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Iffezheim field test—three years experience with a petrographic tracer

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Abstract A long-term field test with a petrographic tracer has been carried out at the Upper Rhine to optimize bed-load management downstream of the Iffezheim weir. In October 1996, 28 000 t of broken granite were dumped into the river. The granite tracer was followed downstream and the sorting and mixing processes were quantified. The mean migration speed varies between 2.5 and 5.5 km year^{-1} depending on grain size and the small gravel fraction does not move faster than medium gravel. A 1% flood did not seem to have a major effect on migration velocity but it did influence the mixing process. Freeze-core sampling detected tracer pebbles down to a depth of 1.0–1.3 m below bed surface. Mass balances showed good agreement with the input of 28 000 t for 1997 and 1998 but after the 1% flood only 55% of the original tracer mass was detected. Therefore, forthcoming sampling has to focus on deeper strata, sediments of the groyne fields and the reach further downstream.
Key words River Rhine; artificial bed-load supply; petrographic tracer; hydraulic sorting; dispersion; mixing; migration velocity; mass balance

INTRODUCTION

Artificial supply of bed-load material for the dynamic stabilization of river reaches affected by erosion has become an accepted method in river engineering and is being applied increasingly on German Federal waterways (BMV, 1997; Gölz, 1999). The material is dumped from hopper barges and forms a thin mobile gravel carpet on the river bottom. The amount of material and its grain-size composition are decided after consideration of the transport capacity of the reach to be stabilized and the grain size of the natural bed-load material. By using coarser material, e.g. in a bed-stabilization project in the River Danube downstream of Vienna (Zottl, 1999), additional stabilizing effects or a reduction of the amount of material to be added are expected. Conversely, the addition of finer material may be appropriate if the aim is to quickly stabilize river reaches further downstream (Gölz, 1990). In German waterways field tests with petrographic tracers are carried out to identify specific features of bed-load transport in the reach to be stabilized and to estimate roughly the effects of bed-load supply. The tracer consists of conspicuous rock material that can be distinguished easily from natural bed material by colour, structure and shape, but has a similar grain-size composition as the material intended for artificial bed-load supply.

ARTIFICIAL BED-LOAD SUPPLY AT IFFEZHEIM

The southern part of the upper Rhine has been impounded during the twentieth

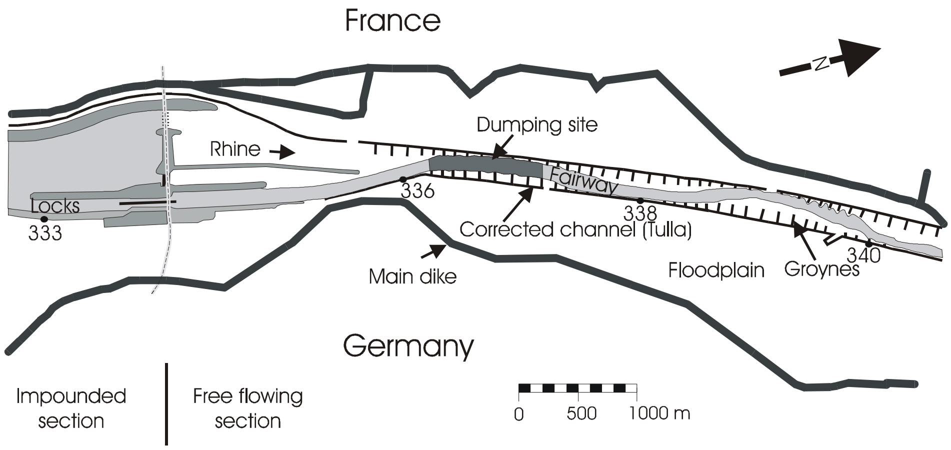

Fig. 1 The upper Rhine near the Iffezheim weir.

century. Although largely changed by regulation and training works, the northern upper Rhine has remained a dynamic gravel-bed river with an annual bed load of about 300 000 t. To avoid bed degradation downstream of the last weir at Iffezheim, the river has been artificially supplied with gravel since 1978 (Kuhl, 1992). Since unhindered access to the ship locks of the impoundment must be ensured (Fig. 1), the primary aim of this measure is to stabilize the river bed and the water stages immediately downstream of the impoundment weir. As the impoundment weirs upstream and the dam regulation of the River Neckar inhibit the natural supply of material, this artificial bed-load supply at Iffezheim is the only major source of bed-load material for the free-flowing upper Rhine. About 300 000 t of gravel are dumped each year, although the quantity may vary between 120 000 and 580 000 t. The latter amount had to be added in 1999. This year was characterized by two flood events, of which the second had a recurrence period of 100 years (Fig. 2).

Although at Iffezheim artificial bed-load supply has been successfully practised over more than two decades, there is now an urgent need for optimizing the procedure applied so far. At high floods the river bed close to the barrage can be stabilized only with great effort and a large amount of material. On the other hand in the reaches further downstream echo-sounding surveys have revealed continuous aggradation of the river bed. Against this background, the German Federal Institute of Hydrology (BfG) together with the Federal Waterways and Shipping Office Freiburg devised a field test to provide a better scientific substantiation for future bed-load supply practice.

EXPERIMENTAL PROCEDURE

The Federal Waterways and Shipping Office Freiburg organized the dumping of 28 000 t of gravel-sized broken granite from a quarry in the Black Forest into the River Rhine between river-km 336.2 and 337.1 during a four-week period in October 1996. The grain size of the tracer material was adjusted to the grain-size composition of the gravel dumped in the past few years. Repeated echo-sounding surveys in the following months proved that the granite tracer had been entrained by the current and transported

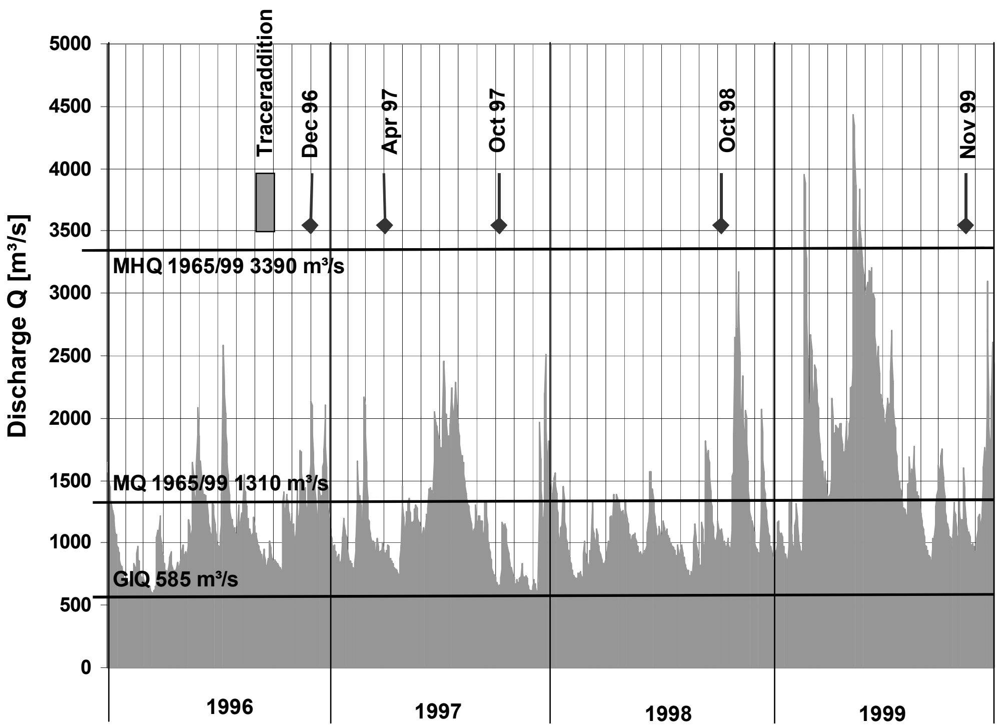

Fig. 2 Hydrological conditions and sampling schedule.

downstream. The spreading of the tracer was recorded by several sampling campaigns at intervals of 2, 6, 12, 24, and 36 months after dumping (Fig. 2). A sixth sampling campaign was scheduled for October 2001, i.e. 60 months after starting the experiment. The samples were collected by means of the diving-bell vessel "Carl Straat", allowing direct sampling at the river bottom down to a depth of 0.5 m below bed surface. Sampling was done at five points within one cross-section. After the floods of 1999, additional samples were taken down to a depth of 1.5 m below bed surface at certain points by means of special freeze-core equipment to examine the influence of floods on mixing and exchange processes. All samples were separated by sieving into five fractions, and the percentage of the mass of tracer in each fraction was determined by picking-out the granite grains. Thanks to its structure and colour, the tracer could be identified reliably and quickly. Only the fraction 4–8 mm was difficult to identify as this grain size matches the size of the individual granite minerals. Each time 10–12 cross-sections with five vertical profiles were sampled, consequently each campaign comprised several hundred petrographic analyses.

RESULTS

This paper presents the first rough evaluation of the data. A more thorough statistical analysis of the voluminous data pool still has to be made. Nevertheless, a number of valuable findings can be derived from this preliminary data review. It is mainly based on data from the petrographic analysis averaged over the cross-profile.

By plotting the tracer concentration along the course of the river a longitudinal distribution that reflects the status at the time of sampling is obtained. As can be seen from Fig. 3, i.e. 24 months after dumping, the tracer had been removed nearly completely from the dumping site and had spread—according to the fraction considered—over 8–21 km of the downstream reach. As expected, due to hydraulic sorting the coarser fractions remained clearly behind the finer ones. The finest fraction of 4–8 mm, however, is not the fastest one. It has nearly the same migration velocity as the fraction of 8–16 mm and is only slightly faster than the medium-sized fraction of 16–31.5 mm. This is caused by "hiding", which means that fine grains are sheltered from entrainment by coarser grains or are trapped in the voids between the coarser grains. Even if the fronts of the individual fractions have already advanced, the mass of the tracer characterized by the centre of gravity of the distribution curve lags notably

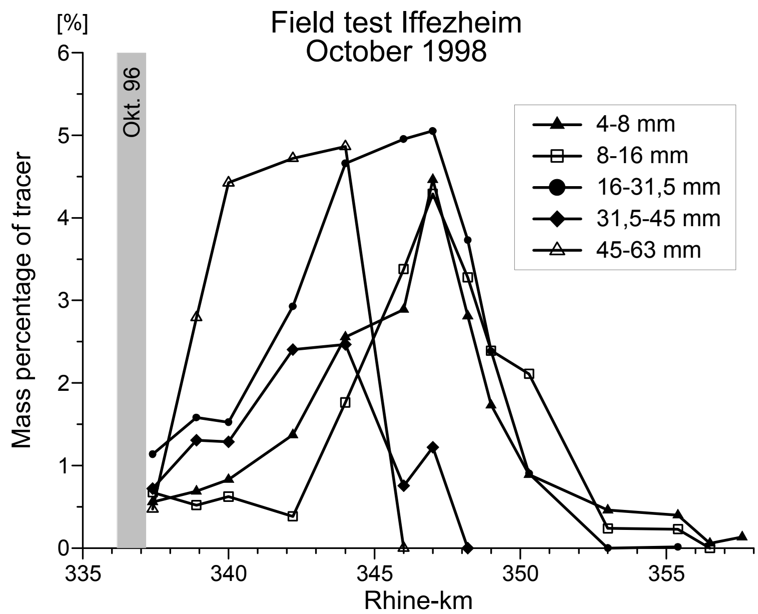

Fig. 3 Longitudinal tracer distribution 24 months after dumping.

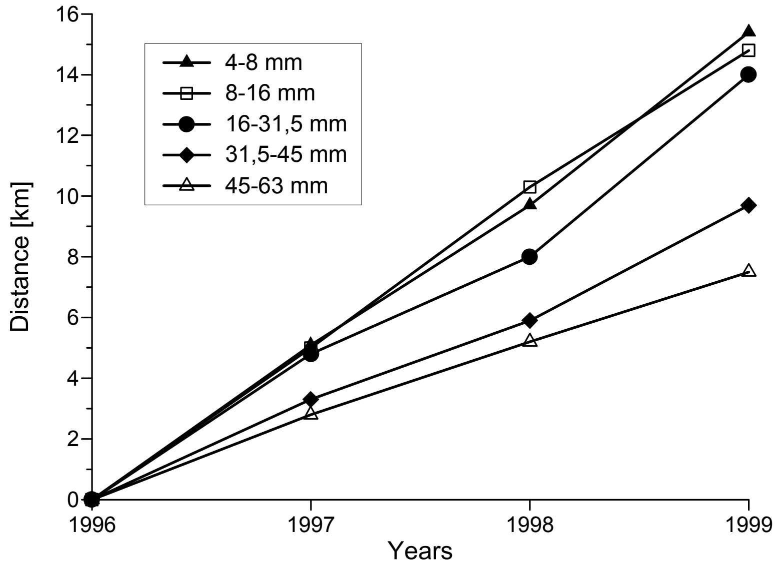

Fig. 4 Travel–time diagram 1996–1999.

behind. Figure 4 illustrates the advancing of the "mass centres" of the individual fractions by means of a travel–time diagram. They move at an average velocity of only 2.5–5.5 km year^{-1} downstream, whereas the fraction heads advances at a rate of 6–11 km year^{-1}.

It is also interesting to note the behaviour of a single fraction. Figure 5 presents the longitudinal distribution patterns of the 16–31.5 mm fraction as observed 2, 6, 12, 24, and 36 months after dumping. Two months after starting the experiment part of the tracer material is still present in the dumping reach, and the distribution curve shows a very sharp peak with a maximum tracer concentration of nearly 40%. After two months the concentrations notably decrease, and the distribution curves flatten more and more, until in November 1999, i.e. three years after the material was added, the distribution curve stretches over 33 km but is still "rooted" in the original dumping area. One can conclude that the tracer will disperse more or less evenly over the whole reach in the course of time.

The stretching of the distribution curve shows the degree of dispersion of the tracer during transport. In this paper the term dispersion is used for the combined effects of a couple of sedimentological processes which cause spatial scattering of particles of the same size in the course of transport. However, dispersion has both a lateral and a vertical component. The lateral dispersion of the tracer has not yet been examined, but the vertical dispersion was studied by means of freeze-core samples. These samples were taken in November 1999, i.e. after the two major flood events, at some selected sites, and they provide essential insight into the depth of mixing of the tracer with sediments of the subsurface. Tracer material was found in the freeze-cores down to a depth of 1.3 m below bed surface. The minimum depth was 0.35 m. On average, one can assume a mixing depth of 0.8 m. Two sedimentological processes could explain such great mixing depths. The first is that bedforms, such as dunes, may contribute to mixing: e.g. when tracer material rolls down the lee slope of a

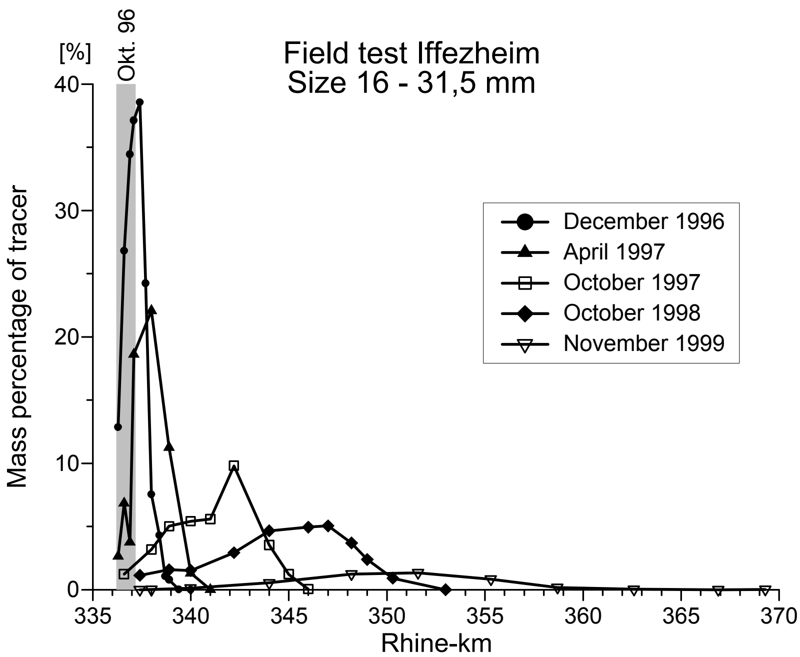

Fig. 5 Longitudinal dispersion of fraction 16–31.5 mm.

dune, becomes covered by the advancing bedform, and is not again involved in the transport process, especially when the height of the bedform decreases due to changing hydraulic conditions. A second explanation might be simple deposition of bed-load material in aggradation reaches. A combination of these two effects seems possible.

Cross-section soundings indicate that there is no evidence for bed aggradation at the sites of freeze-core sampling. However, additional longitudinal soundings, carried out at a discharge of 3000–3500 m^2 s^{-1}, established the presence of large gravel dunes with heights up to 1 m and more (Fig. 6). So bedform development during high floods is responsible for the observed mixing depths.

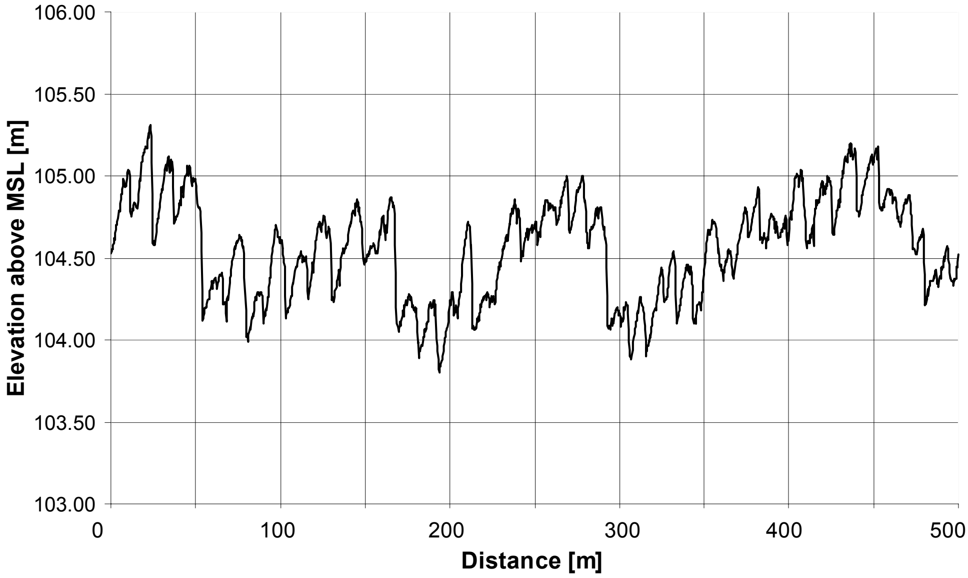

Fig. 6 Bedform development (gravel dunes) at high discharge.

MASS BALANCE

The quality of a tracer experiment can be tested by establishing a mass balance, i.e. comparing the input and output of the tracer. This seemed possible for the tracer experiment at Iffezheim, although only a simple approach was applied. A three-layer model of the river bed was chosen with a variable length and a standard width of 120 m, assuming a thickness of 0.1 m for the first layer, and 0.2 m for the second and third layers. The results are presented together with the initial mass in Fig. 7. One can see that during the sampling campaigns in October 1997 and October 1998 most of the tracer could be found, even if the portions of the individual fractions had shifted slightly. This might be due to the simplification used for computing and the fact that the tracer concentration of the third layer was derived from only one sample within the cross-section. Thus, a certain distortion is inevitable. Nevertheless, one can draw the conclusion that in 1997 and 1998 the tracer was nearly completely recovered , whereas this was certainly not the case in the sampling campaign of 1999. Then, only slightly more than half the tracer appeared in the balance. This means that sampling in October 1999 did not recover the full quantity of tracer, and at the moment it is not clear where

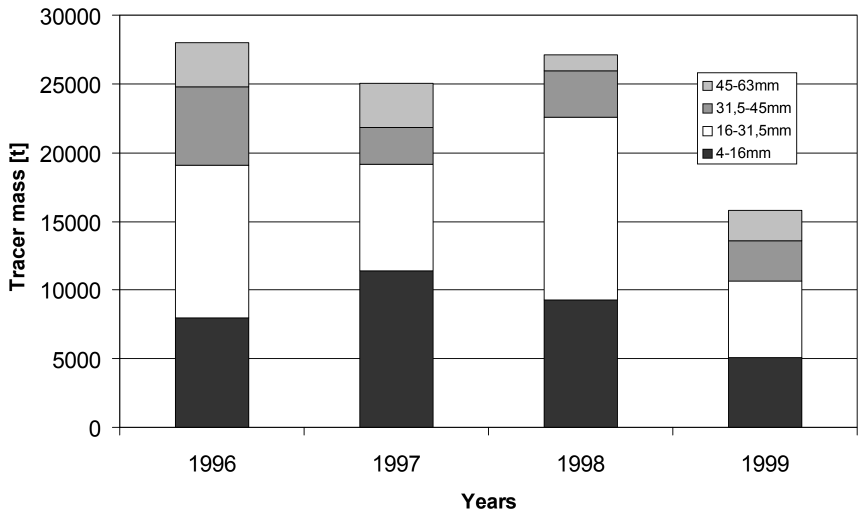

Fig. 7 Tracer input (1996) and mass balances for the years 1997–1999.

the remaining 45% of tracer material has gone. One could assume that the material was transported further downstream without being noticed, that it has invaded deeper layers, and/or that the tracer was transported into the groyne fields at flood stage. This question and other unclarified issues should be examined by the next sampling campaign in autumn 2001.

CONCLUSIONS

The field test at Iffezheim has shown that an appropriate sampling and analysing programme enables us to quantify the transport and spreading of a petrographic tracer. The results obtained have been verified by mass balances, except for the flood year 1999. Although preliminary, the following major findings can be noted:

- The dumped material does not move downstream as a compact sediment wave, but is spread during transport over the whole distance (dispersion).
- This phenomenon is due less to delayed entrainment at the dumping site and the stochastic character of sediment transport than to mixing and exchange processes.
- After the floods in 1999, a maximum mixing depth of 1.3 m below bed surface was observed. The minimum mixing depth is 0.35 m; a mean mixing depth of 0.8 m can be estimated.
- Flood waves do not increase mean migration velocity. They intensify bed deformation by the development of large bedforms thus favouring tracer transfer into deeper strata.
- Strong hydraulic sorting was observed for grain-sizes >32 mm. They clearly lag behind the fractions 4–8, 8–16, and 16–31.5 mm. The latter show a relatively uniform transport behaviour.

Numerical modelling can be an important tool for optimizing bed-load supply at Iffezheim, if the models take into account the sedimentological processes observed in the field. In addition, the data collected in the course of the tracer experiment might be useful for calibrating and validating appropriate sediment transport models.

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