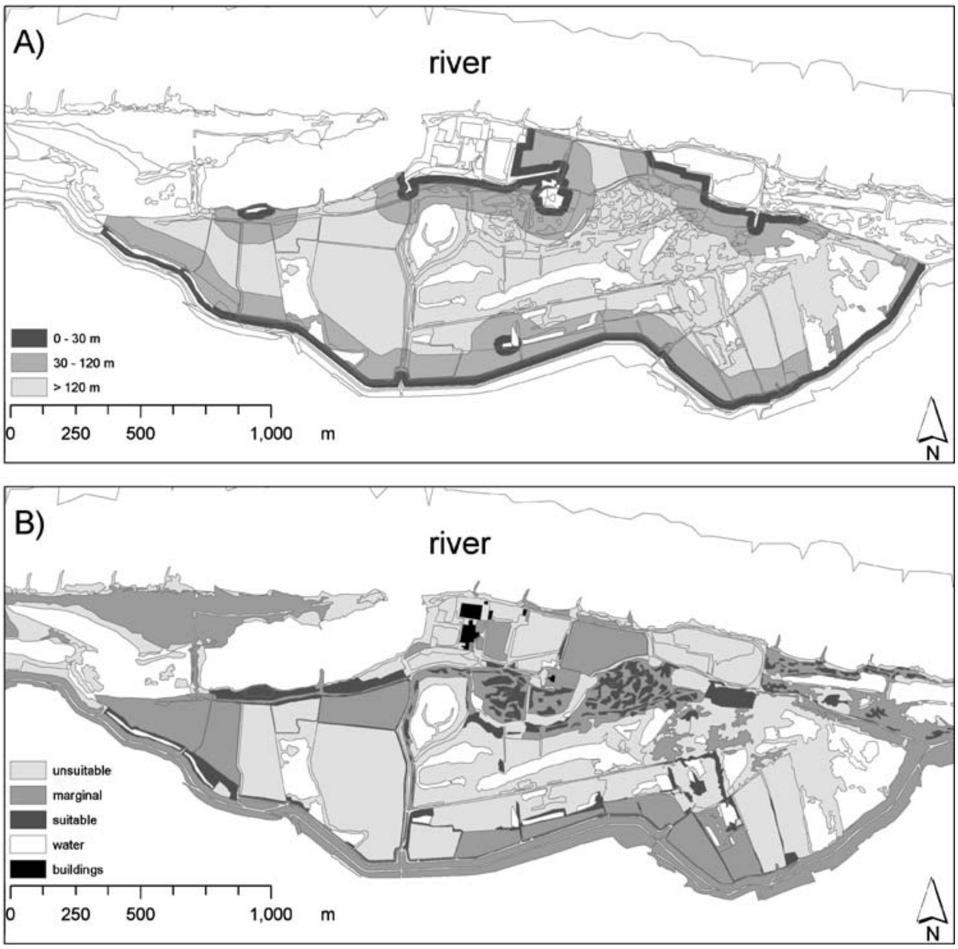

Figure 2. Maps of the 'Afferdensche en Deestsche Waarden' floodplain, showing the research area, which is the embanked part. (a) Classification of the research area into zones at distances of 0–30, 30–120 m and more than 120 m from non-flooded areas. (b) Suitability of the research area for *M. arvalis*, showing the classification into suitable, marginal and unsuitable ecotopes. (c) The distribution of 5080 molehills over an area of 564 000 m^2 in November 2003, just before a flooding event, and the locations where the composition and metal concentrations in the molehills and in the 0–10 cm top soil layer were measured. (d) Zinc deposition during the floods of 2002 visualised in a 25 × 25 m grid, ranging from 192 to 1670 mg/m^2, as calculated from the results of sediment traps.

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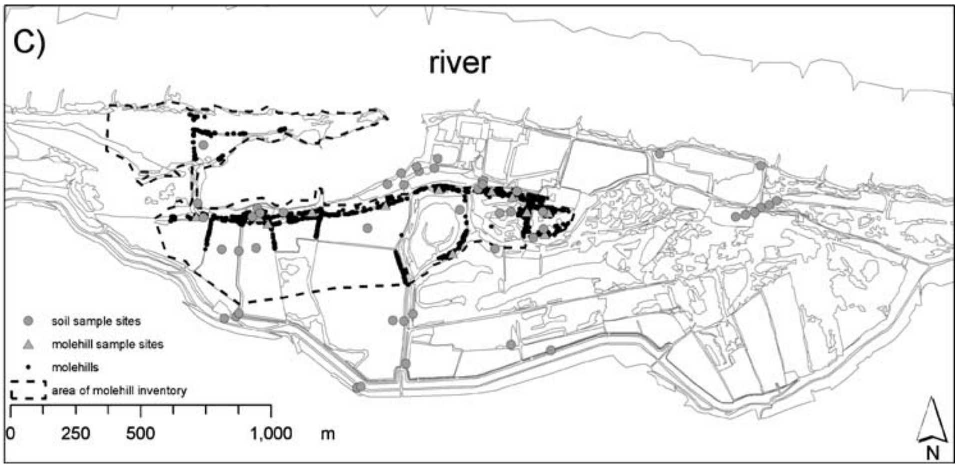

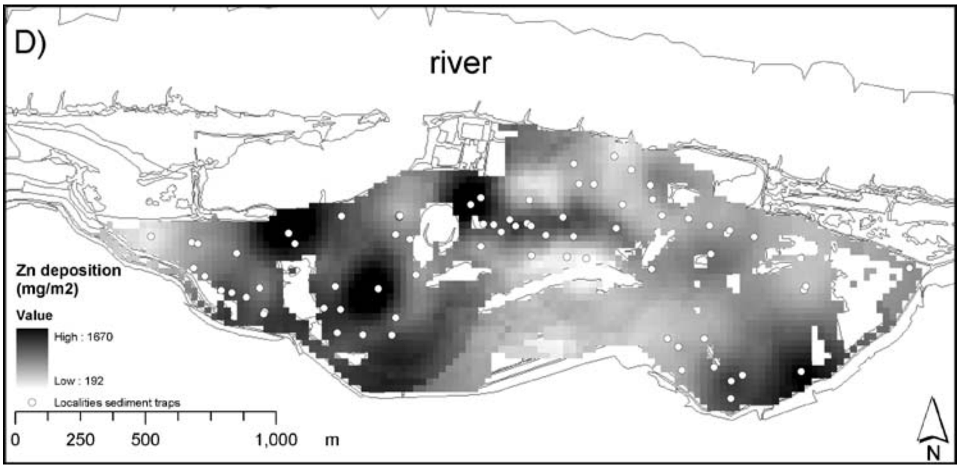

Figure 2. (*Continued*)

2.3. Estimating surfaced substrate

An important factor for the estimation of surfaced substrate during a certain period (e.g. during the period between two floods) is the turnover rate of mole- and volehills. Dependent of the size, new hillocks gradually erode by weathering or trampling, and substrate becomes distributed by which the hillocks disappear. Existing molehills can also increase as new substrate is added from below periodically. Therefore also for the estimation of surfaced substrate different methods were used for voles and moles (Table I). Field enclosure experiments at known vole densities were executed, to measure the amount of substrate surfaced and to establish the volehill turnover at known vole densities. Larger areas are necessary to monitor moles, so measurements for this species were done in the open field, which is less a problem as populations are expected to be more stable than for voles due to larger territories and less fluctuating densities under stable conditions.

For the vole studies two field enclosures ($5 \times 5 \times 1.5$ m with soil surface at 0.75 m) were built in 2003. One was situated in a sandy soil area and one in a clayey area. After the grassland vegetation had recovered from treading during the construction of the enclosures, 5 individuals of *M. arvalis* were introduced into each enclosure on August 6th. The animals were kept there for three months. Each month, we checked the presence of the animals and recorded their burrowing activities (volehills and holes). After three months all volehills were weighed with a field balance, taking all the substrate present above the soil surface. Subsequently, homogenised sub-samples were taken to measure moisture content and to calculate dry weight (DW), which allowed calculating the amount of substrate surfaced per vole in kilograms dry weight per individual (kgDW/ind; Table I).

To estimate the amount of soil surfaced by moles we selected 12 locations within the floodplain with a high density of molehills, on various soil types and with a different vegetation cover (Figure 2c). At these locations ten molehills were weighed with a field balance, taking all the substrate above the soil surface. At each location, we took samples from three molehills, homogenised these, and determined the dry weight in the laboratory. An average molehill weight for the floodplain was calculated (Table I). The turnover time for molehills was calculated by measuring the decrease in molehill height of 132 hillocks (existing and newly built) at regular intervals of 11 days over a period of 66 days, within an area (150 m^2) where moles were active. Sometimes an increase in molehill height was observed. When the hillock had increased in size, we regarded this measurement as a new starting point to calculate the trend of decrease.

2.4. Estimating surfaced metals

Of the weighed and homogenized hillocks (volehills from enclosures and molehills from the selected locations), metal (Zn, Cu, Pb, and Cd) concentrations were determined. In the enclosures, three soil cores were taken within an area of 900 cm^2, after the animals had been removed after their stay for three months. Corresponding core segments with similar depths for 0–5 cm, 5–10 cm, 10–15 cm, 15–25 cm and 25–35 cm layers were mixed. In each enclosure, we took six of these aggregated samples per core segment for measuring moisture content and metal concentrations. For each of the four metals, a regression coefficient was calculated between the concentration in the top 10 cm soil and the concentration in the volehills. Assuming that the average depth to which voles burrow is relatively constant, we can calculate the amount of surfaced metals by using the regression equations, as we estimated the metal load of the top 10 cm of the research area (Table I). Therefore we took three soil samples at 34 periodically flooded locations of the top 10 cm of soil in order to determine the moisture content and metal contents (Figure 2c). In this sampling we included the vole monitoring sites and the selected molehill locations. Mean contaminant levels (Zn, Cu, Pb and Cd) within the top 10 cm for the different zones were calculated. The correlation between the metal concentrations in the top 10 cm of soil, and the metal concentrations in the molehills was calculated. This allowed us to estimate the total amount of substrate and metal loads per zone surfaced by moles, based on molehill densities (Table I).

The dry weight (DW) and moisture content was determined by drying 5 g of wet soil (FW) from depth segments, topsoils and vole- or molehills, for 24 h at 105 °C. Metal concentrations (Zn, Cu, Pb and Cd) were measured after microwave destruction (using a Milestone 1200 microwave oven) of 0.2 mg DW substrate in a mixture of 3.0 ml 65% HNO_3 and 1.5 ml 37% HCl. The samples were diluted with demineralised water to 50 ml, and used to measure metal concentrations by Inductively Coupled Plasma-Atomic Emission Spectrometry (ICP-AES).

2.5. Estimating bioturbation by earthworms

Zorn *et al.* (2005) monitored earthworm densities for three years in ADW in natural grassland with a clayey substrate. Multiple samples were taken and used to establish species composition, number of individuals and biomass. Four species were commonly found: *Allolobophora chlorotica*, *Aporrectodea caliginosa*, *Lumbricus rubellus* and *Lumbricus terrestris*. Zorn *et al.* (2004), measured the cast production of these species in experimental columns with a similar type of substrate for 80 days. The amount of substrate redistributed by various earthworm species was calculated using mean densities and weights recorded by Zorn *et al.* (2005) throughout the monitoring period, as densities and weights were not only negatively influenced by flooding events, but also by drought. To calculate the amount redistributed during a flood, a 10-day cast production (available from Zorn *et al.*, 2004) was assumed to be representative, as during winter, the period in which generally floods occur, marked casts could still be recognised after a week, but no longer after two weeks. The annual production (in 45 weeks, which was the time between two floods in 2001/2002) could be calculated by extrapolating the cast production for 40 and 80 days (Table I). We assumed that the metal distribution over the depth samples within the whole research area was similar to those measured in the enclosure on clay. From the average metal concentration at 0–10 cm depth in the three zones, the average metal concentration in earthworm surfaced cast could be calculated taking the species specific total cast production and the depth distribution of metals into account. Therefore we assume that the casts evenly originate from each horizontal layer between the soil surface and the maximum activity depth.

2.6. Estimating total deposition

Sediment and heavy metal deposition during floods (comprising redistributed floodplain sediment and influx of river sediment) were measured during the partial and complete inundations of the ADW in February and March 2002. Embankments largely prevent sediment transfer out of the floodplain and turn the floodplain into a settling tank where sediment settles easily. We therefore assumed that substrate surfaced by bioturbation is redistributed within the floodplain itself during floods and is not transported out of the floodplain. This is supported by observations during inundations of the ADW floodplain, showing rapid settlement of suspended sediments within the floodplain (Thonon and Van der Perk, 2003; Thonon *et al.*, 2005). For this purpose, we placed 72 sediment traps in a stratified random pattern before the February flooding. Forty-three of those traps fell dry in between the two floods and were replaced by new ones before the March flooding. The sediment traps measured 50 by 50 cm and consisted of artificial grass tufts 2 cm in height, and were also used by Lambert and Walling (1987) and Middelkoop and Asselman (1998). Dry weights and heavy metal loads of trapped sediment were measured as described in paragraph 2.5. We interpolated the dry weights and heavy metal loads by kriging with Gstat (Pebesma and Wesseling, 1998) with 25 by 25 m grid cells. Multiplying the metal (Zn, Cu, Pb and Cd) load (in mg/m^2) by the floodplain area yielded the total annual metal load deposited during flooding (Table I). All calculations for this study are executed in Microsoft Excel 2000, except for calculations of areas and densities of molehills, which are executed in ArcMap 8.0.

3. Results

3.1. Surfacing by moles and voles

The average density of *M. arvalis* for the period just before a flooding event was found to be almost twice as high in the 0–30 m zone as in the 30–120 m zone (Table I), and almost six times higher than in the >120 m zone. The average density development for the whole period after the river water had receded can be described by second order polygons (Table I). The variance explained by the model was more than 61% for the 0–30 m zone, but densities in the two other zones were generally lower, and the variation between the years and monitoring dates appeared to be irregular. Molehill densities just before a flood in 2003 were also differing a lot, with approximately seven times more hillocks in the 0–30 m zone than in the 30–120 m zone, and 44 times more hillocks than in the >120 m zone (Table I). The regression models for the zone-dependent density development throughout the year showed high R^2 values.

The surfaced amount of substrate per individual vole in the enclosure experiments was 6111 gDW/ind. This leads to a total of 2393 kgDW surfaced substrate by voles for the research area, of which 46% originates from the 30–120 m zone (Table I). Weekly surfaced substrate by voles was measured to calculate the amount of substrate surfaced annually. The weekly increase in the number of vole hills was found to increase linearly with 6.5%, after the initial 5 weeks with high burrowing activity.

TABLE II

Relative contaminant distribution over the depth segments in percentages of the total content of the 0 and 35 cm soil layer, as measured from soil cores taken in an enclosure in a clayey area

Depth segment	%Zn	%Cu	%Pb	%Cd
0–5 cm	12.8	15.0	11.8	14.4
5–10 cm	17.8	20.5	16.0	20.8
10–15 cm	21.6	22.4	20.4	25.3
15–25 cm*	33.7	29.3	34.7	29.5
25–35 cm*	14.1	12.7	17.1	10.0

*The volume of these depth segments is double the volume of the others.

Each week 3.1% of the hills could not be found back anymore. It can be concluded that the weekly surfaced amount of substrate was 9.6% of the final 6111 gram surfaced per individual. This means that after 5 weeks, 3130.5 grams substrate (DW) was present at the surface, which weekly increased with 343.8 grams. The weekly amount of substrate surfaced will then be 365.5 gDW/ind/week (Table I). This figure we multiplied with the estimated densities of voles for each week after the recede of the water. The time between two successive floods was 45 weeks (Table I). Taking density development and area into account, this yielded the annual amount of substrate surfaced per zone. The annual amount of substrate surfaced in each of the zones lies in the same range (between 1100 and 1400 kgDW per zone; Table I).

The average weight (gDW $\pm$ sd) of molehills was 948 $\pm$ 630 g (n = 120; Table I). Sixty-six percent of the approximately 31700 kgDW surfaced substrate by moles that is present just before a flood is originating from the 0–30 m zone. The turnover time for molehills was estimated for 73 molehills, which were already present at the start of the measurements, and another 59, which were newly built during the observation period. The average decrease in molehill height was 0.43 cm per week, whereas the average height was 6.7 cm. This means that after 16 weeks, the average molehill was totally refreshed, and could be regarded as a new hill. Each week, 6.4% of the substrate surfaced by moles was redistributed to the near vicinity due to erosion. The cumulative molehill densities per zone and the mean weight of a molehill (948 g), gives the annual surfaced amount of substrate of 701700 kgDW in the whole area of which 53% originates from the 0–30 m zone (Table I).

The amounts of surfaced metals can be calculated from the average metal concentrations in the research zones. A large variability in average metal concentrations was found within the zones, consequently no significant differences between the zones could be established. However, for all metals a similar trend was observed with the lowest concentrations in the 0–30 m zone, and the highest in the 30–120 m zone. Average metal concentration in the first mentioned zone is almost half the concentration in the 30–120 m zone, and combined with uncertainties in other values such as estimated densities it seems to be justified to use these average values and not to calculate average concentrations for the whole floodplain. Metal concentrations of the volehills related to those of the 10 cm topsoil (Table I) were used to calculate the amount of metals surfaced. We assumed that substrate in hillocks is originating in similar amounts from the depth layers between the surface and the maximum depth of burrowing activity. The regression was therefore forced through zero, as no contaminants in the topsoil will than result in no contaminants in the volehills. We checked if the soil cores taken were representative for the column of which the hillocks originated by investigating the heterogeneity of contaminant distributions in the enclosures. On a small scale, a few square meters, the variation in the distribution of contaminants in the floodplain soil was found to be low, justifying regression analyses between concentrations in soil samples and substrate from the volehills. Strong correlations with the upper 10 cm of substrate were found for the amounts of heavy metals within the volehills (Table I). The amounts of heavy metals available at the surface just before a flood were approximately 1.11 kg Zn, 0.15 kg Cu, 0.37 kg Pb and 0.0052 kg Cd for the total floodplain (Figure 3). The total metal loads surfaced on an annual basis were approximately 1.70 kg Zn, 0.24 kg Cu, 0.57 kg Pb and 0.0080 kg Cd (Figure 4).

The heavy metal concentrations within the molehills could also be related to the concentrations in the top 10 cm of substrate (Table I). The regression coefficients were lower than for the case of the volehills, explaining 39 to 47% of the observed variance. Just before the flood, 7.33 kg Zn, 1.02 kg Cu, 2.11 kg Pb and 0.035 kg Cd is available at the surface of the floodplain (Figure 3). On an annual basis this amounts approximately 165 kg Zn, 23.0 kg Cu, 47.7 kg Pb and 0.80 kg Cd, which is much more than surfaced by the common vole (Figure 4).

3.2. Surfacing by earthworms

Table I shows that the four earthworm species cast approximately 7523 tons of substrate at the surface, of which approximately 1166 tons will be redistributed during a flood. Measurements of metal concentrations within the depth profile on clay showed that the metal contamination is not evenly distributed. The highest concentrations are found in the 10–15 cm depth layer, while the 5 cm top soil is less contaminated than the deeper layers for all metals b (Table II). All earthworm species together cast approximately 3241 kg Zn, 425 kg Cu, 1046 kg Pb and 15.4 kg Cd on an annual basis in the research area (Figure 4) with 514 kg Zn, 66.7 kg Cu, 166 kg Pb and 2.42 kg Cd present in casts at the surface just before a flood (Figure 3).

3.3. Deposition of locally redistributed floodplain- and river sediment

Extrapolation of the sediment trap results (for example Figure 2d for the results of Zn deposition) showed that in 2002, about 4140 tons of sediment were deposited during floods in the embanked part of the ADW floodplain, containing about 1300 kg

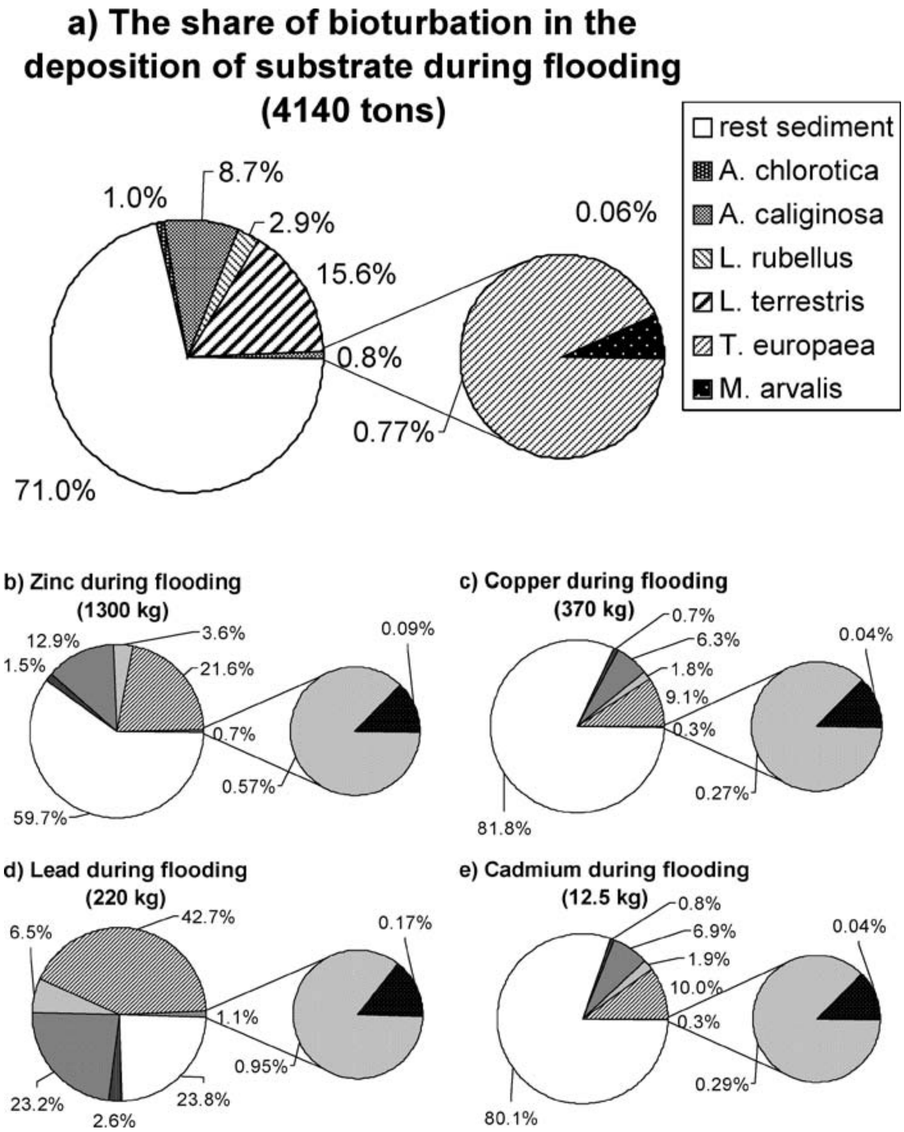

Figure 3. Share of bioturbation by small mammals (*Talpa europaea* and *Microtus arvalis*) and earthworms (*Allolobophora chlorotica*, *Aporectodea caliginosa*, *Lumbricus rubellus* and *Lumbricus terrestris*) in the deposition of (a) substrate, (b) zinc, (c) copper, (d) lead and (e) cadmium, during flooding of the embanked part of the 'Afferdensche en Deestsche Waarden' floodplain.

Zn, 370 kg Cu, 220 kg Pb, and 12.5 kg Cd (Figures 3 and 4). The deposition of sediment and heavy metals during floods was about 100 times larger than the amounts available for redistribution just before the flood due to bioturbation by small mammals (Figure 3). The proportion of heavy metals made available by *T. europaea* was about 5.5 to 7.5 times larger than the amount made available by *M. arvalis*, while

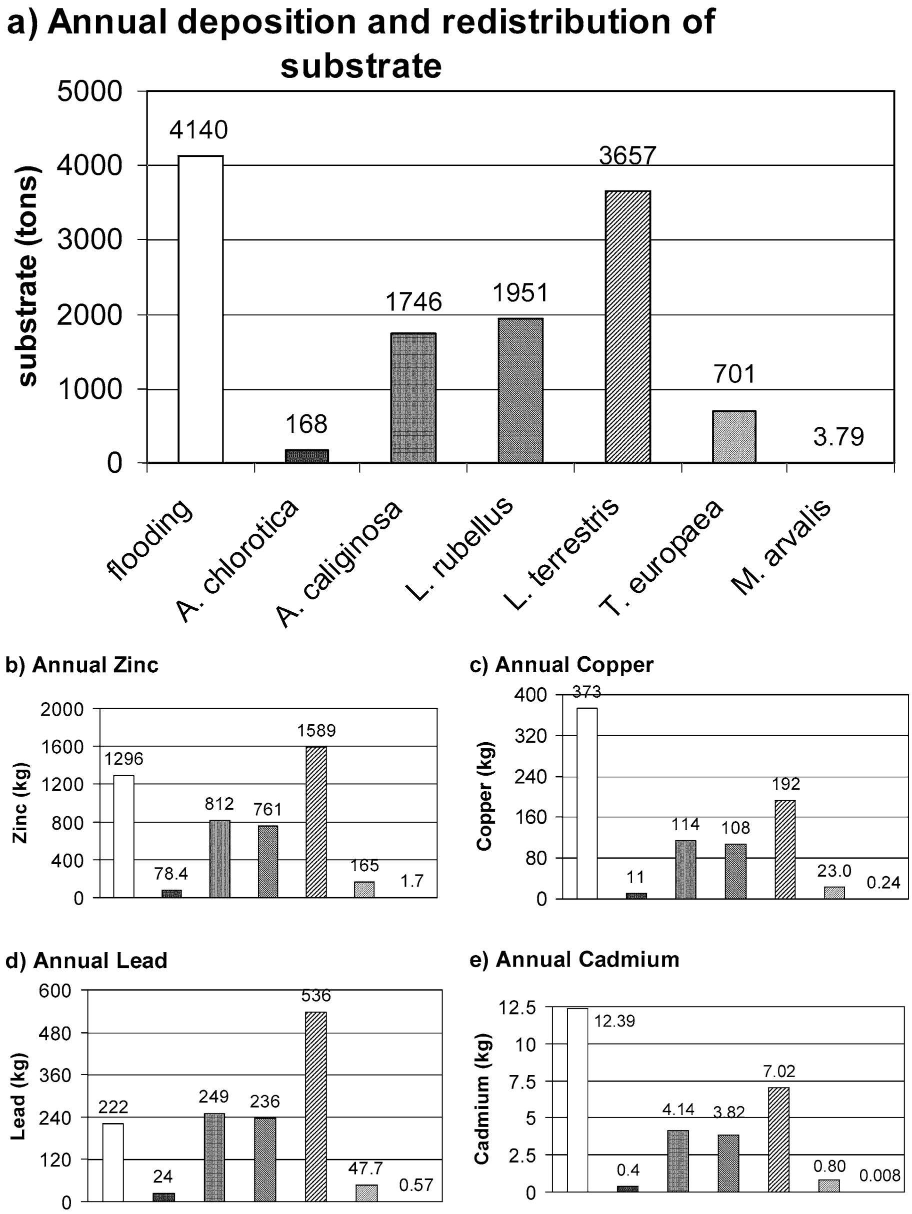

Figure 4. Annual redistribution of (a) substrate, (b) zinc, (c) copper, (d) lead, and (e) cadmium due to bioturbation by small mammals (*Talpa europaea* and *Microtus arvalis*) and earthworms (*Allolobophora chlorotica*, *Aporectodea caliginosa*, *Lumbricus rubellus* and *Lumbricus terrestris*) compared to the annual deposition during floods, calculated for the embanked part of the 'Afferdensche en Deestsche Waarden' floodplain.

the substrate surfaced by *T. europaea* was 13 times more (Figure 3). Earthworm activity, especially bioturbation by *A. caliginosa* and *L. terrestris*, accounted for a substantial part of the sediment and heavy metals deposited in the floodplain during floods. Most striking are the results for Pb, as about three quarters of the amounts deposited probably resulted from the redistribution of soil surfaced by bioturbators (Figure 3).

Over 2002, the amounts of substrate surfaced by *L. terrestris* approached the amounts deposited during floods (Figure 4). Taking the six bioturbator species studied (four earthworms and two small mammal species) into account, the amounts of substrate surfaced were more than twice the total deposition during floods during that year. The share of *T. europaea* in the total amount of substrate surfaced by bioturbators seemed to be larger (8.5%) than just before the floods, where *T. europaea* only accounts for 2.7% of the total amount of substrate at the surface due to bioturbation. The share of moles in the total bioturbation on an annual basis was larger than that of the earthworm *A. chlorotica*, while the role of *M. arvalis* was minimal for both substrate and heavy metal redistribution (Figure 4). The earthworms *L. terrestris*, *A. caliginosa* and *L. rubellus* surfaced more lead on an annual basis than was added by floods, while the amount of zinc surfaced by these species was similar to the annual total deposition during floods.

4. Discussion

The results show that large differences are present in the amounts of substrate and metals redistributed by the investigated bioturbating species. Given the uncertainties in the calculations (by incorporating averages or up-scaling results of a selection of samples) differences of a factor 5 to 12 between the two mammal species in the share of the deposition of substrate and heavy metals during a flood may be called considerable. This is even more the case for differences of a factor 83 to 185 between the share of the two mammals in the annual deposition of substrate and heavy metals. This also accounts for observed differences between the mammals and the earthworms. The amounts of substrate and heavy metals surfaced just before a flood differ a factor 35 to 68, while on an annual basis the amounts differ a factor 10 to 22.

Our calculations show that substantial proportions of the deposition of substrate and heavy metals during floods originate from bioturbation. It is not possible to measure the exact proportion of hillocks or cast that is redistributed during a flood, as this depends on factors like flow velocity of the water, vegetation and soil type. However, it is clear that a large part of the heavy metal deposition comes from redistributed floodplain soil. In particular the earthworm species appear to be important for this redistribution. The share of *T. europaea* and *M. arvalis* in the deposition of heavy metals by redistribution of surfaced substrate during floods was less than 1%. As it seems that the worm casts and the mole- and volehills were less contaminated with these elements than the new deposits introduced from outside the floodplain the share of bioturbators in the Cu and Cd deposition is smaller than their share in substrate deposition. Pb concentrations in river sediments, however, have been declined considerably compared to the past, which means that the Pb deposition could largely be attributed to the redistribution of surfaced material.

Moles redistributed 13 times more substrate than common voles, but only 5.5 to 7.5 times more heavy metals. This is related to the depth at which the species are active in the floodplain soil, combined with the different heavy metal concentrations at different depths. We assumed a constant relation between the metal concentrations in the 10 cm topsoil and in the hillocks. For the excavated areas where the top clay layer, including most contaminants, has been removed several years ago, this results in a slight overestimation of the surfaced amounts of especially Zn, Cu and Pb by bioturbators as we found that here the top 10 cm is the most contaminated layer. However, considering the total floodplain area, the impact of this overestimation is small as the metal concentrations in the clayey unexcavated areas are much higher. Depending on the annual sediment deposition, in clayey areas, the highest Zn, Cu, Pb and Cd concentrations were found between 10 and 15 cm below the surface. The concentrations were often also increased at depths between 5 and 20 cm, sometimes the whole top layer (0–20 cm) contained high heavy metal concentrations. Pollutant levels were always much lower at depths of more than 25 cm below the surface (Table II), which is in agreement with observations at similar sites in embanked floodplains along the Waal river (Middelkoop, 2002). Species burrowing deeper than 25 cm consequently also brought large amounts of cleaner soil to the surface. Moles are known to burrow to depths of up to 1 sm (Verbeke, 1997; Witte, 1997). This is reflected by the low regression coefficients ($\pm$ 0.4) for the ratio between metal concentrations in hillocks and in the 0–10 cm top soil (Table II). Half of the substrate surfaced by moles originated from depths below 25 cm, since heavy metal concentrations were highest at depths of 10–15 cm. This means, assuming similar quantities of substrate originating from each of the upper layers, that the activities of the moles did indeed reach depths of 50 to 60 cm. However, from the high regression coefficients ($\pm$ 0.97) for the relation between metal concentrations in volehills and the 0–10 cm soil layer we concluded that the major part of the substrate surfaced by the common vole originated from the top 10 cm soil. This was confirmed when using Ca, Fe, Al, Mn and organic matter as tracers. These elements also showed strong correlations with the amounts found at depths of 0–10 cm (data not shown). It has been shown that in the floodplain soil, with pH values around 7–8 and a high clay content, the mobility of these elements and the heavy metals is low (Gäbler, 1997; Eijsackers and Doelman, 2000; Wijnhoven *et al.*, 2006a), so leaching of elements to deeper layers can be neglected.

Earthworms were found to be important bioturbators. Amounts calculated for these species are estimations based on densities measured on a few monitoring sites. These monitoring sites were representative for the remaining part of the floodplain. Also at much lower densities than recorded, their role in the redistribution of substrate and metals during floods will be considerable. Earthworms have quiescence and diapause periods, during which their burrowing activities will be reduced. Therefore extrapolation of the column experiments with earthworms will lead to some overestimation of the amounts of surfaced substrate. However, earthworms in the field will show more burrowing behaviour as their corridors are continuously destroyed by weathering, trampling and flooding, which processes were absent in the columns. Since the origin of the surfaced substrate is important for the assessment of the amounts of heavy metals redistributed, the proportional impact of *L. terrestris* in heavy metal redistribution could have been overestimated, as we assumed an activity depth of 35 cm. However, burrowing depths below 35 cm, even up to 3 m below ground level, have also been reported (Zorn *et al.*, 2004). This could reduce the estimates for metal concentrations considerably, as soils at these depths are unpolluted (Middelkoop, 2000, 2002). However, it is expected that the species will not be active at depths below the water table, which is generally shallow in the ADW floodplain. We are aware that earthworm bioturbation was calculated from cast production in laboratory experiments. Intensive burrowing activity by earthworms is expected in the field immediately after flooding, as flooding probably destroyes a large percentage of the earthworm burrows. Initially the number of burrows increase rapidly. Later the production of burrows gradually stabilizes when equilibrium between formation and redistribution is reached (Zorn *et al.*, 2004). Besides, earthworms extend or divert their burrows, newly hatched individuals create new burrows in the field, and burrows are destroyed by weathering and trampling. Under field conditions, the epigeic and endogeic earthworm species will be mainly present in the rooted zone and burrow less deep than Zorn *et al.* (2004) observed in their experimental setting. Therefore the depth of burrowing activity used for our calculations for *A. chlorotica* (0–10 cm), *A. caliginosa* (0–10 cm) and *L. rubellus* (0–5 cm) was based on field observations.

Our results show that the impact of small mammals on the redistribution of heavy metals in floodplains is much smaller than that of earthworm species. This is the result of the relatively low densities of small mammals in floodplains due to the frequent inundations, and the temporary absence of small mammals in large areas of the floodplain after the water has receded, as recolonisation is a gradual and slow process (Haeck, 1969; Wijnhoven *et al.*, 2005, 2006b). Other bioturbating small mammal species in the floodplain, like *Clethrionomys glareolus*, *Apodemus sylvaticus*, *Sorex araneus* and *Crocidura russula*, have even lower densities than *M. arvalis*, especially in the parts of the floodplains that become inundated (Wijnhoven *et al.*, 2005, 2006b). In addition, the amounts of substrate surfaced are assumed to be smaller for those species, especially for the shrews (*S. araneus* and *C. russula*) (Lange *et al.*, 1994). The bioturbating capacities of *Microtus agrestis* are assumed to be similar to those of *M. arvalis*, but the two species seldom co-exist. It is therefore to be expected that the amounts of substrate surfaced by Microtidae in floodplains are similar and independent of the species (or combination of species) present. In contrast, large quantities of earthworms survive the floods, resulting in bioturbation throughout the floodplain (Zorn *et al.*, 2005). Small mammal bioturbation activities are potentially important on a local scale; in about 6% of the research area (the 0–30 m zone) they were responsible for more than a quarter of the heavy metals redistributed during floods in the ADW (Table I). In these areas, the bioturbation activity was 2.6 to 5.3 times (voles) or 4.4 to 18.6 times (moles) higher than in the other parts, on an annual basis (Table I). The impact of other species with bioturbating capacities, like rabbits and ants, has not been investigated in this project.

Bioturbation plays a quantitatively important role in the redistribution of heavy metals in river floodplains. Part of the measured deposition by floods is related to bioturbation. In addition, 2002 was an exceptional year with two floods, whereas normally one flood per 1.3 years occurs. This means that the average annual deposition of sediment and heavy metals is generally smaller than found in 2002. When no floods occur during a particular year, the bioturbation activity of the small mammals will be considerably larger. We found that the decrease in heavy metal loads in rivers has less influence on the deposited sediment and soil profiles because of bioturbation, due to the continuous mixing of polluted and clean layers by bioturbation.

Substrate originating from the floodplain itself is largely redistributed within the floodplain itself. This is caused by the embankments, which prevent sediment transfer out of the floodplain and turn the floodplain into a settling tank, where sediment settles easily. As an essential part of several ecological rehabilitation programmes now being planned along the large European rivers, the summer dikes will be partially removed (Silva *et al.*, 2001; Nienhuis *et al.*, 2002). In addition, more frequent flooding is expected as a consequence of climate change (Kwadijk and Middelkoop, 1994). When flooding occurs more frequently and embankments are removed, the river will wash away most of the surfaced substrate and heavy metals. This will have a cleansing effect on the floodplain topsoils in the longer term, especially in combination with improved water quality. This will be a very slow process as substrate can be surfaced in one floodplain and settle in another floodplain downstream. Further, the results have implications for the estimation of floodplain aggradation using sediment trap results (e.g. Middelkoop, 2000; Thonon, 2006). As substantial parts of the sediment originate from the floodplain itself, aggradation will be substantially overestimated if not corrected for bioturbation activity. Also for dating of sediment layers by tracers as radionuclides or heavy metals, bioturbation activity should be taken into account (Tyler *et al.*, 2001; Ciszewski, 2002), because tracers from layers will be mixed, and spread over a larger soil column.

5. Conclusions

A substantial proportion of the deposition of substrate and heavy metals during floods in embanked Rhine floodplains originates from bioturbation. Especially earthworm species are found to be important in this, due to their high density in floodplains throughout the year. The four most common earthworm species together accounted for approximately 28, 40, 18, 75 and 20% of the 4140 tons substrate, 1300 kg Zn, 370 kg Cu, 220 kg Pb and 12.5 kg Cd respectively, deposited during a flood in the embanked part of the ‘Afferdensche en Deestsche Waarden’ floodplain. Moles and voles only accounted for 0.3 to 1.1% of the share in substrate and metal deposition. On an annual basis, the amounts of substrate and heavy metals surfaced by bioturbators are much larger than the amounts of sediment and metals deposited during floods at present. Although the impact of small mammals was found to be smaller than that of earthworms, the role of especially moles cannot be neglected. Bioturbation activities of moles and voles in the periodically flooded parts on an annual basis were largest in the zone close to the non-flooded areas. In this zone (6% of the total area), 2.6 to 5.3 and 4.4 to 18.6 more substrate and metals were surfaced by voles and moles respectively, than they surfaced in the remaining parts of the floodplain. Our data imply that bioturbation may strongly affect vertical distribution profiles of contaminants.

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