Erosion without sediment supply? The crux of a flood-plain restoration project downstream of dammed headwaters

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Abstract During the first half of the 19th century, work started to embank the main parts of the Upper Danube River completely. Since that time, the river has flowed in levees. The second half of the 20th century was characterized by dam building for hydro-power stations. Since then, only sandy material has reached the banks of the Danube. In 2006, a pilot project named "*Remediation of riparian areas on the Danube flood plain between Neuburg and Ingolstadt*" started. About 1200 ha of forests are used for controlled artificial flooding to improve biodiversity in the riparian forest. Besides the controlled artificial flooding, a new distributary will be installed using old ox-bow structures. Meander migration, erosion and sedimentation are explicitly allowed. But what if the material from the upper part of the restoration area is completely eroded and transported downstream? This question is still to be answered. This contribution illustrates the scope and problems of this flood-plain remediation pilot project.

Key words erosion; sedimentation; flood-plain remediation; laser scanning; cross-profiles

INTRODUCTION

It is common knowledge that man contributes to landscape changes. Especially significant are the changes to our flood plains. In Germany, this started at the beginning of the 19th century. People did not want to accept the "restrictions" caused by the rivers, and began the embankment of rivers such as the Rhine and the Danube. The restrictions were the frequent flooding that made it impossible to use this land for settlements and agriculture. To begin with, man was victorious; embankment and straightening showed positive effects, and rivers and flood plains were separated as far as the hydraulic and ecological connections were concerned. During those times, people ignored the effects of the changes because other priorities existed. But times have changed and now it is necessary to correct the mistakes made in the past (Cyffka, 2006). On 21 November 2005, the Bavarian Minister for the Environment, Health, and Consumer Protection dug the first turf for the €11 million project: *Remediation of riparian areas on the Danube flood plain between Neuburg and Ingolstadt*. The project study area is shown in Fig. 1.

Today, the study area still includes 2100 ha of riparian forests—one of the largest coherent riparian forests in Europe. It is owned and managed by the Duke of Bavaria, and also suffers from the changes. The lack of water in the flood plain made forestry more lucrative. Non-riparian tree species were planted but, luckily, the forest management kept some natural areas as well. Therefore, the riparian forest between Neuburg and Ingolstadt did not completely change from a natural to a cultural landscape. The natural adjustments and the modifications of the River Danube in Germany are shown in Fig. 2.

The corrections of the Danube River are clearly visible. Today, former meanders can not be seen anymore. In the early 1970s, two hydropower stations (Bergheim in the west and Ingolstadt in the east; cf. Figs 2 and 3) were built. Up to that time, the Danube gushed through its river bed, with virtually no hydraulic contact to the flood plain and the riparian areas. No water was left for this terrestrial–aquatic biotope. The dams of the hydro-power stations did not change this situation.

The question is how to remediate the flood plains of today, as well as determining the final goal of the remediation (Dister, 1992; Hügin & Henrichfreise, 1992). Is it sensible to achieve the noble goal of restoring the former "natural" flood plain? It may be sensible, but in most cases it is not possible because of the aforementioned reasons.

The main goal of the restoration in this case is to bring more dynamics to the existing flood plain. Dynamics to the groundwater level, to the water surface and water courses, and to the

Fig. 1 Sketch map of Europe with the location of the study area (white ellipse). Source: de.wikipedia.org; graphics by David S. Liuzzo, modified.

Fig. 2 Course of the River Danube in 1823 and today.

morphological features such as sand and gravel banks and the watersides itself (Cyffka & Haas, 2007). Therefore, the hydrological processes are targeted as the most important ones. Nearly everything in a natural flood plain has a relation to hydrological processes and is connected hydraulically. If one is able to use water as an "adjusting screw", many other related features (e.g. vegetation) will adjust itself after a certain period (Cyffka, 2006).

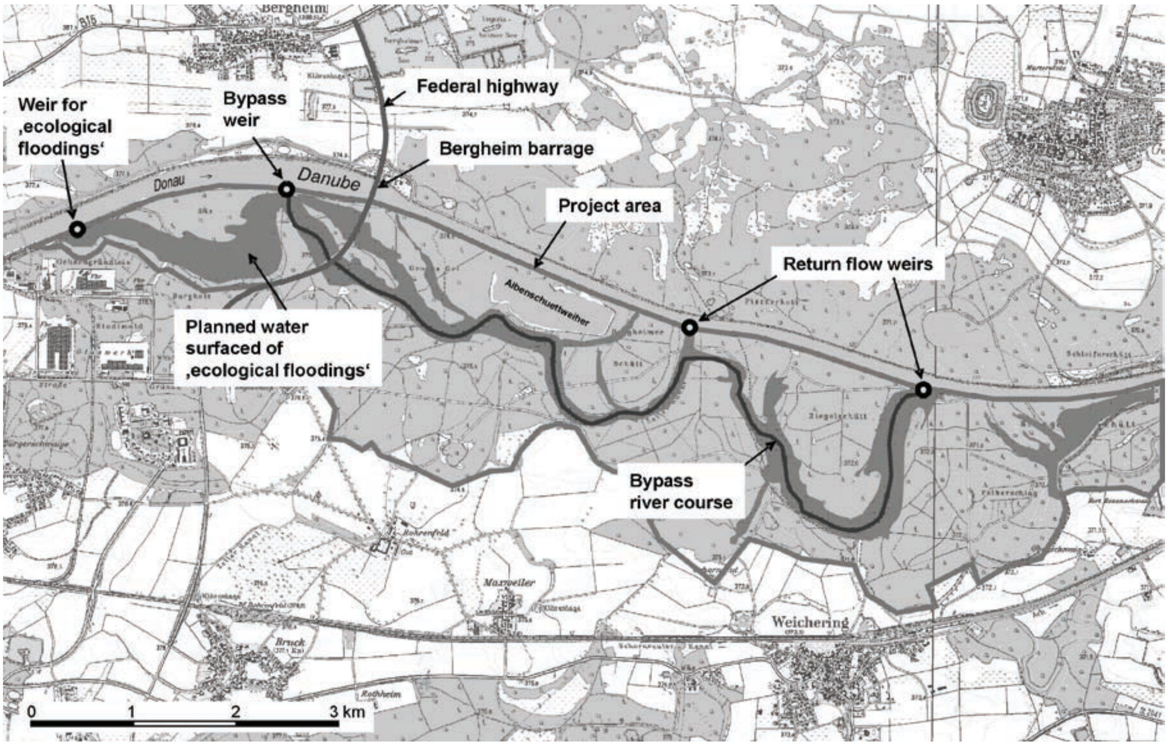

Fig. 3 Project area and location of the planned weirs, the bypass and the area of "ecological flooding".

The riparian forests in this area will experience a major change during the next several years. The plan is to install two weirs in the Danube dikes (see Fig. 3). The first will permanently discharge 0.5–5.0 m^3/s into a former riverbed of the Danube. The riverbed is not continuous or even over its complete length of 8 km, so the scientifically exciting situation is to determine the path which the water will choose. The question is: what role will erosion and accumulation play? Of course there will be some initial digging to pre-determine the main course of this new river from former ox-bow to ox-bow, but that is all. Nature will direct the details.

This is not only the re-activation of a former Danube River course; it is simultaneously a bypass of the Bergheim hydro-power station (Fig. 3).

In this part the Danube River will be open again for migrating fish. It is only a first step because there are also hydro-power stations at Bittenbrunn, Ingolstadt, etc., that are still impassable, but it is a step in the right direction. The bypass is controllable, so it is possible to imitate natural conditions, e.g. during summer at low water there will be a water emission of only 0.5 m^3/s. This will give back dynamics to the new side river, and fauna and flora will have to adapt to this. But 0.5 m^3/s is the minimum discharge, and of course, there will be no complete drain so that fish can migrate throughout the year (Cyffka, 2006).

METHODS

The project area is marked by numerous old ox-bow structures of the River Danube. These depressions are only filled with water during high floods with recurrence intervals of more than five years. Parts of these old ox-bows will be hydrologically re-activated. The new river banks are prone to lateral erosion and new undercut slopes will develop. From the beginning, a new morphological activity will start which might be self-sustaining or self-cumulative. In order to follow the developing form of this new river channel, the *status quo* was recorded by several measurements and investigations. The methods include standard grain-size analyses, cross-profile measurements, and terrestrial laser scanning.

The cross-profiles are measured with a Leica Total Station TPS 1205. The Terrestrial Laser Scanning (TLS) is done with a profile scanner (LaserAce® Survey from Measurement Devices Ltd – MDL), the detailed scan (cf. Fig. 7) has a resolution of 1 cm. The system covers this area in about 15 min. The large scan shown in Fig. 6 covers 400 m^2 in 90 min with a resolution of 10 cm. A Digital Terrain Model was calculated with the open source GIS software called SAGA (System for Automated Geoscientific Analyses) (Böhner, 2006).

The investigations are at their beginning. The authors plan to intensify the preliminary research until the phase of construction is over and the main project starts in October 2009 with the opening of the weir for the bypass river. The main objective prior to that date is to gain as much knowledge of the channel topography and sediment distribution in the channel as possible. The methods applied so far are described and discussed below.

RESULTS AND DISCUSSION

Grain size as an indicator for change

Sediment samples were taken from the bottom of the future river channel. The grain size distributions show considerable variations (Table 1). The reason for this is that the River Danube was very active in former times as far as ox-bow generation and migration is concerned. One can guess it from Fig. 4 where the hillshade illustration of the flood plain Digital Terrain Model (DTM) gives an impression of the former highly dynamic environment. Many relocated ox-bow structures can be identified, even in this small detail of the DTM (Bock *et al.*, 2006).

Table 1 Grain size distribution in selected samples along the old ox-bow. All values in percent. Source: analyses by U. Harpe, unpublished. Samplings sites shown in Fig. 4, black squares and Roman numerals.

Sampling site	Sand	Silt	Clay
1	43.78	43.28	12.94
2	17.39	73.83	8.78
3	8.65	67.54	23.81
4	13.38	65.45	21.17
5	8.71	77.20	14.08

The future river channel will cross older ox-bow structures, thereby exposing different sediments. That is why the values from Table 1 change from sampling point to sampling point along the channel. Every time when the material changes, e.g. from sand to silt or clay (mostly alluvial clay from mediaeval times), there is a new working point for erosion. Therefore, it is necessary to identify such working points, especially where they coincide with a change in direction of the channel. At these sites, erosion will be most intensive and undercut slopes will develop to a real ox-bow.

Measurement of cross-sections

In the western part of the newly-built bypass river, a total of 28 cross-profiles have been installed as places for long-term monitoring. By means of regular and event-related measurements at the cross-profiles, accurate recording of any changes of the course, of bed erosion, and of accumulation is possible. In order to carry out multi-temporal surveys, the starting points as well as the end points were precisely marked. In between these points the cross-profiles were measured in 1-m steps. Figure 4 shows the position of all cross-profiles in the channel and Fig. 5 shows three of those cross-profiles in full detail. Clearly visible are the undercut slopes in the flow direction. These undercut slopes are the target of the high-precision measurement by both cross-profiles and laser scanning.

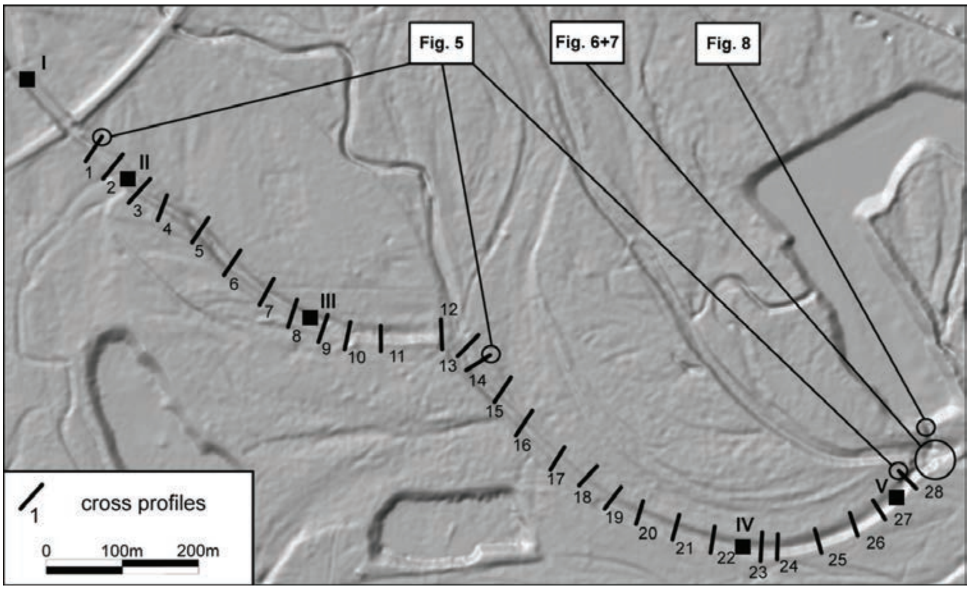

Fig. 4 Positions of cross-profiles and terrestrial laser scanning sites. Background: analytic hillshade of the DTM. Black square and Roman numerals show location of grain-size sampling sites (see text).

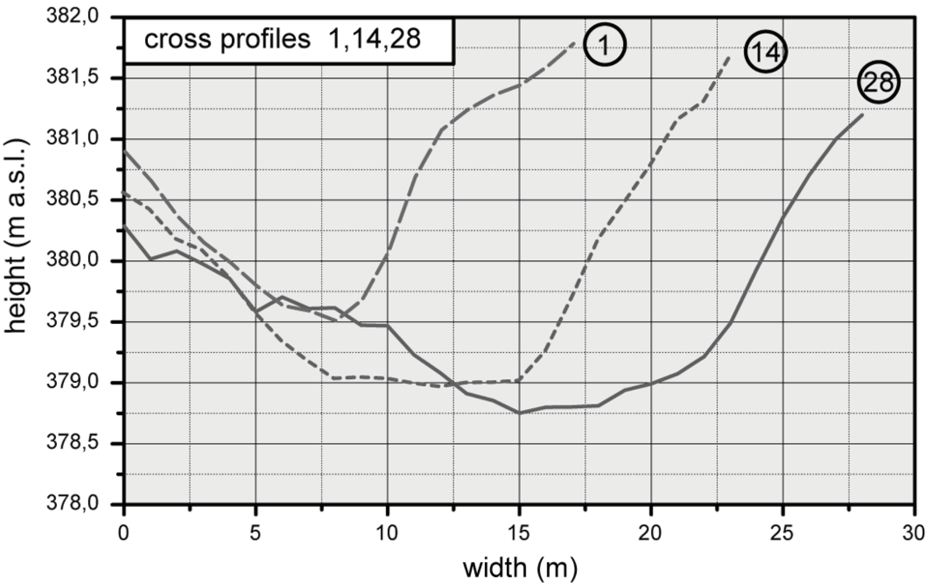

Fig. 5 Detailed cross-profiles; nos 1, 14 and 28.

Furthermore, from the cross-profiles we learn that there are several forms of the channel design. Profile 1 (see Fig. 5) is a v-shaped channel with similar side slopes. Profile 14 is more or less u-shaped also with similar side slopes, whereas profile 28 is wider and has one steep and one smooth slope. If water tackles the steep slope of profile 28 and the sediment is weak at this position (e.g. grit or coarse uncompacted sand) the slope will easily retreat backwards at normal discharge. One can imagine the erosion rate and the slope retreat at a 1-in-100 year discharge. The sediment loss will be very great and that position will possibly be the starting point of a new ox-bow.

Terrestrial laser scanning (TLS)

Figure 6(a) shows an erosion stretch of the planned bypass river, called Wetterloch. Erosion was initiated by the 1-in-100 year flood of 1999, and since then there has been major morphological

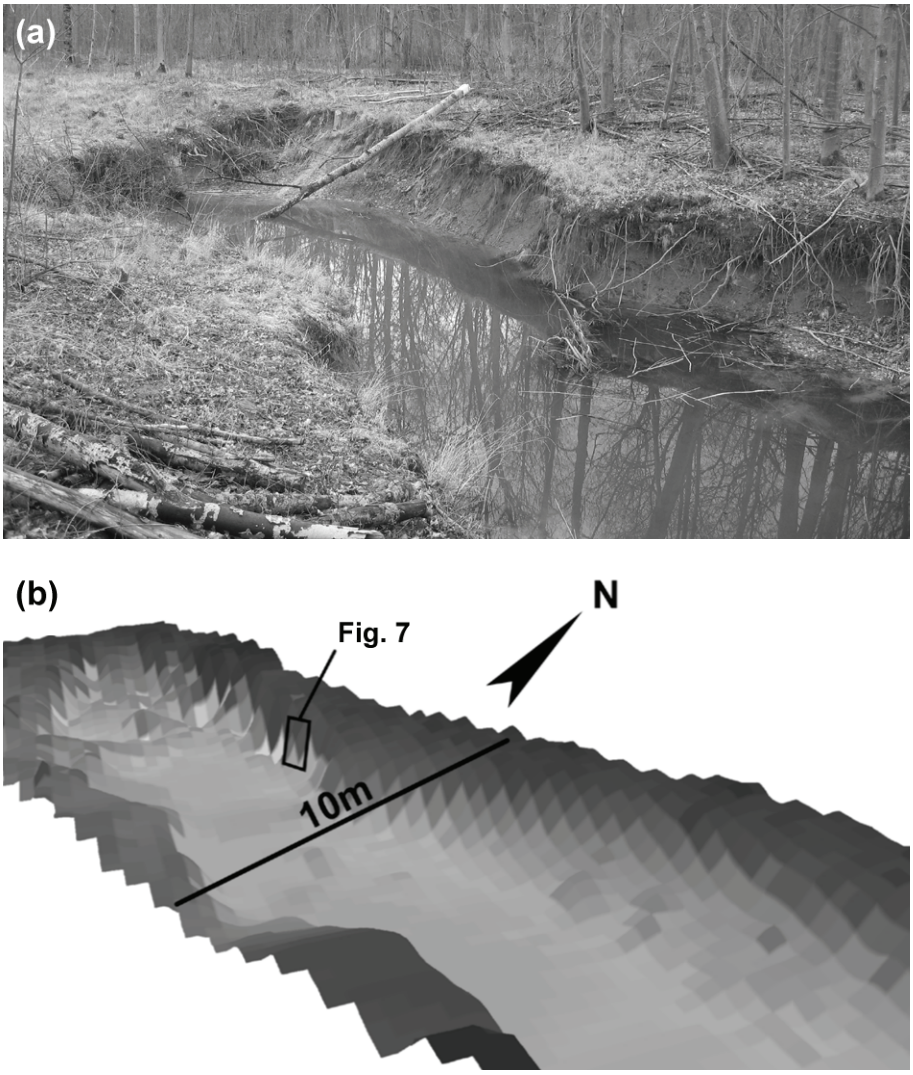

Fig. 6 (a) Photo of active channel erosion at Wetterloch (photo: F. Haas, 2007). (b) 3-D-view of the Wetterloch area, based on terrestrial laser scanning data; rectangle indicates position of detailed 3-D view in Fig. 7.

changes. In particular, retrograde erosion takes place with every new flood. These stretches are important sources for debris and must be precisely and frequently measured. Here, and at other undercut slopes, as well as at potential accumulation areas (sand and gravel banks) a terrestrial laser scanner will be used for high-precision measurements. This relatively new method allows fast and highly precise measurements, and thus eroded or accumulated material can be detected easily. Figure 6(b) shows a 3-D view of the Wetterloch erosion stretch calculated from laser scanning data. In this way larger changes in the river can be determined. In order to detect the bank erosion at undercut slopes, it is necessary in addition to do detailed measurements from those banks.

Figure 7 shows a high resolution DTM of a part of the bank of the Wetterloch. Using multi-temporal uptakes it is possible to determine the amount of bank erosion in cubic metres. In comparison with other methods, e.g. erosion pins (Evans & Warburton, 2005), Terrestrial Laser Scanning (TLS) offers many advantages which are listed in detail by Haas (2008) and Haas & Heckmann (2007). The main advantages are:

(a) the areas do not need to be entered;
(b) no influence by data sampling (footprints);

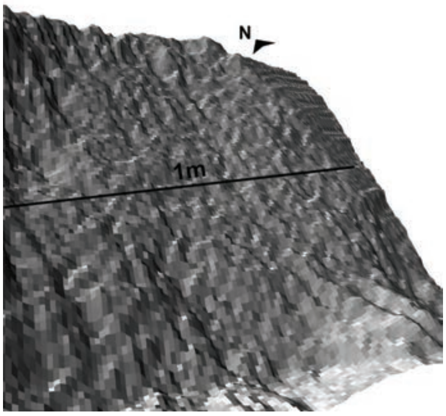

Fig. 7 Detailed 3-D view of a bank at the Wetterloch area, based on terrestrial laser scanning data. For location of the 3-D view in the erosion stretch, see Fig. 6.

(c) even hardly accessible undercut slopes can be measured (e.g. from the opposite river bank);
(d) no influence from erosion pins and other equipment;
(e) high resolution, the distance of measurement points is only a few centimetres;
(f) higher precision with inhomogeneous sediments; even coarse material can be measure (it is not possible to strike erosion pins into coarse and blocky material).

TLS is used for the calculation of DTMs from different scans as a time series after erosion events. In this way it will be possible to calculate the volume of sediment erosion. This leads to the crux of the matter: Erosion disposes material from the upper to the lower part of the project area, and there is no further sediment supply in the upper part. Both the bypass river and ecological flooding take place in an embanked environment. Only sediments of a grain size less than grit, and only with floods of a frequency of more than 1-in-5 years, will be able to enter the project area. This loose sediment may accumulate in the project area, but will be easily washed out with a new flood. This leads to another problem: Where does coarse sediment accumulate in the project area? Suspended sediment will leave the project area with the water flow. But gravel will not manage to pass the return flow weir under normal flow conditions. After several years there might be large accumulation patches, as shown in Fig. 8.

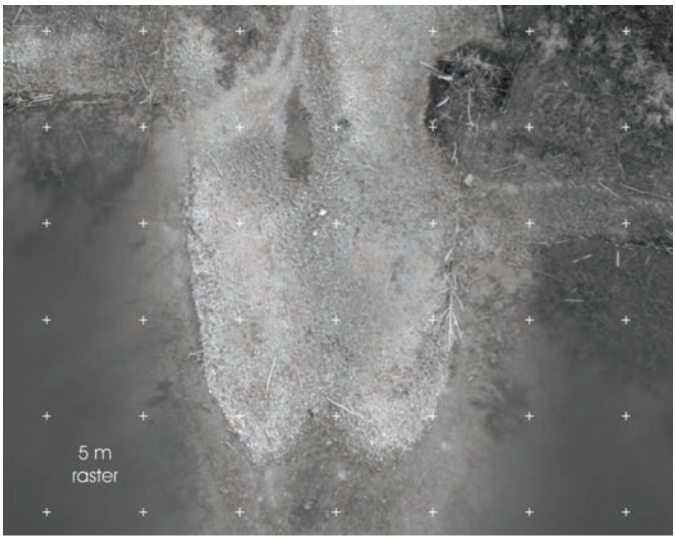

Fig. 8 Detailed aerial photograph of an alluvial fan which developed up the erosion stretch shown in Fig. 4.

Regular aerial survey of the project area

In order to record morphological changes of the entire 8 km river course at a large scale, aerial photographs of the project area were taken from a helicopter. The photos were taken with a calibrated SLR camera, and are suitable for stereoscopic analyses, as far as surveyed ground control points are present. This aerial survey will be carried out regularly and event related (during and after floods). Figure 8 shows an alluvial fan from the survey of 2006. The location is again the Wetterloch area (cf. Fig. 3), at the end of the erosion stretch.

The material shown in Fig. 8 is not at its final destination; that will be the zone in front of the return flow weir in the eastern project area. So the eastern part will fill up with gravel and other coarse sediment that is unable to pass the weir under the planned discharge regime. Finally, there will be a levelling. The topographically higher western part will decline by erosion and the topographically lower eastern part will rise by accumulation.

OUTLOOK

The most exciting research question is nearly the last one in this large field experiment: What will happen when the sediment budget is in balance? What will happen when the 5 m^3/s from the maximum discharge of the bypass river and the 30 m^3/s from the “ecological flooding” no longer have an effect because all the sediment which is erodable by this water discharge and velocity has gone? Will bed erosion stop? This is to be assumed because energy for bed erosion is missing. But what about the lateral erosion, the migration of the ox-bows? If this stops, one objective of the project will not be achieved. There should be dynamic and ever-lasting changing conditions on this part of the flood plain again. But the project can only produce these conditions for a certain period, until the system will have balanced out itself. At present nobody can say how static the conditions will get, and if they become static, how long the initial dynamic period will be. But perhaps the progress of this research can give a few answers to help the understanding of this system a bit better.

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