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Sediment monitoring, long-term loads, balances and management strategies in southern Bavaria

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Abstract Sediment transport (bed load and suspended load) is an important part of the river discharge, especially in the alpine affluents of the Danube River. In Bavaria, suspended sediment measurements commenced in the early twentieth century when the construction of dams and water power plants caused changes in the morphological equilibrium of the rivers. Long-term sediment data are therefore available for a period of more than 60 years. The bed load component for establishing the sediment balance is provided by statistics of gravel excavations mainly from the reach where the inflowing water enters the reservoirs and lakes. Because suspended load contributes little to meeting the bed load deficits downstream of reservoirs, management strategies should be limited to the bed load component. Some case studies from the upper part of the Danube basin are presented.

HISTORICAL REVIEW

In comparison with stream discharge gauging which began in Bavaria in 1826, sediment sampling and monitoring has only been undertaken for several decades. This task became necessary during the early twentieth century when the construction of dams and water power plants caused changes of the morphological equilibrium of the bed load transporting rivers.

MEASUREMENT METHODS

Measuring suspended load

As is well known, a method for direct measurement of suspended sediment over the whole cross-section of a river does not yet exist. When sediment monitoring commenced in Bavaria in the early twentieth century, it was decided to use a method which was as simple as possible. This involved one-point sampling with a 10 l bucket. This is an acceptable methodology, supplying useful results (Table 1). In addition to this one-point sampling, multi-point sampling is used for more precise investigations and for controlling and calibrating the one-point sampling.

Measuring bed load

Information on the bed load component of sediment transport is obtained primarily from

Table 1 Long-term records of mean annual suspended load transport in Bavarian rivers (based on the period 1971-1990).

River	Measuring station	Catchment area	Suspended sediment concentration:		Annual suspended sediment transport	Specific sediment yield
			Average	Maximum		
		(km^2)	(g m^{-3})	(g m^{-3})	($\times$ 10^3 t)	(t km^{-2} year^{-1})
Donau	Neu Ulm	5460	48	1766	80.9	14.8
Donau	Ingolstadt	20 008	39	2406	400.6	20.0
Iller	Kempten	953	102	12 730	149.1	156.5
Iller	Wiblingen	2115	60	2208	136.1	64.4
Lech	Füssen	1422	174	8576	315.7	222.0
Naab	Heitzenhofen	5426	27	923	44.7	8.3
Isar	München	2855	38	2855	108.0	37.8
Isar	Plattling	8839	36	1806	198.2	22.4
Ammer	Weilheim	600	133	12 107	61.0	101.7
Amper	Inkofen	3043	27	1209	39.5	13.0
Inn	Oberaudorf	9712	187	10 268	1782.6	183.5
Tiroler Achen	Marquartstein	937	198	15 914	219.3	232.4
Traun	Altenmarkt	378	90	12 219	35.0	92.7
Saalach	Unterjettenberg	940	206	10 427	234.5	249.4
Salzach	Burghausen	6649	166	6919	1287.5	193.6

annual records of gravel excavation, especially from the head works of reservoirs and lakes. From these long-term records of gravel removal we determine the average annual bed load transport (Table 2). Because the direct measurement of bed load transport takes a lot of time and money and only provides approximate results, we have limited it to special investigations.

THE SEDIMENT BALANCE

The necessity for establishing sediment balances in river morphological investigations has considerably increased in recent years. This is because the classical demands (e.g. stabilizing of degrading and aggrading reaches) have been supplemented by additional requirements such as investigations to determine a minimum discharge in diversion reaches and to reconstruct or restore trained rivers.

For planning of rehabilitation or restoration measures, a morphological inventory of the river or stock-taking should initially be undertaken (Fig. 1). This consists of a geological and historical review in which the channel changes caused by human impacts are documented. This is carried out using river measurements such as cross-sections and

Table 2 Annual bed load transport in Bavarian rivers.

River	Location	Catchment area (km^2)	Time of observation	Average annual bed load transport (m^3 $year^{-1}$)	Remarks
Donau	Hofkirchen	47 489	1989-1990	28 000	Bed load sampling with basket sampler
Inn	Rosenheim	10 000	1961-1980	104 000	Excavation from the headwater
Isar	Sylvenstein	1156	1958-1983	53 600	Delta survey
Isar	Plattling	8839	1988-1989	57 000	Bed load sampling with basket sampler
Saalach	Reichenhall	940	1969-1984	95 000	Excavation from the headwater
Salzach	Mouth	6717	1953-1987	112 600	Excavation from the headwater
Ammer	Ammersee	709	1962-1988	24 000	Delta survey
Tiroler Achen	Chiemsee	952	1869-1965	40 000	Delta survey

low water surveys, gauging records, aerial photos and historical maps. To establish the sediment balance for a river reach, long-term records of sediment transport are necessary. While the bed load component is deposited in the topmost weir site of a series of power plants, the suspended particles are only partly retained in the reservoirs and will continue to be transported. From long-term suspended sediment data (Fig. 2) we can, for example, detect the reduction in suspended sediment transport on some rivers resulting from the increasing installation of water power plants since the early 1940s.

The present state of bed stabilization for the River Danube and its southern tributaries is shown in Fig. 3. Due to the continued construction of power plants on its

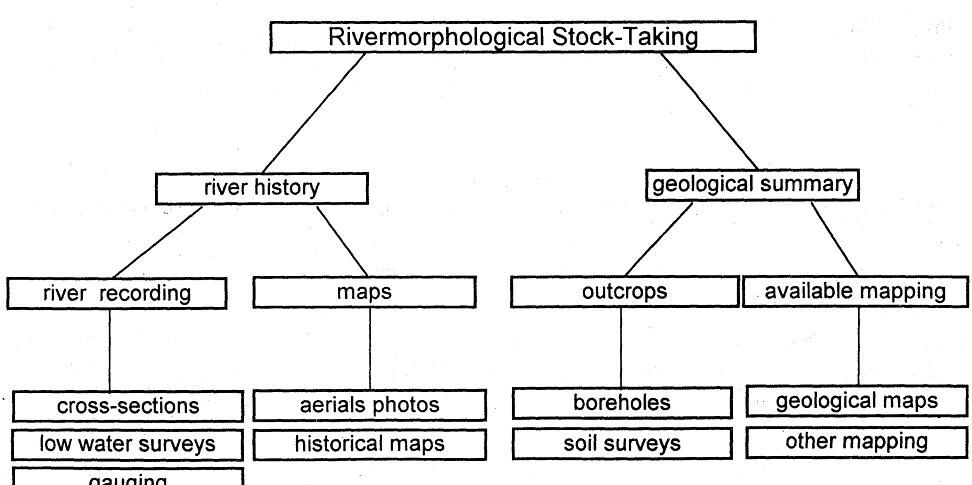

Fig. 1 River morphological inventories.

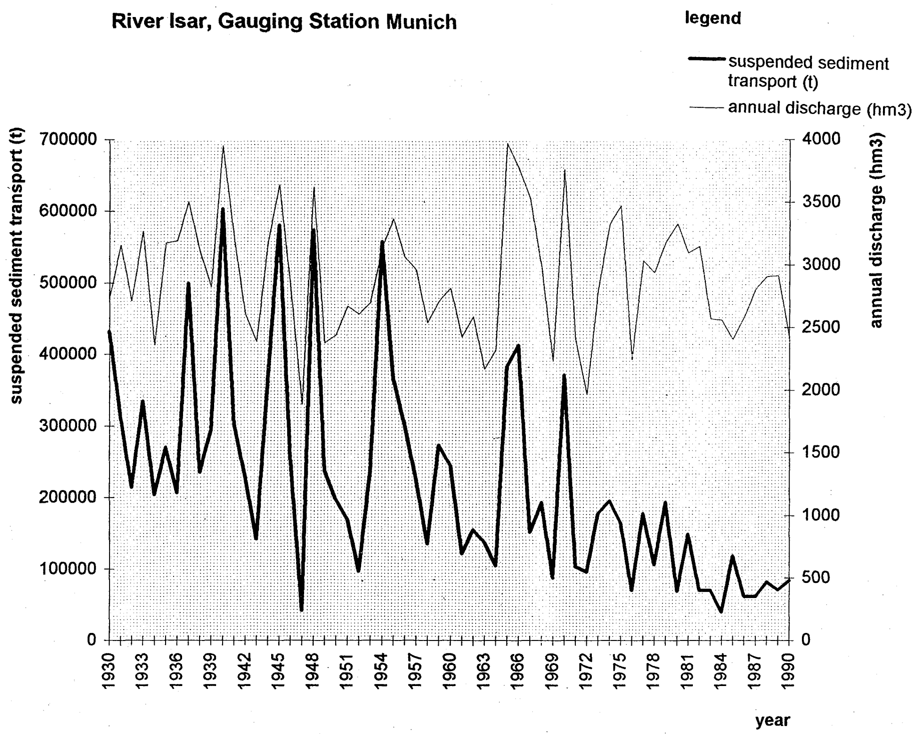

Fig. 2 Long-term records of mean annual suspended sediment transport by the River Isar.

tributaries, the bed load input into the River Danube has also decreased. Only small inputs remain from the River Iller (less than 10 000 m^3 $year^{-1}$) and from the River Isar (about 50 000 m^3 $year^{-1}$) and these will be reduced to zero by further bed stabilizing measures to be installed in future years.

SEDIMENT MANAGEMENT

In river stretches where the banks and other measures are threatened by increasing down cutting and decline of groundwater levels, a need for action is apparent. Because suspended load contributes little to meeting the bed load deficit downstream of a reservoir, the management strategy must be focused primarily on the bed load component. This means that possibilities for maintaining at least a residual bed load transport in the unstabilized stretches must be sought. This status should be maintained as long as possible in order to minimize further bed erosion and to defer the construction of stabilizing measures for as long as possible. The following attempts at bed load management have been developed from numerous investigations of river morphology in the Bavarian River Danube basin (Weiss & Mangelsdorf, 1982; Weiss 1983; 1989; Kortmann, 1989). They mainly refer to the alpine tributaries of the River Danube.

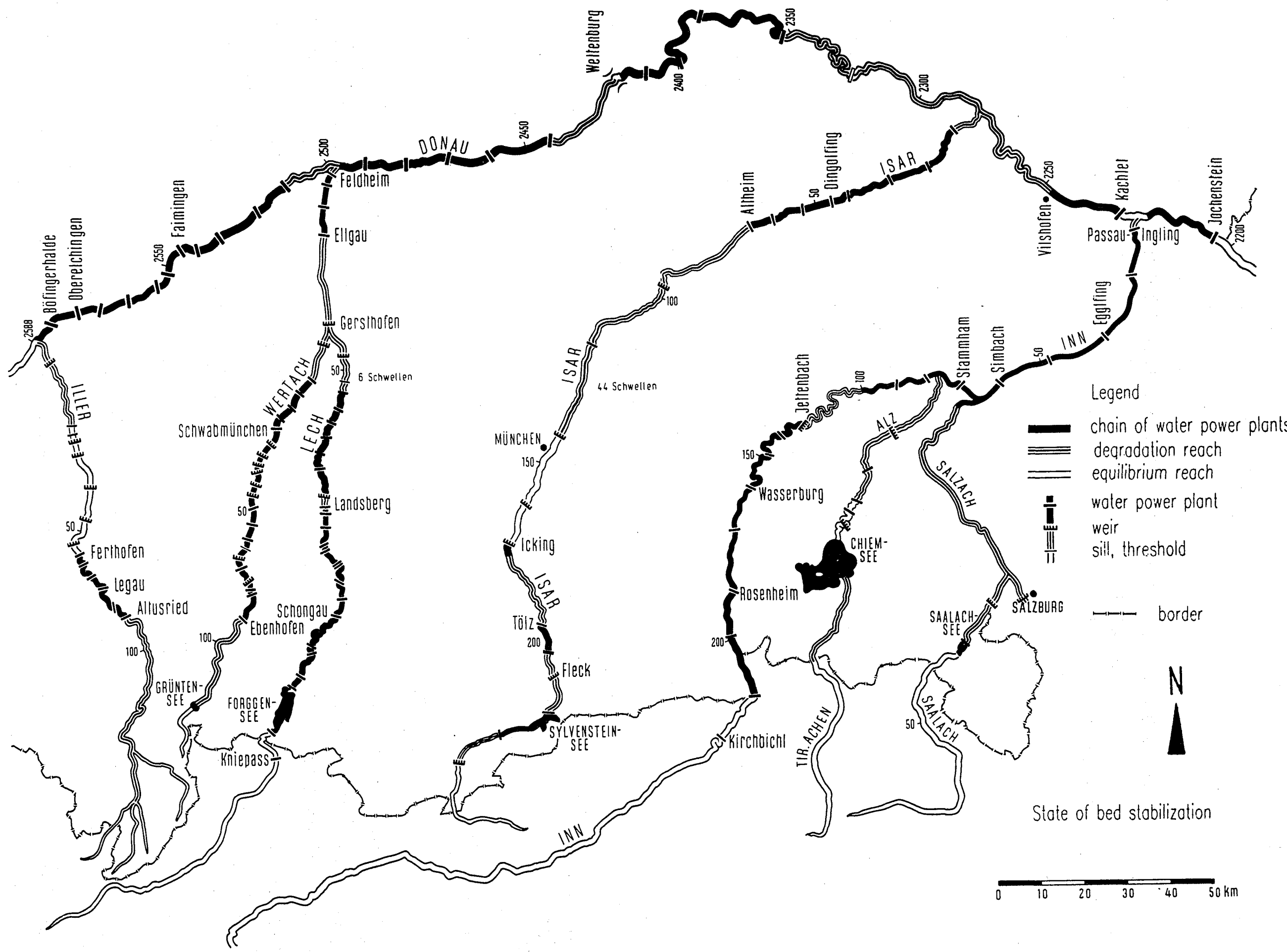

Fig. 3 The state of bed stabilization of the River Danube and its southern tributaries.

Sediment feeding

In the tributaries of the River Danube, bed load will collect in the topmost reservoir of a chain of reservoirs. If this is not replaced, there will be a deficit of bed load a few kilometres downstream of the reservoir of the same amount and size as the material removed, and bed erosion will occur. It seems reasonable to replace the material lost by removing the bed load trapped in the reservoir and reintroducing it downstream. The concept of replacing the bed load deficit in eroding reaches by downstream addition of the bed load collected in a reservoir or selectively removed in a trap, is not new. With the construction of the River Saalach dam near Bad Reichenhall 80 years ago, the water authority required that the bed load deposits should be removed from the reservoir and reintroduced downstream of the dam. However this condition was not fulfilled until 1985. Using luminescent tracers, it has been proved that this approach works in the case of the River Saalach and that the added material is transported downstream over a distance of more than 60 km (Weiss, 1991). There is, however, a question as to how far these results from the River Saalach can be applied to other river stretches. The conditions required for sediment feeding, such as same grain-size distribution and quantity, possibilities for adding and dispensing the sediment, a short transport distance from the excavation to the addition point, limited influence on and disturbance of public transport, the local environment, etc. cannot always be completely fulfilled. However, there are some possibilities in the upper River Isar and the lower River Lech to increase the low residual bed load transport effectively by feeding the river its own bed load. Critics could view this as a measure which is not creating stable and durable conditions in the conventional sense of hydraulic engineering. Against this view, however, it must be recognized that reintroducing the bed load could be seen as "understanding" the river, in contrast to traditional hydraulic engineering measures, and therefore as a contribution to up-to-date ecologically-orientated river maintenance. In this way the present form of the river could be preserved close to its natural state and bed load transport maintained. Although the residual bed load transport will be modest in comparison with the transport capacity, it should be able to balance local erosion of Quaternary sediments, which should not be underestimated.

Reservoir flushing

Transport of the bed load collecting at the head of a reservoir through the reservoir is only feasible under favourable conditions such as synchronous lowering of the reservoir level during rising flood waves and maintaining higher discharges over a period of some days. When the reservoir has silted up between dam closure and the intended flushing, bed load transport can eventually be established by dredging a flushing channel (e.g. the River Isar reservoir at Bad Tölz). When silting has progressed too far, however, flushing alone cannot achieve the transport of bed load to the downstream site (e.g. the River Saalach reservoir at Bad Reichenhall).

Remobilization of gravel banks

Especially in longer diversion reaches, gravel banks of large dimensions are often found downstream of the weir. Parts of these gravel banks can no longer function as bed forms, because the discharge regime has changed. Continuing compaction and covering with vegetation prevents mobilization and reforming of the gravel banks. In this situation, the river tries to pick up bed material from the lower parts of the bed (channel, thalweg). In order to prevent the penetration of the remaining thin alluvial layer and rapid down cutting into the Tertiary sub-layer it is recommended not only that the erodibility of the flanks of the gravel banks should be increased but also that the surface and the inner structure of the gravel banks should be ripped up and loosened and the excavated surface material deposited in the neighbouring channels.

Removal of bank protection

Partial removal of bank protection can also be useful, especially in over-narrow channels. The first attempts at using this approach were undertaken in a former braided stretch of the upper River Isar. This was being influenced by bed load retention in a reservoir, which caused extensive straightening and degradation of the channel. Because the bed load discharge could not be modified in this case, the bank protection was partly removed or no longer maintained. The river therefore had the opportunity to erode its banks and to pick up bed material. Similar considerations led to a partial removal of the bank protection within a diversion reach of the River Inn.

Modification of torrent check dams

Extensive construction of check dams as torrent control measures often leads to local stabilization of bed load, so that the supply of bed load is cut off from the river. The bed load discharge to the river is therefore stopped. Especially in rivers with degradation

Rivermorphological Investigation of a River Reach

rivermorphological stock-taking with a geological and a river historical summary investigation of specific impacts on channel formation and development	case history **(anamnesis)**
problems of sediment balance, bed load transport, passage of storage reservoirs and activating of grain reserves	chances for an improvement of bed load balance **(measures)** **therapy**
prediction of the effectiveness of bed load activating measures, if necessary in combination with other alternatives or supporting measures for channel stabilization.	**prognoses**

Fig. 4 River morphological investigations.

effects in their upper reaches, the potential for at least a partial modification of bed load retention dams to dosing dams should be considered. In this way, a downstream bed load transport can be achieved at effective discharges.

CONCLUSION

Through careful sediment management including not only bed load feeding but also a combination of remobilizing gravel banks, restoring the passage of torrent controls, reservoir flushing and removal of bank protection, it is possible to at least achieve an increase in the minimum bed load transport, so that the need for an operation in the medical sense, e.g. the construction of solid supporting structures, can be deferred and we can take care of our landscape. The long-term success of sediment management, with the objective of reducing degradation, will in many cases only be achieved using combined measures, eventually including the local stabilization of existing knickpoints. Sediment feeding should not be regarded as a universal remedy, but it should be integrated in to the overall concept of sediment management on the basis of river morphological investigations (Fig. 4).

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