The sediment budget of an alpine catchment in a scaling context

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Abstract This paper discusses the sediment budget of an alpine catchment in a scaling context. Over a three-year period, the spatio-temporal development of the sediment budget of the alpine Sölk-basin in Austria was analysed by means of monitoring and modelling. Sedimentation problems in a reservoir at the outlet of the basin required improved sediment management. From a scaling perspective, the boundary conditions and major processes operating within a catchment, such as the geomorphological setting, are controlled by its long-term development. Within this long-term development, short-term unsteady sediment supply, erosion, transfer, deposition, and remobilization processes control reservoir sedimentation and determine the appropriate management strategy. The results show that overall sediment budget management (beyond managing the reservoir itself) must address catchment analysis (down- and upscaling, the River Scaling Concept) and that a scale-oriented approach leads to sustainable development of the sediment regime.

Key words reservoir sedimentation; scaling; sediment budget

INTRODUCTION

Since anthropogenic influences have impacted the morphodynamics of river systems, one of the major boundary conditions for the abiotic and biotic conditions found in running waters has been changed significantly, namely the sediment budget (Habersack *et al.*, 2004). Under natural conditions, the sediment budget is commonly characterized by erosion in the upper parts of a catchment and deposition in the lower parts, so that any retention of sediment upstream causes a lack of material for downstream transport. At least in central Europe the consequence is an increasing discrepancy between sediment supply and transport capacity, and a lack of sediments in various regions of alpine catchments. Coarse material is frequently artificially retained in the higher parts of catchments by bed load retention basins or reservoirs for hydropower production. In the remaining free-flowing sections, the lack of bed load causes bed degradation problems, combined with ecological effects.

In order to achieve a good ecological status by the year 2015, according to the European Water Framework Directive, the sediment budget has to be "restored" in the long term. Otherwise, only hard engineering works (such as drop structures or weirs) can reduce the degradation tendency. At the same time—especially in relation to fine sediments—increasing sediment deposition in reservoirs creates severe technical (reduced energy production, dam stability, floodway functioning) and ecological (flushing of sediments, etc.) problems (Habersack *et al.*, 2001). This creates a strong

demand improved understanding and management of sediments in a catchment-wide context. A catchment-wide analysis of erosion, transfer, and deposition/remobilization remains difficult due to scale-dependent processes. The main aim of this paper is to analyse the sediment budget for an alpine catchment in a scaling context, based on the River Scaling Concept, in relation to bed load, suspended load, and sediment management.

THE RIVER SCALING CONCEPT (RSC)

The RSC differentiates five hierarchically-dependent scales, with the following two-stage procedure as the central concept (Habersack, 2000). The first stage is a downscaling phase. This phase initially examines abiotic components at a regional to catchment-wide scale, which includes the analysis of mountain orogenesis, geology, digital elevation models etc.; this allows the definition of representative sections and a partitioning of the catchment into subcatchments. The results of models and measurements applied at the sectional scale lead to a further subdivision into sections and local-scale areas. The second stage involves locating representative measurement plots at the point scale. In order to provide practical answers regarding catchment management, an upscaling process has to be performed. This mainly involves estimating, deriving, and transforming parameters—measured or calculated at the point scale. The upscaling to the catchment-wide scale consists of an integration and combination of sectional information. It is important to recognize that there are changing processes with changing scales, yielding new information at a larger scale.

STUDY AREA

The study area is the Großsölk River basin in Austria, a southern tributary of the Upper Enns River. The basin itself covers 140.9 km^2 and is drained by the Sölk, the Bräualmbach, the Hansenalmbach, the Seifriedbach, and the Strickerbach rivers (Habersack *et al.*, 2001, Fig. 1). When water diversions are considered, the area increases to 385.7 km^2. The average elevation of the basin is 1680 m above the sea level of the Adriatic (m a.s.l.). Of the area, 37% is covered by forests (Bierlinger, 1984), 28% is alpine pasture, and 21% is agricultural. The basic geological unit of the Großsölk valley is a very firm and stable gneiss-complex, whereas micaceous schist tends to be less stable. The Sölk reservoir, belonging to the Verbund (hydropower company), is situated at the outlet of the catchment in the northern part of the basin. Reservoir sedimentation results in reduced storage volume and technical problems, including turbine abrasion and dam stability.

SEDIMENT BUDGET

Due to their different transport behaviour and management requirements, coarse bed load material and fine suspended sediments are discussed separately. In general terms,

the sediment budget of a catchment consists of a comparison between erosion, transfer, deposition, and remobilisation of sediments. The basic outline of the components of the sediment budget of the Sölk basin is shown in Fig. 2.
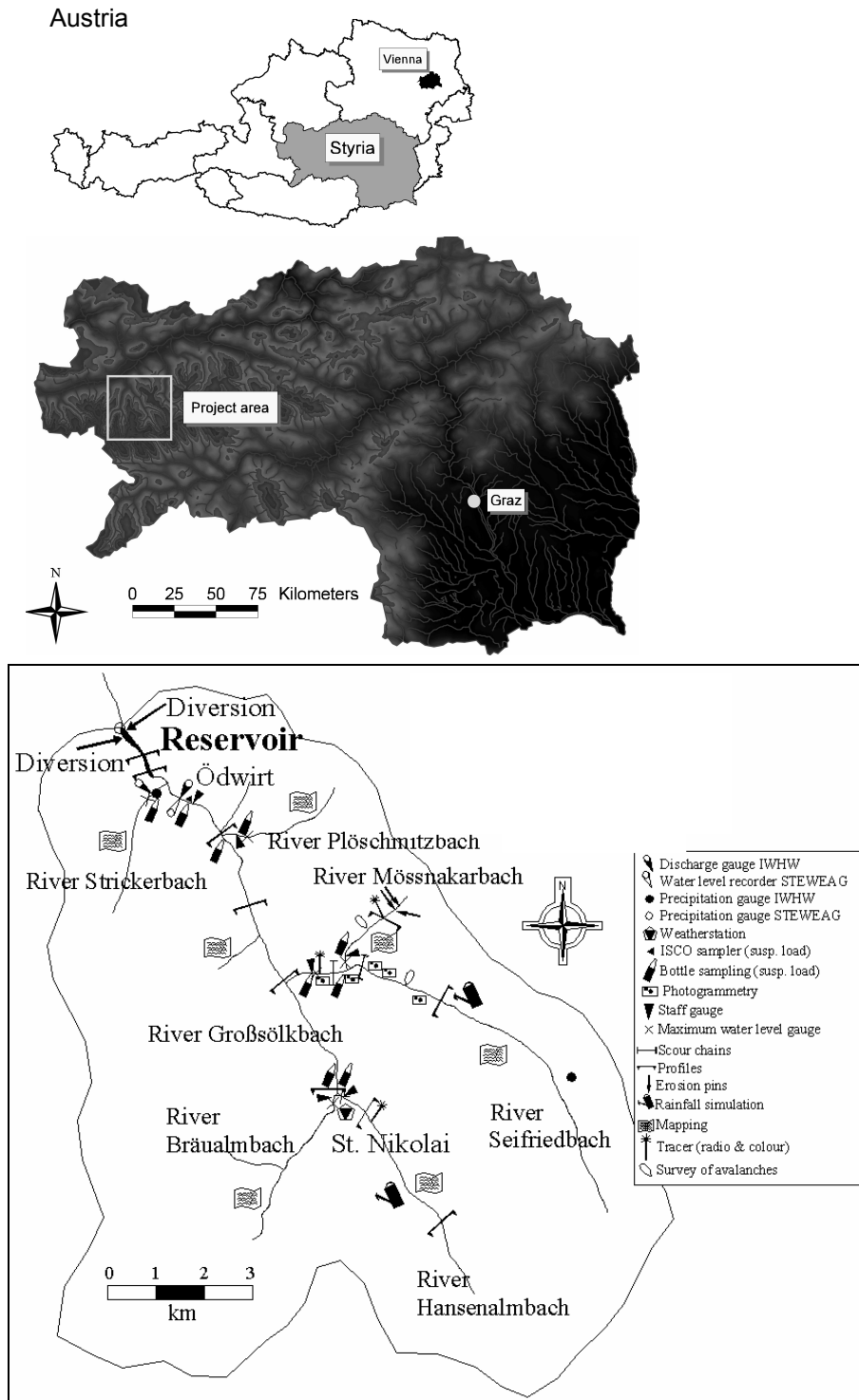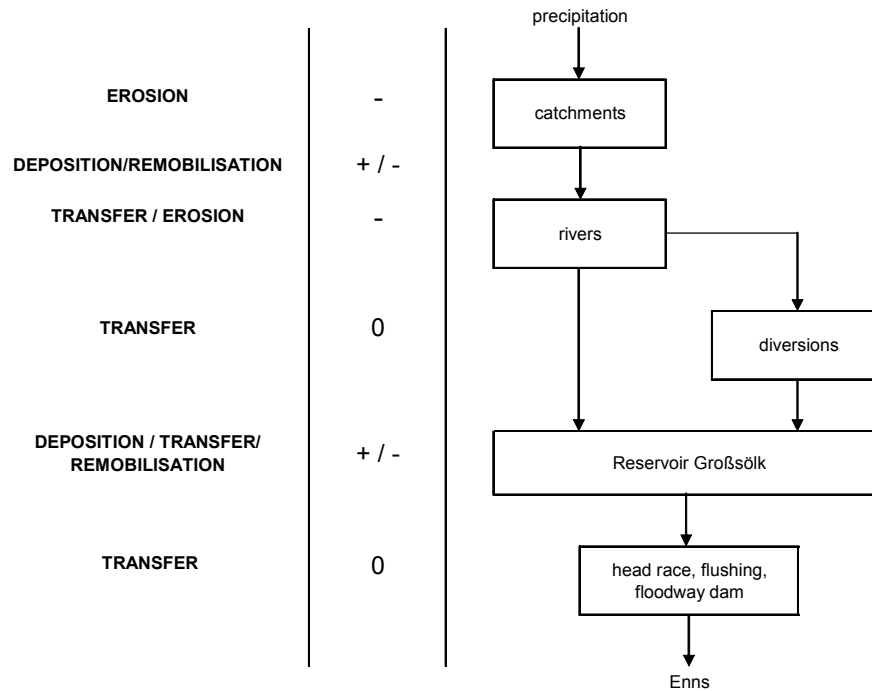

Fig. 1 The study area; the Sölk basin in Austria.

Fig. 2 Sediment budget/delivery for the Sölk basin (modified after Badura, 2002). (–: lack; +: surplus; 0: transport.)

Field measurements and numerical models were used to quantify the sediment budget. To obtain a total sediment budget, the RSC was implemented. The procedure, described below, consists of a two-stage approach: down- and upscaling.

BED LOAD REGIME

Downscaling

Continental/regional scale About 500 to 350 million years ago, the crystalline schists of this part of the Alps were marine sedimentary rocks. During the alpine orogenesis, the Variscian mountain chain (metamorphic material (i.e. crystalline schists)) was again modified, causing major fault lines and folding due to mountain range narrowing. During the later alpine cycles mountain uplift took place. At this stage, erosion commenced and this, in combination with the Ice Age, modelled the existing landscape. Wider valley sections are characterized by U-shaped main valleys and the remains of moraines, gravel terraces, and clay (Becker, 1989). The thickness of the ice sheet reached about 1100 m (Hermann *et al.*, 1999). Glacial and fluvial activity covered the rocks with coarse and fine sediments of varying thickness. Pleistocene gravel and finer material were deposited in the Sölk valley. Moraines often can be found as layers, above or in river deposits. These processes led to the existing boundary conditions (geology, geomorphology, deep-seated gravitational slope deformations (DGSDs etc.)), which have to be understood before proceeding with downscaling. Hermann *et al.* (1999) showed that DGSDs affect up to 70% of the total slopes in several areas of the basin.

Catchment scale As torrential sub-catchments play an important role in sediment delivery and transportation, their process dynamics should be estimated both qualitatively and quantitatively. In the Sölkbach valley, the torrential catchments occupy 108 km², some 79% of the whole area. Unfortunately, an area this size cannot be comprehensively monitored, at a sectional to point scale, with reasonable effort. This calls for the application of a procedure based on readily measurable parameters and sub-catchment-wide classification. This assumes that the geomorphic processes influencing the sediment dynamics are homogeneous within such sub-catchments. Geomorphic mapping of the digital elevation model yielded the following different subcatchments (Brauner, 1999; Habersack *et al*., 2001; Gamerith, 2003; Santner, 2003; Fig. 1):

(a) Zero-order catchments—immature (Ploeschmitz- and Mössnakarbach): They are very steep, and due to their steep, gorge-like middle reaches, most of the eroded material is transported directly to depositional areas.
(b) Mature alpine catchments (Seifried-, Bräualm- and Hansenalmbach): They are characterized by backward channel cutting into glacial valley fill. The sediment retention potential in the upper parts of the catchments is dominant due to flat valley floors.
(c) Intermediate type (Stricker- and Knallbach): These are catchments with a steep intermittent valley fill, and thus, limited sediment retention potential. Therefore, debris flows are the dominant sediment-transporting process during high-precipitation events.

Sectional scale Representative river reaches were selected within the three types of typical subcatchment. Mapping, sediment transport measurements, and numerical simulations were undertaken for these reaches. Homogeneous reaches were defined to estimate the sediment budget based on a balance model (Brauner, 1999; Santner, 2003).

Local and point scale Field measurements of coarse material were undertaken using erosion pins and terrestrial photogrammetry (lateral erosion in tributaries). The erosion potential was estimated based on geomorphic mapping of the tributaries. Additionally, geodetic re-surveys of representative cross sections were made, accompanied by deployment of colour and radio tracers in the rivers, to obtain a relationship between discharge and bed load transport.

Tracers showed, for example, that for mature alpine catchments, during a single event, particles were transported—depending on grain size—for a mean length of around 200 m (Habersack *et al*., 2001; Schneider, 2001). Consequently, bed load transport evidences a "time lag" effect in terms of transfer from erosion to reservoir deposition. This is accompanied by natural and artificial transport influences, such as changes in the longitudinal profile, and changes in retention basins; moreover, selective transport processes and particle abrasion during movement through the system, cause grain size reductions (Gamerith, 2003).

Upscaling

Sediment delivery of alpine catchments Based on mapping and modelling at point and local scales, sediment delivery and sediment retention potential for the seven

test catchments was estimated (Table 1). Sediment routing through the channel network was not considered. The range of values for the delivery potential and the erosion rate reflects the minimum and maximum scenarios (= worst case) and the stochastic character of process triggering (Brauner, 1999). The calculated erosion rate and retention capacity per stream length, are correlated with catchment type and hence, the spatial process pattern and linkage. The individual character of each catchment is reflected in highly variable erosion rates per unit area. These findings show the importance of individually estimating sediment delivery, transport, and retention processes in such catchments. The strong correlation between delivery potential and catchment type indicates the influence of morphology and catchment evolution, making this concept suitable for upscaling from local to sectional to catchment-wide scales. The erosion rate per unit area varies considerably (between about 153 and 7380 m^3 km^{-2}), but is largely consistent with the findings of other studies in the Alps (Tschada, 1975; Becht, 1994).

The sediment delivery potential for the Sölk River was calculated by subtracting the retained delivery potential from the maximum potential (Gamerith, 2003). In total, this yields a bed load potential of 178 000 m^3 for the whole catchment, as input to the Sölk River. The presedimentation-basin at the outlet of the catchment is dredged yearly. Between September 1999 and November 2000, about 2100 m^3 of sediment were delivered, and in the following year until mid-November about 2300 m^3 The 10-year event in July 1999 led up to 1.5 m of bed load deposition in the upper part of the reservoir, corresponding to some 2600 m^3. This comparison shows that only about 1% of potential (not including all tributaries, weathering processes, varying percentage of fine material along the rivers, etc.) sediment annually reaches the reservoir. No bed load is transported downstream of the dam, causing a lack of material below this reach.

SUSPENDED LOAD REGIME

One of the main contrasts between the bed load and the suspended load, with respect to reservoir sedimentation is that, during an event, suspended material is transported from its source to a deposition zone without a major time lag (see bed load), and a significant proportion is transported downstream.

Table 1 Sediment budgets for the test catchments (modified after Brauner, 1999).

Catchment	Catchment type	Area (m²)	Stream length (m)	Total delivery potential min (m^3)	max	Retained delivery potential (m^3)	Erosion rate per stream length (m^3 m^{-1})		Erosion rate per unit area (m^3 km^{-2})	
Hansenalm	Mature	22728700	43420	8700	33000	21000	0.2	0.8	383	528
Stricker	Intermediate	9466397	15471	4600	33600	9600	0.3	2.2	486	2535
Ploeschmitz	Zero-order	5178135	8440	3400	24900	0	0.3	3.0	657	4809
Moessnerkar	Zero-order	4607766	9653	3800	34000	0	0.4	3.5	825	7379
Seifried	Mature	26776500	66816	13300	44600	2000	0.2	0.7	497	1591
Knallbach	Intermediate	6900000	6980	2500	45000	18000	0.7	6.4	263	6522
Bräualmbach	Mature	32600000	32900	5000	15000	2000	0.1	0.5	153	460

Downscaling

Continental/regional scale, catchment scale The general regional boundary conditions have already been described in the bed load section. For later modelling purposes, the catchment was divided into a series of more-or-less homogeneous units. These units can be planes or channels, linked as a series of cascading planes and channels (Fig. 3(a)). In order to obtain the necessary geometric attributes, a GIS software package known as TOPAZ (Garbrecht & Martz, 1997) was modified and coupled with the sediment transport model KINEROS (Koboltschnig, 2001). Further input parameters were obtained by overlaying digitized land-use maps (Fig. 3(b)), geology, and features extrapolated from field measurements to the catchment scale.

Sectional scale, local to point scale Based on subcatchments and representative river sections, plots were selected for fieldwork (e.g. rainfall–runoff simulations). Water samples were collected automatically using an ISCO sampler (stage dependent). In addition, manual samples were collected along longitudinal sections and cross sections during floods, within different representative tributaries and downstream of the powerhouse, to quantify the throughput of sediment via the turbines and through the bottom outlet during flushing. In alpine catchments, the erosion of fine material occurs predominately during heavy rainfall events. Rainfall–runoff simulations were performed on several representative 80-m^2 plots distributed in the catchment. A heavy rainfall (100 mm h^{-1}) was simulated, and the runoff was measured. Besides surface runoff, the suspended sediment concentrations also were measured. This showed a significant difference between various land uses (forest and meadows deliver only about 10 to 1000 g h^{-1}, open spaces along roads or caused by avalanches yielded up to 100 000 g h^{-1}, Kohl *et al*., 2001, Fig. 4). Measurements by pump and manual sampling demonstrated the importance of large floods (e.g. 9.5 g l^{-1} during a 10-year flood compared to 0.08–0.14 g l^{-1} during minor floods).
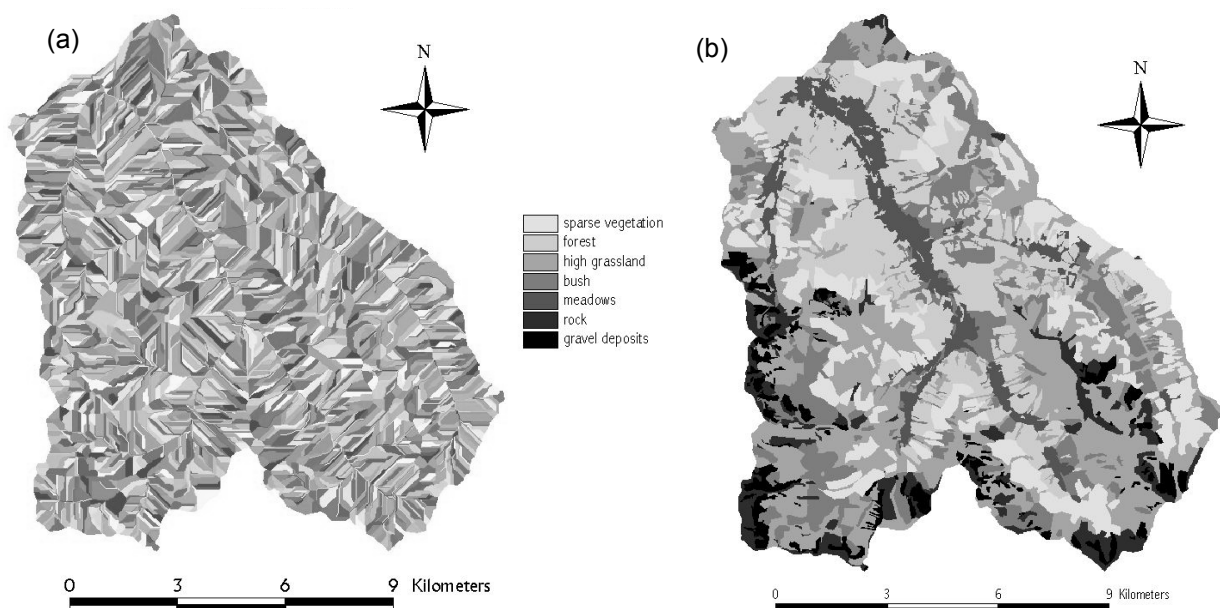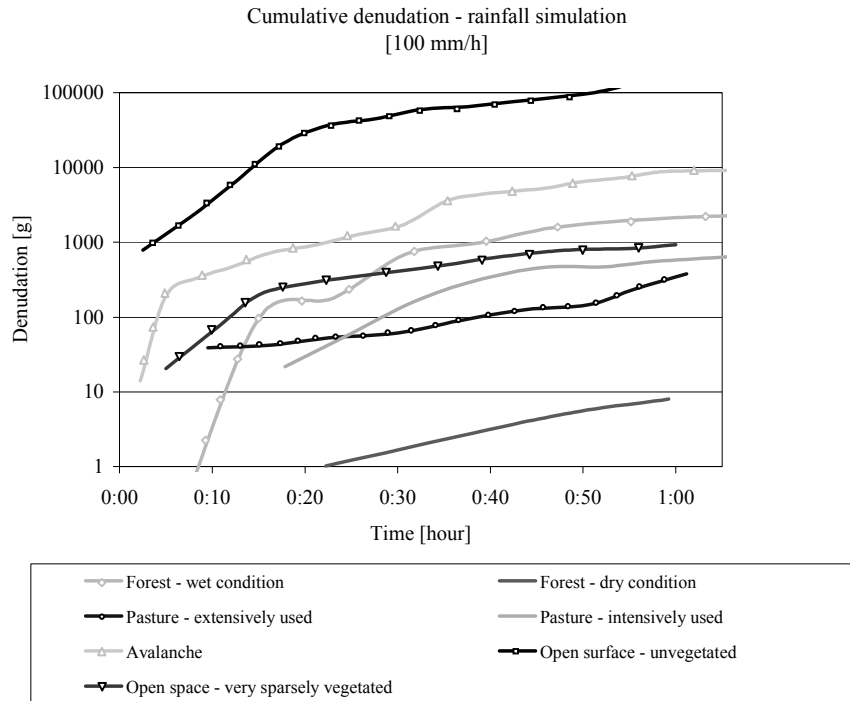

Fig. 3 (a) Delineation of the contributing areas of the Sölk catchment; (b) land use.

Cumulative denudation - rainfall simulation
[100 mm/h]

Fig. 4 Cumulative denudation of areas with varying land use (modified after Kohl *et al.*, 2001).

The information about the quantity of eroded material obtained by rainfall-runoff simulations, as well as measurements in the rivers were used as an input (calibration, validation) for the runoff-erosion model KINEROS (Woolhiser *et al.*, 1990). At the point scale, the rainfall-runoff simulation on the plots was numerically modelled, and the results used for upscaling.

Upscaling

Based on the calibrated, and later validated, KINEROS model, Badura (2002) used slope-sediment relations (result of point-scale modelling) in combination with GIS to obtain a soil erosion map of a subcatchment (Fig. 5). In practice, the potential erosion value should be considered as a qualitative erodibility index, which can be an important planning tool in management operations (e.g. land-use changes). Additionally, the fine sediment budget of the rivers was calculated based on measurements (calibration), routed by KINEROS. Unlike bed load, the suspended load originates from two other catchment areas (diversions), in addition to the Großsölk basin. Contributions from the diversions were estimated based on turbidity measurements at the intake structures. The suspended sediment load between April 2000 and December 2000 was about 17 000 t, and the value between January 2001 and October 2001 was 11 000 t. Both years were characterized by relatively low discharges. The impact of floods on suspended sediment concentration was monitored during the 10-year event in July 1999, when concentrations of 9.46 g l^{-1} were measured and approx. 53 000 t and approx. 86 000 t entered the reservoir from the study catchment and the diversions, respectively.
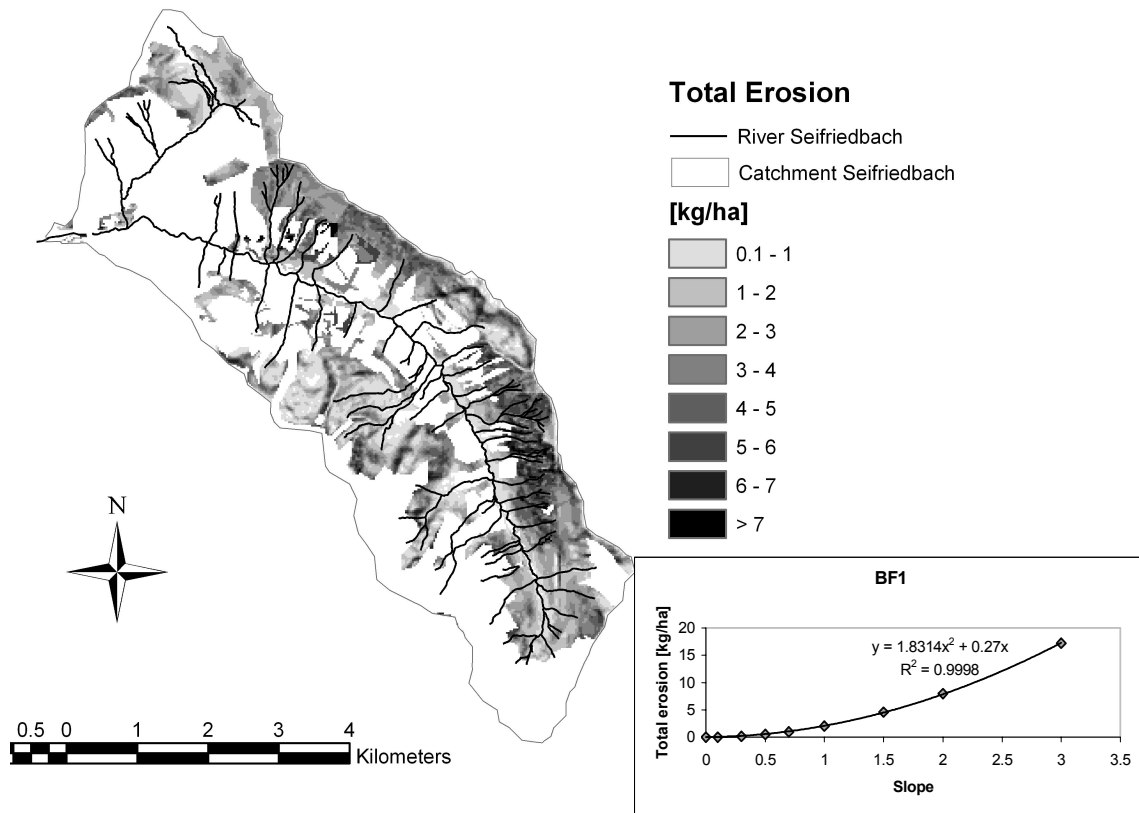
Fig. 5 Erosion potential of the Seifried subcatchment and the slope–erosion relation (insert) (modified after Badura, 2002).

Simulation of the catchment-wide erosion-transfer and deposition/remobilization Based on the calibrated and validated model, a catchment-wide simulation of erosion-transfer and deposition/remobilization was performed. An analysis of the relative contribution of various subcatchments to the overall sediment budget showed that the individual contribution of various subcatchments differed substantially from what might be expected, based purely on relative size. For example, one subcatchment delivered approx. 49% of the total sediment budget for a given event, although it represented only 27% of the total area of the study catchment (important for effective management). Within the scope of this project, besides quantifying the entire year 2000, a suspended sediment budget was established for the period between 1 January 2001 and 23 July 2001. This restricted period reflects the limited availability of turbidity data. The Großsölk catchment contributes 36% of the discharge to the reservoir, the tributaries Donnersbach/Walchenbach 33%, and the Kleinsölk 31%; hence the impact of suspended sediment should be about equally distributed. The suspended sediment load that leaves the reservoir through the turbines was determined by concentration measurements in 2000. Furthermore, the reservoir was flushed, and concentration measurements were made downstream during this event. Table 2 gives the yields of suspended sediment during the observed period (for details see Habersack *et al*., 2001).

The difference between input and output as a consequence of flushing in May 2001 shows a deficit of about 22 000 t, which is equivalent to 15 000 m^3 (assuming a

Table 2 Sediment input to the reservoir from the catchment, and output from the reservoir, 1 January 2001–23 July 2001.

Input (t)		Output (t)	
Großsölk	8322	Turbine	25220
Donnerbach/Walchenbach	7830	Flushing	22000
Kleinsölk	8570		
Total	24722		47220

mean density of 1.472 kg m^3, Schneider, 2003). This corresponds quite well with the results from a bathymetric survey performed in the reservoir, where a difference of about 15 000 m^3 was determined between April and May 2001.

DISCONTINUITIES

The transfer of sediment from erosion to deposition is strongly influenced by discontinuities which totally or temporarily reduce or interrupt sediment transport. Such discontinuities include natural depressions, lakes, or flat river reaches. Anthropogenic discontinuities include retention structures, roads, or reservoirs. The project demonstrated that, depending on the trap efficiency, up to 100% of bed load can be contained in retention structures (see Table 1, retained delivery potential). The upscaling of suspended load by KINEROS was limited due to the use of mean values for slope, land use etc., within individual planes (reaching from a channel to the divide) in the model. An Austrian Academy of Sciences' project (Habersack *et al*., 2004) showed that a more detailed calculation, based on a numerical structure that reflects the natural situation (more cells instead of one plane) is able to include discontinuities and is necessary for the upscaling process.

SEDIMENT MANAGEMENT AND GENERAL CONCLUSIONS

Management activities should begin in the sediment source areas, thus influencing transport in the river network and as well as deposition in the reservoir. According to the processes discussed in this paper, management activities should be planned at various scales. At the catchment-wide scale, measures range from flood warning systems to land-use changes such as aforestation, to reduce sediment availability. Sectional to local and point scale activities include the erection or, better, the management of hydraulic structures, such as retention basins, river regulation, and bank protection measures to modify erosion and sediment transfer. The main aim is to achieve a natural balance between erosion, sediment transfer, and sediment deposition; this balance currently is missing due to the construction of additional infrastructure (e.g. roads) and land-use effects. Clearly, at the local to point scale, management activities have to be directed toward the reservoir itself (e.g. sluicing, density currents, dredging, changes in operation, reservoir geometry, by-pass operations, bottom outlet configuration, flushing tunnels). Catchment-oriented management requires a study of local sediment budgets in a scaling context, including both measurements and model-

ling, with respect to discontinuities, and the spatio-temporal variability of sediment transport at various scales.

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