

Deformation of a modern alluvial plain

A.J. (Tom) van Loon*

Faculty of Earth Sciences, University of Silesia, Bedzinska 60, 41-200 Sosnowiec, Poland

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Abstract

The alluvial plain of the Waal River (The Netherlands), over 4000 m², showed large flow-lobe like structures after it had fallen dry following floodings. The upstream-directed parabola-shaped folds had mutual distances from <1 m to about 10 m and amplitudes of up to a few decimeters. The deformation is ascribed to a rare coincidence of hydrological, topographic, and weather conditions. Local high-energy currents developed opposite to the main river current direction, dragging the top layer along over several meters. A drilled section indicates that no true detachment plane but rather a detachment zone is present. Similar structures formed under comparable conditions have not been described previously in the literature.

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1. Introduction

Relatively high temperatures in the Alpine region in January and February 1995 led to early snow melting. In combination with heavy rainfall in the German/French border region, this resulted in an exceptionally high discharge of the Rhine River, and thus to a high water level in its lower course. A result was flooding of large parts of the alluvial plains in The Netherlands (Fig. 1). Such floodings are not exceptional in the country, but the water level rose extremely high in February 1995. Dikes became endangered, which forced the evacuation of over 200,000 people from the threatened Dutch areas behind the river dikes.

The largest branch of the Rhine River, named “Waal”, runs roughly E–W from Nijmegen to Gor-

inchem (Fig. 2). It follows a slightly meandering course through a fairly level, low-lying (thus commonly wet) alluvial plain (cf. Hickin, 2003) that is covered almost exclusively by grasslands used mainly for cattle. The study area is in one of these grasslands, between the villages of Oosterhout and Slijk-Ewijk, at the northern side of the Waal (Fig. 3).

The flooding of the alluvial plain in the study area lasted almost 2 months, and the water level was at least 3 m above the local sedimentary surface for several weeks. The weather conditions varied during this time, but some storms occurred; one heavy storm came from a westerly direction, thus blowing opposite of the Waal current direction.

The structures described here (Fig. 4) were discovered immediately after the study area had fell dry. A second, much less intense, flooding started several days later and lasted 1 week; when the area fell dry for the second time, the structures were still present without any observable modifications (Fig. 5). According to earlier observations, the structures had

* Tel.: +31 26 3390908.

E-mail addresses: tom.van.loon@wxs.nl,
tvanloon@ultra.cto.us.edu.pl.

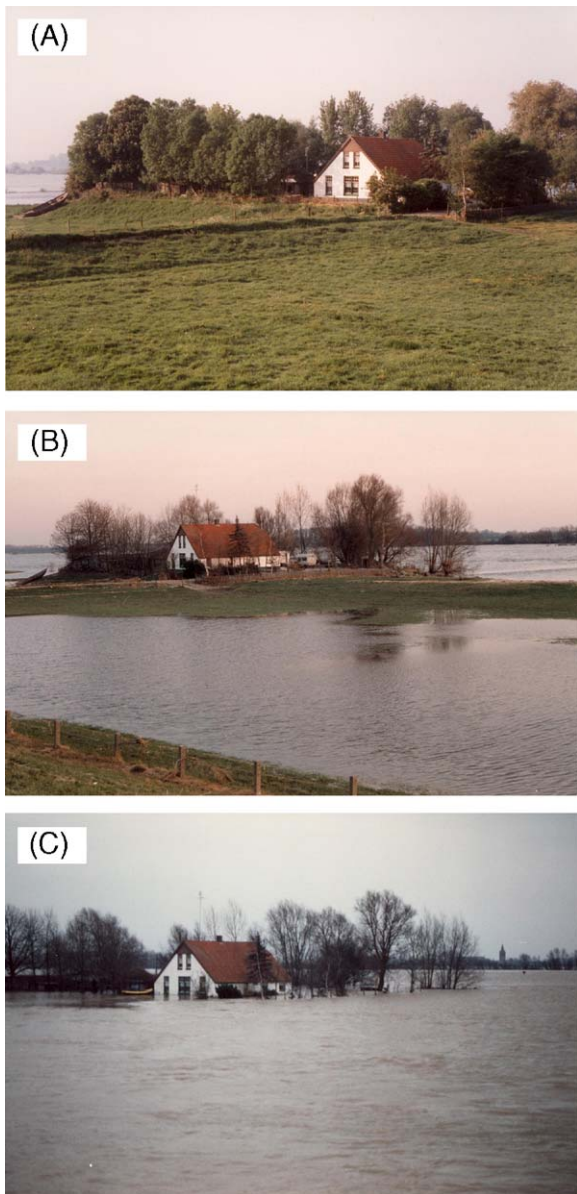


Fig. 1. A house in the alluvial plain near Slijk-Ewijk: (A) during normal summer low water; (B) during a normal flooding phase; (C) during the extreme 1995 flooding.

not been present before the first 1995 flooding; this was confirmed by the landowner. Nevertheless, finding out whether comparable structures were to be formed during later floodings was considered worthwhile; one of the reasons was that the precise wind and current conditions at the site during a subsequent phase of deformation might be registered. The area was therefore monitored for 10 more years (1995–2005), but no such structures were formed again; and the original folds were gradually levelled

out. In summer 2002, they were only still vaguely traceable. This underlines the exceptional character of the 1995 conditions and of the structures then formed.

2. Environmental conditions during the deformation

As will be detailed below, the structures described in the present study owe their genesis to a combination of factors, particularly local topography and the weather (jointly resulting in specific flow conditions). Therefore, describing the relevant data regarding these aspects in some detail first seems justified; this will be followed by a description of the local soil profile and, finally, a description of the structures studied.

The study area forms part of the alluvial plain of the Waal. The river shows considerable variations in discharge with the seasons. This results in a relatively narrow stream ($\sim 250\text{--}500\text{m}$ in the study area) during low-discharge periods, with the Waal flowing in the main channel, and bordered by either natural highs (old bars, natural levees) or artificial ones (so-called summer dikes). In high-discharge periods, the river overflows the bars, natural levee, and summer dikes, spreading out on both sides over the alluvial plain (thus resulting in a river width of some $1250\text{--}1750\text{m}$) that is bordered mainly by the so-called winter dikes, which are considerably higher than the summer dikes (Fig. 6).

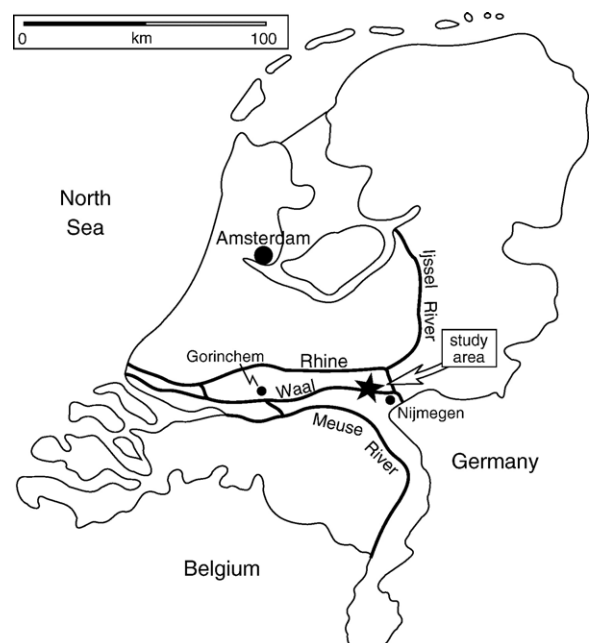


Fig. 2. Location of the study area within The Netherlands.

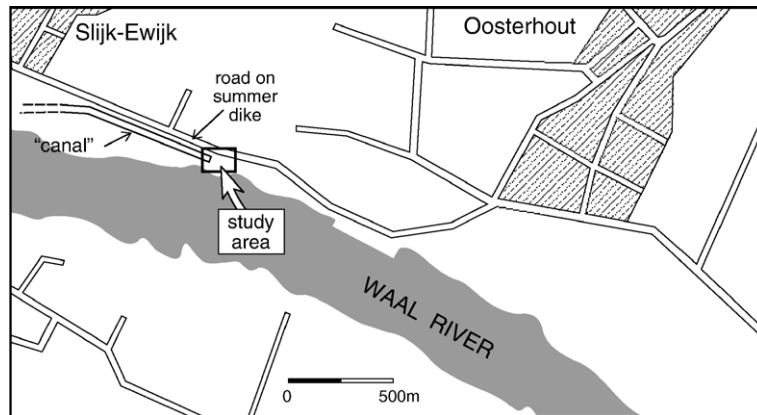


Fig. 3. Detailed map of the study site.

2.1. Local topography

The alluvial plain at the study site is somewhat irregular but, in general, relatively level. It is situated slightly (<1 m to a few meters) above the Waal River level during normal low-discharge periods (the water level can be lower during drought periods at the end of the summer when hardly any snow melt remains in the Alpine catchment area). It is a relatively wet, uniform area that only can be used for a few purposes. At the site of the study area, part of the alluvial plain was excavated in former times for loamy clay (for brick factories), so that locally a long, relatively narrow, fairly deep (up to 5 m) pit (indicated as “canal” in the following) is present, more or less parallel to the main channel of the Waal River and (at high water) connected with the river in the downcurrent direction (Fig. 3). The structures described are situated immediately east (thus upstream) of the eastern end of the canal.



Fig. 4. The parabolic-shaped crests in the alluvial plain as visible shortly after the first 1995 flooding.

2.2. Soil characteristics

Deformations of soft sediments are well known to be largely influenced by the lithological characteristics. Folds in unconsolidated sediments are formed, generally, by vertically unstable density gradients, flowage over an inclined surface, shocks, or shearing over a detachment plane. Therefore, studying the topmost meters of the alluvial plain in the study area was considered useful. A handboring was made for this purpose (May 1995) soon after the area had fallen dry after the second 1995 flooding.

The boring (Fig. 7) yielded a profile of sediments that can be grouped into four units, from bottom to top:

- (i) a lower unit (1), reaching down from 110 cm beneath the surface and consisting of light brown clays with small shell fragments and coloured spots from manganese concentrations. The groundwater table was reached at –205 cm, and boring through the dark, wet clay underneath was



Fig. 5. The deformation structures in the alluvial plain as visible after the area had fallen dry after the second 1995 flooding. The stick above the water is exactly 1 m long.

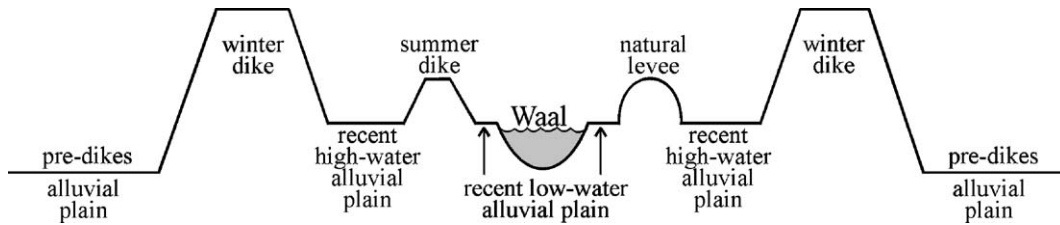


Fig. 6. Schematic cross-section through the Waal River and its alluvial plains (not to scale).

possible for only a few decimeters, in which the sediment did not change.

- (ii) The lower unit (1) passes gradually upwards into an intermediate unit (2), which reaches from -110 to -75 cm and consists of clays and clayey loams that have a sticky consistency. Small shell fragments are present and rusty spots occur.
- (iii) The intermediate unit (2) gradually passes upwards into a top unit (3) from -75 to -30 cm. This unit consists of clayey loam with shell fragments and rusty spots (this unit differs from unit (2) in that the clay is not sticky).
- (iv) Unit (3) is followed gradually by unit (4), reaching from -30 cm to the surface and consisting of a very dark brown crumbly humic loam.

Unit (1) is interpreted as representing alluvial-plain sediments, whereas unit (2) is interpreted as representing the sediments of a natural levee. This is in accordance with the local topographic expression. In 2002, after an earlier phase of high discharge, part of the natural levee at the study site was eroded, and the vertical cliffs formed showed sedimentary characteris-

tics identical to those of unit (2). Unit (3) is also considered to represent a natural levee, but from a later stage, as the sediments are distinctly less compacted/consolidated. The depositional environment of unit (4), which coincides roughly with the soil, cannot be easily reconstructed. It most likely represents the most recent stage of alluvial plain, although we cannot exclude that this unit (which no longer shows the original characteristics due to pedogenesis) has – in whole or in part – been deposited in the same way as unit (3), representing a natural levee.

2.3. Wind conditions

The precise conditions under which the deformation structures were formed are not known, as the study area was flooded during the deformation process. Considering the exceptional storm that occurred during a couple of days of the flooding (16 and 17 January, and 11 and 12 February), the structures were formed most probably during these storm days (Table 1).

2.4. River discharge

A second important parameter for the deformation process must have been the exceptionally high discharge. The river-water levels at Nijmegen and Tiel (the two most nearby measuring stations) turned out to show considerable fluctuations during January and February 1995 (Table 2).

3. Description of the deformation structures

The overall structure of the deformed area (Fig. 8), which covers $\sim 4000\text{m}^2$, closely resembles that of a plastic mass flow, constituting a number of parabola-shaped folds (Fig. 9). The structure displays the following characteristics:

- (i) the folds jointly form a flow-lobe like structure, with the end of the tongues pointing in the upstream direction;

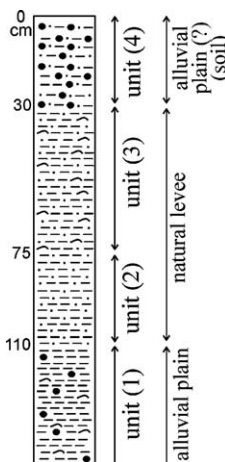


Fig. 7. Profile of the top meters in the deformed alluvial plane and interpretation of its depositional environments.

Table 1

Wind direction (WD)^a, average wind velocity (AWV)^b per hour, and maximum wind velocity (MWV)^b per hour during the four most stormy days in January and February 1995, measured at the Volkel measuring station

Hour	1995-01-16			1995-01-17			1995-02-11			1995-02-12		
	WD	AWV	MWV	WD	AWV	MWV	WD	AWV	MWV	WD	AWV	MWV
01	180	3.6	5.1	150	4.6	6.7	190	3.6	5.7	230	11.3	16.4
02	180	3.6	5.7	150	4.6	7.7	200	3.6	6.7	240	9.8	17.0
03	180	3.1	5.1	170	4.6	8.7	190	4.6	7.7	250	9.8	17.5
04	170	3.1	5.1	150	4.1	6.7	180	4.1	6.2	250	7.7	12.8
05	170	3.1	5.1	160	4.1	6.2	190	3.6	5.7	240	7.2	10.8
06	190	4.6	7.7	160	4.6	7.2	190	4.1	7.2	250	8.2	13.4
07	190	4.6	8.2	160	4.1	6.7	190	5.7	9.8	260	8.2	15.9
08	180	4.6	6.7	160	5.1	8.2	180	4.6	8.2	250	7.7	12.8
09	160	3.6	5.7	160	5.1	7.7	180	4.1	6.2	240	6.7	11.3
10	160	4.1	7.2	150	5.7	8.2	180	4.6	7.7	240	7.2	15.9
11	150	4.6	7.7	160	5.1	8.7	190	4.6	7.2	250	8.2	13.4
12	170	5.7	8.7	150	5.1	8.2	190	4.6	6.7	250	8.2	13.9
13	160	6.2	8.7	160	6.7	11.3	210	5.7	8.7	250	8.2	14.4
14	150	6.2	9.8	160	7.2	11.8	220	7.2	10.3	240	9.3	13.9
15	160	6.2	9.8	140	6.2	10.3	220	6.7	11.8	250	8.2	13.9
16	170	5.1	8.2	150	6.2	10.3	210	7.2	11.3	240	7.7	11.8
17	160	4.6	7.7	140	6.2	10.8	200	6.7	10.8	230	7.7	11.3
18	170	4.1	6.2	140	6.2	9.3	180	6.7	11.3	210	5.1	10.8
19	170	5.1	7.7	140	6.2	9.8	180	6.7	11.3	190	3.1	4.6
20	180	5.76	9.3	140	6.7	10.3	190	8.2	13.4	180	3.1	4.6
21	160	5.1	8.2	150	7.2	10.3	200	9.3	14.9	180	3.1	5.1
22	160	4.6	6.2	150	7.2	10.8	200	10.8	15.9	190	3.6	6.2
23	160	3.6	5.7	150	6.2	9.8	200	10.8	17.0	180	2.6	4.1
24	150	4.1	6.2	140	6.7	9.8	210	11.8	17.0	170	2.6	4.6

Source: Royal Netherlands Meteorological Institute.

^a In degrees (0=north; 90=east).

^b Velocity in m/s.

- (ii) the structure is more or less symmetrical, with the axis of symmetry being a continuation of the longitudinal axis of the canal;
- (iii) close to the end of the canal, the axes of the individual folds “follow” roughly the canal outline;
- (iv) at the southern side of the canal, the fold axes “follow” the corner of the canal for 5–15 m; they do not “follow” the corner at the northern side, probably because the nearby position of the winter dike is prohibitive;
- (v) the farther away from the canal end, the more obvious the parabolic shape of the successive fold axes is;
- (vi) not all folds can be traced from one side of the canal to the other side; some gradually disappear (or appear), and a few split, in the same way as the lobes of high-viscosity mudflows do;
- (vii) the farther away from the canal end, the smaller (on the average) the amplitudes of the folds; and
- (viii) the grass cover makes the outline of the folds highly irregular, but the folds give an overall

impression of being somewhat steeper at the sides dipping westward (towards the canal) and somewhat flatter at the other (eastward dipping) side that is directed upstream of the Waal River.

The exact position of the fold crests has been established by measuring the area (in May 1995) according to a network with 5×5-m cells, in which the positions of the crests were indicated.

4. Genesis of the folds

The flow-lobe pattern of the folds indicates that the top part of the displaced material must have moved as an entity (though with both horizontal and lateral velocity gradients, like in a mudflow). Such a movement is known to occur under specific conditions, viz. as a downward flow of water-rich material or as a result of dragging over a rough detachment plane (Bridge, 2003). Drag folds are also known to have formed from glaciotectionics (Rocha-Campos et al., 2000),

Table 2

Water levels^a of the Waal River at Nijmegen and Tiel (the two most nearby measuring stations east and west of the study site, respectively) during January and February 1995

Date	January		February	
	Nijmegen	Tiel	Nijmegen	Tiel
01	1014	685	1352	743
02	1028	1300	1334	735
03	1028	708	1300	706
04	1025	708	1260	670
05	1000	692	1221	633
06	948	650	1180	593
07	895	600	1135	547
08	855	559	1091	508
09	823	527	1050	471
10	804	506	1022	443
11	799	497	999	422
12	828	511	988	407
13	872	549	988	402
14	936	608	988	400
15	971	648	986	399
16	961	652	985	397
17	923	623	989	401
18	889	591	1021	413
19	861	561	1054	439
20	838	539	1084	466
21	831	524	1102	484
22	838	530	1114	497
23	852	538	1112	502
24	920	581	1089	493
25	1102	731	1063	471
26	1194	840	1042	451
27	1227	887	1042	443
28	1255	924	1064	450
29	1296	961		
30	1326	995		
31	1347	013		

Source: Directoraat-Generaal Rijkswaterstaat, Directie Oost-Nederland.

^a Height in cm above sea level.

earthquakes (Anand and Jain, 1987), and other tectonic activity (Goscombe and Passchier, 2003); but these three options can be ruled out with certainty for the structures described here.

That the deformation of the folds was related to a downslope movement can be excluded because the floodplain as a whole follows the course of the river, which shows regionally an overall gradient of ~1 m/km. The inclination of the (irregular) floodplain at the study site is even somewhat higher (~0.5–1 cm/m). Gravity-induced mass movement should therefore have taken place in an upslope direction, which can be excluded.

If the structures were formed by dragging, a detachment plane should be present, and the upstream direction of the fold pattern should be explainable by

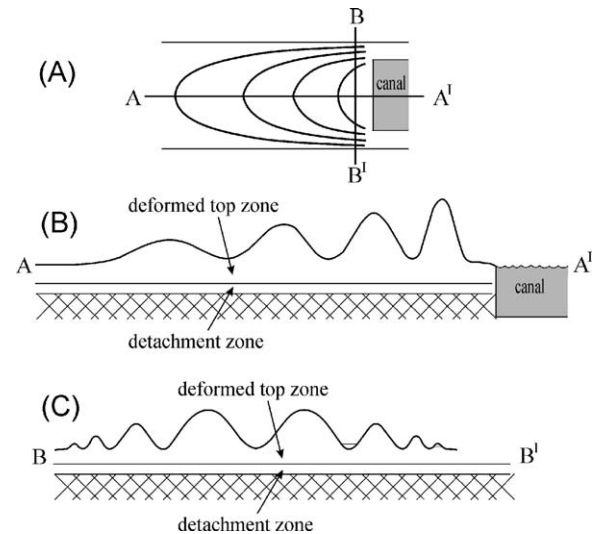


Fig. 8. Schematic characteristics of the parabolic-shaped ridges (not to scale): (A) plan view, with position of the schematic longitudinal and transverse cross-sections; (B) longitudinal cross-section; (C) transverse cross-section.

the action of a specific mechanism. A detachment plane is present, although as a detachment zone rather than as a plane. This zone is constituted by the gradual transition between units (3) and (4) in the boring described above.

Dragging is a result of relative movement of two masses with respect to each other. The drag folds are formed at the contact plane. Because the folds at the study site are at the sedimentary surface, they must have formed at the contact plane between the alluvial sediments and the overlying medium. The folds were formed while the floodplain was flooded, so that the overlying medium must have been the Waal River water.



Fig. 9. Southward view of the deformed area near the "canal" (right), showing the parabolic-shaped deformations.

This leaves the problem of how the folds can have formed in such a way that their configuration implies water movement from W to E, i.e., in a direction opposite to the main current direction of the Waal. In this context, the precise location of the folds seems to be important, because comparable structures were not formed simultaneously at other places in the Waal floodplain. Considering the local characteristics, the relationship between the “base” of the folds and the end of the canal is too close to be incidental. In fact, it seems that the folds developed with the end of the canal as a starting point.

However clear the relationship may be between the configuration of the deformations and the position of the canal’s end, the deformations were formed exclusively in 1995 so that one or more additional parameters must have played a part. February 1995 was exceptional because of the high discharge, but comparable discharges have occurred before without the development of such folds. Another uncommon situation in February 1995 was an exceptionally heavy storm from the West. Western storms are not uncommon inland within The Netherlands, but storms of this intensity are. Nevertheless, they occur on rare occasions, but they never led to folds such as those formed at the study site.

A combination of these two exceptional situations, i.e., an exceptionally high discharge and an exceptionally heavy western storm, could not be traced in the records and also did not occur after 1995. Therefore, the coincidence of these two exceptional conditions seems likely to have played a role. If so, it is still to find out which process was triggered by these circumstances that could lead to upstream-directed drag folds.

The shape of the folds implies water movement from W to E. Because the Waal flows from E to W, a powerful agent must have forced the water to move upstream locally. The exceptionally heavy western storm on 11–12 February seems the most probable agent. Because of the high river discharge, the great majority of the water must have flowed from E to W (as was well visible during the time of flooding). In the shallower parts of the flooded alluvial plain, between the summer and the winter dikes, however, the western storm was apparently strong enough to cause wind-driven “counter currents” from W to E.

The counter currents were, as a rule, apparently not strong enough to affect the grass-covered sedimentary surface, as the deformation took place only at one site. The question is, therefore, which conditions made the countercurrents strong enough to produce drag folds just at the study site. The most likely explanation is that

water was also moved by the storm in an upstream direction within the W–E trending canal. A vertical velocity gradient must have been present in the canal water, with the highest velocity in the uppermost meters. The velocity in the uppermost meters must have been comparable with that in the surrounding water mass flowing over the floodplain behind the summer dikes. Although the velocity of the water in the canal must have been slower at greater depth, the W–E-directed movement of the water implies that, per meter width of the canal, more water was moved into an upstream direction in the canal than in other sections of the alluvial plain with equal width. At the eastern end of the channel, which is characterised by an irregular wall dipping, on the average, $\sim 15^{\circ}$ – 60° towards the west, this must necessarily have induced a strongly increased water velocity just upstream of the canal’s end; this is proven by the erosional scarp that was created during the flood when the deformations were formed (Fig. 10). The increased current velocity there was apparently strong enough to cause dragging of the irregular, grass-covered surface of the floodplain.



Fig. 10. “Cliff” in the wall of the “canal” formed due to erosion by an “upstream” current from left (=west) to right (=east).

The parabolic configuration of the drag folds can thus be explained, just as their gradually diminishing amplitude in a longitudinal direction and perpendicular to the current: the “additional” water mass coming from the deeper part of the channel mixed gradually with the water of the surrounding “counter currents”. Such intermixing of moving fluids tends to take a parabolic configuration.

5. Conclusions

Monitoring of the study site – and of a section several kilometers both upstream and downstream along the Waal River – during the 1995–2005 period did not result in the observation of freshly formed, comparable fold structures. Both flooding and strong western winds occurred several times during the monitoring period, but never simultaneously with strengths as in 1995. This supports the interpretation of the deformation structures as caused by a coincidence of some exceptional conditions.

A literature search did not result in finding descriptions of comparable deformations. This also supports the hypothesis that an exceptional combination of conditions must be held responsible for the genesis of the remarkable upstream-directed fold pattern in the Waal floodplain. These include:

- (i) the exceptional topography (a fairly narrow “canal”, parallel to the main river course but behind protective summer dikes, in combination with the fairly abrupt eastern end of the canal);
- (ii) exceptional discharge conditions (a fairly rare combination of rapid snow melt and heavy rains in the upstream catchment area); and
- (iii) exceptional weather conditions (uncommonly heavy storm).

The considerable deformation of the top layer of the alluvial plain is proof of the high-energy conditions that may occur under specific conditions and should be considered as a warning for authorities that building houses in alluvial plains involves risks (cf. Meyer, 2001).

Acknowledgements

I dedicate this contribution to the memory of my late friend and colleague Jacques Schwan who helped me with the core drilling and the interpretation of the cores; he deceased shortly after the manuscript had been submitted. Tomasz Zielinski (University of Poznan) kindly prepared the drawings.

References

- Anand, A., Jain, A.K., 1987. Earthquakes and deformational structures (seismites) in Holocene sediments from the Himalayan–Andaman Arc, India. *Tectonophysics* 133, 105–120.
- Bridge, J.S., 2003. Sediment transport by unidirectional water flows. In: Middleton, G.V. (Ed.), *Encyclopedia of Sediments and Sedimentary Rocks*. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 609–619.
- Goscombe, B.D., Passchier, C.W., 2003. Asymmetric boudins as shear sense indicators—an assessment from field data. *Journal of Structural Geology* 25, 575–589.
- Hickin, E.J., 2003. Meandering channels. In: Middleton, G.V. (Ed.), *Encyclopedia of Sediments and Sedimentary Rocks*. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 430–434.
- Meyer, G.A., 2001. Recent large-magnitude floods and their impact on valley-floor environments of northeastern Yellowstone. *Geomorphology* 40, 271–290.
- Rocha-Campos, A.R., Canuto, J.R., Dos Santos, P.R., 2000. Late Paleozoic glaciotectionic structures in northern Paraná Basin, Brazil. *Sedimentary Geology* 130, 131–143.