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Channel erosion and erosion monitoring along the Rhine River

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ABSTRACT During the last decades bed degradation of the Rhine river has been closely observed using various methods. The lowering of the river stages at the gauging stations gives valuable information about the long time development of channel degradation, varying between 0,5 and 5 cm/a. Measurements of sediment transport have also proved to be a useful method, as degradation between two stations can be estimated from the difference of partial sediment loads. A further possibility for calculating the bed material loss is to compare the results of cross section surveys carried out in 5-year intervals by the Water and Navigation authorities. In order to get more detailed information about the different erosion processes, the river bed has been directly investigated using two diving bell watercrafts. The combined monitoring of bed degradation by different measurement techniques has resulted in a better understanding of causes, dimensions, and future development of channel erosion.

INTRODUCTION

In the course of the past 100 years the Rhine river between Basel and the North Sea has been developed as an efficient navigation channel. In its upper course the river is regulated by dams (Fig. 1). In the freely flowing reach downstream of Iffezheim the river bed is fixed by groynes, guide dikes and bank revetments to such an extent that morphological changes occur nearly exclusively at the river bottom. In this connexion bed degradation has special significance as it is accompanied by lowering of water levels in the range of 5 - 50 mm $year^{-1}$. In the longrun, an advancing bed degradation will entail severe ecological and economic consequences (Gölz, 1992a).In order to be able to assess causes, extent and future development of river bed degradation, the Federal Minister for Transport had initiated several years ago hydrological, morphological, and sedimentological studies (BMV, 1987). For a better interpretation of the results of these studies it seems useful to consider first the erosion capacity of the natural system.

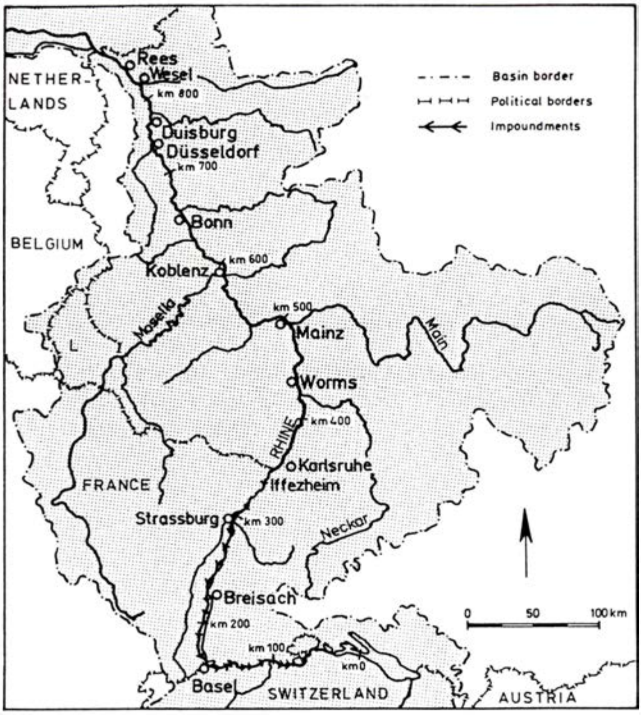


FIG. 1 The Rhine basin.

EROSION - PAST AND PRESENT

The extreme climatic changes during the Quarternary and the tectonic movements in the Rhine basin determined the morphological development of the river. Over the past two million years, for instance, the Middle Rhine has cut its valley 200 m deep into the Rhenish Massif. The development of a marked series of terraces testifies that there has been a climate-induced alternation of erosion and accumulation periods. According to Bibus (1980) the degradation rate in the last 65 million years was 0.3 mm $year^{-1}$. Since the end of the Weichselian about 10 000 years ago, the Middle Rhine has lowered its bed another 7 to 12 m, which corresponds to an average degradation rate of 1 mm $year^{-1}$ (Table 1).

In historic times, increasingly since the middle ages, man has interfered with the river regime. Especially rectifications and river training works during the 19th and 20th centuries caused severe changes in discharge and sediment transport conditions. The best-known example is the Upper Rhine between Basel and Breisach. As a consequence of the correction there the river bottom lowered by 50 mm per year on an average. Other drastic interferences were the dam regulations of the Southern Upper Rhine and of the major tributaries Neckar, Main and Mosella. These activities strongly reduced the natural sediment supply and had lasting consequences for the sediment budget of the Rhine river.

TABLE 1 Degradation rates of various periods (Middle Rhine).

Period	Average degradation rate	Effective width of erosion
last 10^6 years	0.2 mm $year^{-1}$	width of valley
last 10^4 years	1 mm $year^{-1}$	holocene floodplain
last 10^2 years	5 mm $year^{-1}$	channel
last 10^1 years	10 mm $year^{-1}$	navigation channel

Due to river training works, the Lower Rhine, too, has lowered its bed over the past 100 years. Extreme gravel exploitation in the channel and mining below the river accelerated bed lowering to such a degree that the water level at the gauging station of Rees dropped by nearly one metre between 1930 and 1950 (Fig. 3). This corresponds to a lowering-rate of 50 mm $year^{-1}$.

INVESTIGATION OF RIVER STAGES

From around 1770 onwards gauging stations have been systematically established in the Rhine basin. Around 1820 a basic network of gauging stations existed on the Rhine river. Another 50 years later, around 1870, water level gauging records could be supplemented by information on the related discharges (establishment of rating curves). Today there are 77 gauging stations along the freely flowing reach between km 334 (Iffezheim impounding) and km 865.5 (German-Dutch border). At fifteen of these stations discharge measurements are carried out additionally.

Monitoring and assessment of bed level changes in a channel reach can be supported by analyzing the water stage records of the gauging stations. However, the conclusions drawn on the basis of such data are often distorted or useless if major changes in discharge occur, especially if there is a marked trend.

A look at the situation at the gauging station of Rees shall help to understand the problem: The station is located at Rhine-km 837.4 on a reach that has been affected by degradation for decades. After World War II possibilities for river-bed stabilization have been intensively tested and implemented. In Fig. 2 the low water level (LW) shows a striking change of trend around 1950, which is clearly marked by two regression lines (1900 to 1950 and 1950 to 1990). The apparent conclusion is that the above-mentioned bed stabilization measures have been successful as the severe water level lowering has strongly decreased after 1950 and the further development has nearly levelled.

An additional analysis of the respective discharges

(LQ), however, indicates a steady increase in LQ and consequently a counter-trend to the LW development. This increase is especially obvious for the years after 1950.

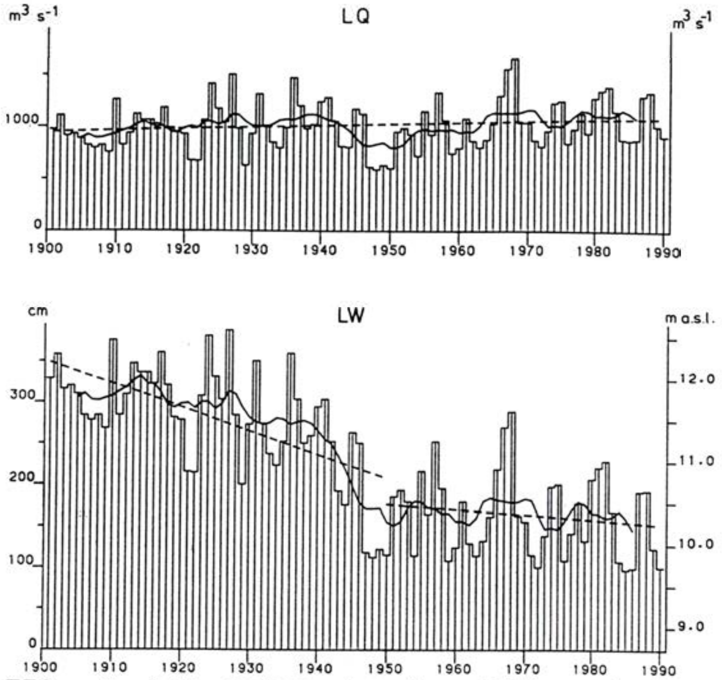


FIG. 2 Low water levels (NW) and low water discharges (NQ) 1900/1990 at the Rees station (Lower Rhine).

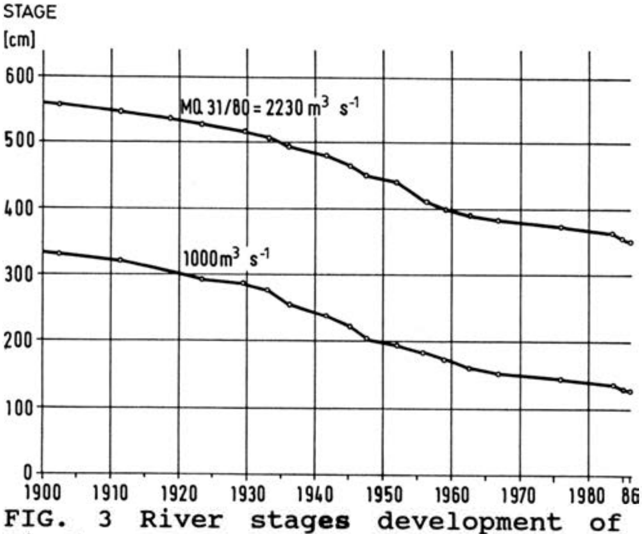


FIG. 3 River stages development of equivalent discharges (Rees, km 837,4).

Therefore the actual development of the river stages can be assessed only by a combined consideration of W and Q, i.e. the development of W has to be analyzed only for a defined value of discharge. Fig. 3 shows e.g. the variation of water stages for selected discharges in the period from 1900 to 1986 by means of the existing 18 rating curves of the Rees station (Engel et al., 1988). It becomes clear now that the change in water level development assumed according to Fig. 2 is not true. The real water level development according to Fig. 3 shows only little changes in the low-water range with turning points in the years around 1930 and 1965.

This example supports the above mentioned finding that the development of river stages can only be interpreted correctly in combination with discharge data. Consequently, Engel & Gundert (1991) use a procedure allowing a combination with discharge data also for stations recording only water levels. The data of the nearest discharge gauge are used for this purpose. When analyzing the low water development the MLQ of the discharge station is used as reference value. To each annual low water level of the water level station the respective discharge of the reference station is adjoined. From a LW/LQ series established in such a way a high and a low pair of values is selected (preferably from a short period) to determine a mean gradient ΔQ per cm water level variation. Now the annual discharge difference ΔW can be calculated by means of the gradient. By additon of LW + ΔW standardized water levels are obtained.

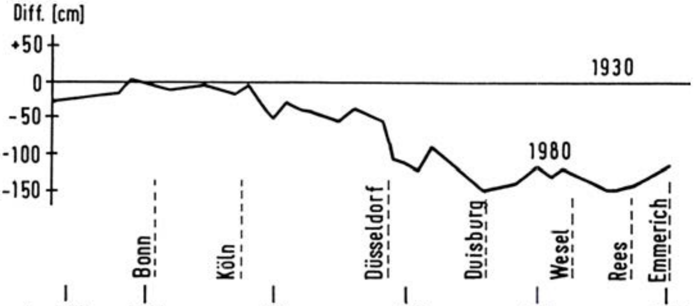


FIG. 4 Differences of the GlQ water surface profiles 1930 and 1980 between Koblenz and the German-Dutch border.

A continous survey on a certain river reach requires additional calculations of water surface profiles for equal discharges but different bed conditions. The comparison of the two surface profiles results in a difference line showing the water level changes along the whole reach considered (Fig. 4). In case of evident changes it may be assumed that these are due to morphological processes. Especially the change of the low water surface allows direct conclusions on the bed level development.

EVALUATION OF ECHO-SOUNDING SURVEYS

Echo-sounding surveys are needed both for maintenance of the navigation channel and for hydrological studies. According to the significance of the navigation channel special measuring boats with modern position finding and vertical sounding equipments are used (Keydana & Suntrop, 1986). On the Rhine river, every five years a main survey is carried out. On this occasion every 100 metres cross sections are surveyed by echo-sounding along the whole German reach of the river. Since 1975 the data have been digitally recorded, stored, and after a plausibility check entered into a data base on cross-sections. The comparison of the data from different main surveys allows to derive information on the change of the mean bed level. It should be kept in mind, however, that certain errors may occur due to the inaccuracy of the sounding, of the position finding and because of the fact that only a momentarily recorded state is used for comparison.

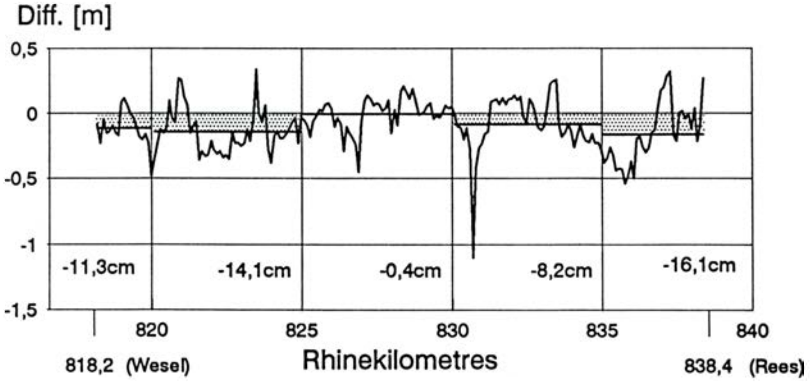


FIG. 5 Bed level changes 1980 - 1985 in the reach Wesel - Rees

The example of the reach Wesel-Rees (Lower Rhine, km 818.2 - km 838.4) shall be used here to illustrate the method and to present its results. In order to compare the results of the individual surveys a common reference level, the so-called GlW, has been chosen. This low water level belongs to the discharge GlQ which has been used as reference discharge for several decades. The GlW forms the upper boundary of the cross-section areas to be compared. As surveys on cross-section portions outside the discharge channel (groyne fields, flood plain) are not regularly updated, it is not useful to include these zones in the investigation, although this may be a source of error for the overall balance.

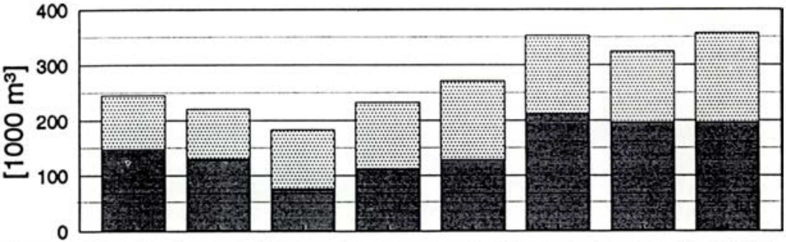
The cross-section areas determined by this procedure range between 850 and 1,400 m^2 and the width measures between 240 and 370 m. From the area and width data the mean bed surface levels of the years 1980 and 1985 can be calculated, thus getting an indication of the changes that occurred within this period. Fig. 5 shows both the bed level differences at each cross section and their average over several kilometres. Between 1980 and 1985 the bed level changes were negative, ranging between 0.4 and 16.1 cm. In average the bed surface has lowered by 9.3 cm. This corresponds to an annual bed surface change of -18 mm $year^{-1}$. The causes (e.g. erosion, mining subsidence) cannot be derived from this study alone.

SEDIMENT TRANSPORT MEASUREMENTS

First measurements of bed load transport in the Rhine river were made already in the mid-1960s. Since 1975 these measurements have been carried out systematically to predict and control the artificial bed load supply downstream of the Iffezheim dam (Tippner et al., 1985). In the early 1980s, the network of stations was extended along the whole freely flowing river down to the Dutch border. Temporarily there were 35 measuring stations. After the evaluation of the measured data and the establishment of a bed load balance (the first one to cover the whole reach!), the number of stations was reduced to 20. The data regularly collected at these permanent stations provide an important decision-aid for all major investment projects and maintenance measures on the Rhine river (Dröge, 1992).

As described by Deyhle et al. (1986) the measurements are carried out from boats. A basket sampler is used to measure bed load transport at six to twelve verticals in the cross section. At the same verticals the concentration of suspended sediment < 63 μm and the content of suspended sand are measured in combination with the flow velocity in four to five depth levels. More detailed investigations revealed that in the average one third of the suspendable sand (0.2 - 1 mm) is involved in the bed-forming process.

The measurements are made under different discharge conditions. If sufficient data are available it is possible to establish sediment rating curves. In combination with the daily discharges (from a data base) these enable the calculation of sediment loads for periods of any duration. The comparison of the partial sediment loads (bed load plus one third of suspended sand load) of two neighbouring stations allows to derive the mass deficit or profit in the reach between them. Conversion by the weight per unit of volume of 1.8 t m^{-3} results in the volume change. This value, in turn, can be converted by inclusion of the channel width into the value of bed level change. However, a complete balance will require the consideration of further impacts like bed load supply of tributaries, dredging operations, or mining subsidences.



Station [km]	782,0	794,6	800,0	808,5	812,2	838,4	845,0	857,5
Bed Load ■ [m³]	148	130	76	113	129	212	196	196
1/3 of Susp. ▨ Sand Load [m³]	97	91	107	119	142	141	128	161
Sum [m³]	245	221	183	232	271	353	324	357

FIG. 6 Mean annual sediment loads (bed load plus one third of suspended sand load) of the Lower Rhine 1980/1985 (converted in units of volume).

Fig. 6 shows the mean annual sediment loads (bed load and one third of suspended sand load) from 1981 to 1985 at eight stations on the Lower Rhine (Dröge *et al.*, 1992). The decrease in sediment loads between km 782 to km 800 indicates deposition, whereas the following reach to km 838.4 represents a typical degradation zone where sediment loads are steadily increasing. Between the stations of Wesel (km 818.2) and Rees (km 838.4) the difference amounts to 82,000 m^3. This deficit belongs to a bed area of 20,200 m x 300 m, i.e. 6,060,000 m^2, which allows to calculate a mean bed-degradation rate of 0.014 m $year^{-1}$.

INVESTIGATION OF BED SURFACE AND SUBSURFACE BY CAISSON

Whether erosion occurs in a certain river reach depends - as described above - mainly on the sediment budget. Extent and course of bed degradation, however, essentially depend on the nature of bed surface and subsurface. That is why the river bed has been examined by means of two diving bell crafts for several years (Gölz, 1992b). These studies allow not only to make direct sedimentological examinations of the bed surface but also to explore the subsurface by means of probing and drilling.

The substratum of the river bottom consists mainly of Pleistocene deposits of the Rhine river. How strongly the composition of the subsurface can differ already in the uppermost metre is shown by the grain-size cumulative curves of a core sample taken on the Northern Upper Rhine (Fig. 7). The coarsening in the upper surface layer is clearly visible. However, it provides only a temporary protection of the bed surface. As can be seen from the grain-size composition of the deeper strata, a durable armouring cannot develop because the subsurface does not contain sufficiently coarse components. With a continuing bed load deficit, bed degradation will advance.

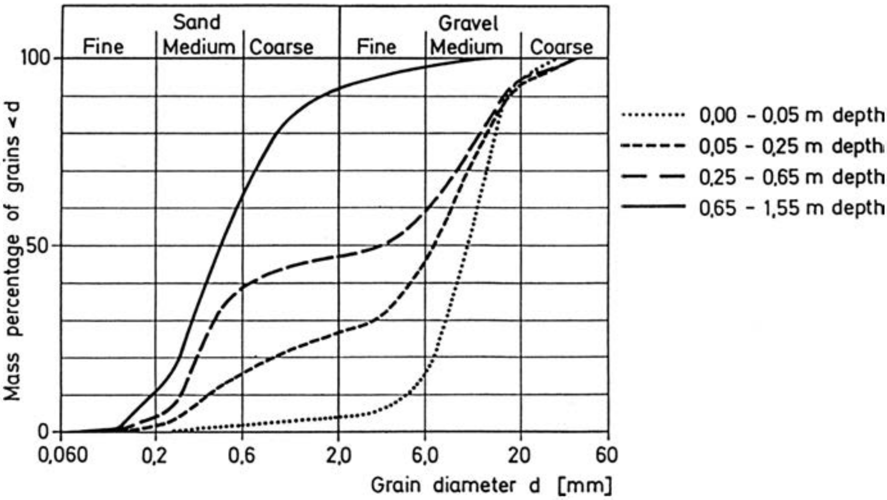


FIG. 7 Grain-size composition of bed surface and subsurface layers. Northern Upper Rhine.

On the Middle and Lower Rhine the composition of the Pleistocene valley fill is clearly coarser and often less uniform than on the Northern Upper Rhine. This situation favours the development of an armoured bed. Extended investigations of the bed surface from the diving bell have revealed that armoured reaches exist locally but are mostly limited in size. Outside these reaches degradation continues.

Between Düsseldorf and Rees the Pleistocene gravel layer thins out so that locally sediments of Tertiary age are exposed at the river bottom. They consist prevailingly of fine sands which are little compacted. Such sediments are easily washed out by the current and carried off as suspended load. Mechanism and course of degradation have been intensively studied by means of the diving bell craft "Carl Straat". Gölz (1987) found that in these fine sands large scours may easily develop which shift downstream until the Pleistocene gravel layer becomes thicker again. Sections downstream of mining subsidence zones are particularly vulnerable as retention of bed load in the subsidence troughs promotes exposing of the fine sands.

COMPARISON OF METHODS - CONCLUSIONS

The direct investigation of the river bed by caisson has considerably contributed to the understanding of bed degradation processes on the Lower Rhine and on other reaches of the river. The sedimentological data thus acquired provide an important basis for stability analyses.

River stage investigations enable to obtain a continuous overview on the development of bed degradation from the beginning of systematic stream gauging in 1870 to the present time. An important precondition for the correct interpretation is the consideration of changing discharge conditions by means of suitable standardization methods. Here, it is mainly the development of low water stages that provides information on river bed degradation, as in case of depth / width ratios of approx. 1:100, the lowering of the water level can be equalled to the bed lowering in good approximation, provided external interferences do not distort the development.

Contrary to this indirect determination of bed level changes, the comparison of the results of repeated cross-section surveys has the advantage that the geometry of the river bed is directly measured. Due to the inaccuracy of echo-sounding, however, reliable results can be obtained only on reaches with high degradation rates (>1 cm $year^{-1}$) and by considering appropriate temporal intervals (five years or more).

TABLE 2 Bed level changes determined by different methods in the period 1980 - 1985 (Wesel - Rees).

Method	Degradation rates [cm 5^{-1} $year^{-1}$]	[mm $year^{-1}$]	Deviation from the average [%]
River stages	7.4	15	6
Cross sections	9.3	18	18
Sediment loads	6.9	14	12

Another indirect method of determining river bed degradation is to measure sediment transport and to calculate the annual sediment loads. The deficit of the partial sediment load between two neighbouring stations allows to calculate the eroded volume of bed material and consequently to derive the degradation in the reach between the two stations. This presupposes frequent measurements of sediment transport under different discharge conditions for the updating of the sediment rating curves. Sediment transport rates are needed in connection with the above mentioned sedimentological data for the calibration of numerical sediment transport models and thus constitute an important prerequisite for the prediction of future degradation.

The degradation rates (Table 2) determined by means of river stage investigations, cross-section surveys, and sediment transport measurements deviate by only about 20 percent. For hydrological investigations this is a high degree of agreement, demonstrating that the methods applied are appropriate for the task of erosion monitoring.

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