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Sediment budgets, dynamics, and variability: new approaches and techniques

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Abstract The papers for the theme "Techniques" are considered within the framework of a dynamic sediment budget. Gaps in knowledge of such a framework are identified, and the contributions of the papers considered against the gaps. The key gaps are documentation and understanding of the dynamics of sediment budgets, the scale dependence of the dynamics, and the spatial variability of the components of budgets.

Key words sediment budget; catchment dynamics; knowledge gaps

INTRODUCTION

Sediment budgets are a useful and powerful conceptual framework for examining the relationships between sources, sinks, river transport, catchment yield, land use, climate variability/change, seismicity and isostatic adjustment. Major progress has been made over the last 30 years in methods for developing sediment budgets, with mean annual sediment budgets being developed from many parts of the world. There has also been progress made in studying the dynamics of budget components and, in some cases, of whole catchment budgets. But much remains to be done (see Trimble, 1999; Wasson & Sidorchuk, 2000; Phillips, 1986). The development of new techniques now makes it possible to take the "next step" in sediment budget construction and analysis.

Mean annual budgets are relatively easy to construct using: measurements of sediment accumulation in reservoirs, farm ponds and lakes; rating curves of sediment concentration and flow duration; field surveys of channel change; tracers of sediment source; and models such as the universal soil loss equation (see Reid & Dunne, 1996, for a survey of methods and their applications). These budgets can be used to judge the quantitative significance of various sources (e.g. sheet erosion *vs* channel *vs* landslides erosion) for different catchment sizes in different parts of the world, and also for targeting catchment management. They are usually averaged over years to decades. More such budgets are required, particularly in dryland and mountain regions where they are currently under-represented.

An equally pressing need is for studies of the temporal dynamics of budgets in catchments with different source dominance, for both large and small catchments, and for catchments where perturbation by land use and climate change can be well documented (Wasson, 1996).

Many studies of the dynamics of individual budget components already exist; for example, hillslope erosion by sheet and rill processes, flood plain accumulation rates, river suspended sediment transport, channel bed load accumulation and transport, landslide frequency and magnitude (see Reid & Dunne, 1996). However, studies of the dynamics of the coupled system (i.e. the whole system of interlinked budget components) are rare, but urgently needed. This need arises from the likelihood that the time-varying sediment yield is an emergent property of the interaction of the many components of the catchment, and therefore cannot be estimated directly from characteristics of a catchment. This is not the same as saying that the average yield cannot be estimated from the average characteristics of catchments (Milliman & Syvitiski, 1992). But even these average relationships can be misleading.

Trimble (1999) has been following the course of change in the Coon Creek catchment in the USA for decades, and can now show that catchment yield has not changed since 1853 despite marked changes in land use. The buffering provided by storage change has decoupled yield from land-use change. Therefore there is no simple relationship between soil conservation and/or best agronomic practice and sediment yield in such a system. We urgently need to know how typical such a system is to judge whether or not the monitoring of yield can tell us anything about catchment change (Wasson & Sidorchuk, 2000).

Wasson *et al.* (in preparation) show, in the Kalgan catchment in southwest Western Australia, that removal of trees along the valley floor, and cultivation in the same area, during the 1910s and 1920s led to incision and a large increase in sediment yield. Later clearance of tree cover over much of the rest of the catchment increased hillslope erosion at a time when incision of valley floors was waning. Hence, after an increase following initial incision, yield remained approximately constant because a new sediment source became available, thereby offsetting the effect of declining yield as the incisions stabilized.

Examples of these kinds are needed to explore the idea of sediment yield as an emergent property of a complex system. Static, time-averaged budgets cannot be used for this task, and usually the length of record from conventional instrumental monitoring is inadequate to detect the time-varying properties of yield. Studies of yield and budget components over decades to centuries, and sometimes millennia, are needed. Stratigraphic methods, tracers, high-resolution chronometers, sedimentological analyses, and coupled systems dynamic models are therefore required.

Delays in the movement of sediment through catchments are fundamental properties of the dynamics, created by lags between inputs and outputs to sinks and by transit times. Traditional budgets can be used to calculate transit times, but require steady-state assumptions. High quality time series data derived for budget components for long periods can also be used to estimate transit times. One of the most promising methods relies upon the clocks present in particle-reactive radionuclides, a technique that has thus far not received a great deal of attention.

The papers presented in this session of the conference deal with some aspects of the priority issues raised above. They are grouped below, and their contribution to the priority issues considered. In the Concluding Remarks, the major gaps in knowledge are identified in summary form, along with comment about the application of developing techniques and methods.

SEDIMENT BUDGET COMPONENTS

Flood plains

Delays in river catchments between, for example, a yield response to a perturbation caused by land use and/or climate change, are largely the result of deposition of material in sinks (also called stores or depositional stocks). Sediment released by erosion of hillslopes and old alluvium by sheet, gully and channel erosion is stored in fans, channel beds, flood plains, reservoirs and farm dams. This material has a residence time determined by the difference in time between deposition and re-entrainment. Particles released into a river also have a residence time determined by their velocity and whether or not they are deposited before they become part of the catchment yield. Flood plains are probably the most important storage along rivers, and so play the largest role in creating the delays that are a characteristic feature of the dynamics of a catchment's sedimentary system. Flood plains also are important ecosystems, and floods play a crucial role in connecting rivers to wetlands. Flood plains are also repositories of sedimentary and pollutant histories, providing information about the evolution of catchment state. But the interpretation of these histories as responses to perturbations requires information about delays, a paradoxical situation given the importance of flood plains as a major source of delay. This paradox is generally not recognized, and presents a methodological problem that is largely unresolved.

Flood plains are not homogenous, either along a river or between rivers. Knowledge of spatial variability of flood plains is limited to a few cases, but is needed to estimate spatial variations of sedimentation rate (storage rate), the role of substrate in flood plain ecosystems, and for management. Foster *et al.* (2002a) use multivariate statistical analyses of 17 textural, nutrient, and major element variables to demonstrate differences in sediment character along the lower Balonne River flood plain in southeast Queensland, Australia. This is a lowland river with a catchment area of 87 300 km^2, with multiple channels and complex landform patterns. The differences in sediment character are related to variations in energy conditions, flow regimes and sediment supply, although quantitative relationships between theses variables are yet to be determined.

Spatial variations in flood plain sediment and landforms are also likely to be reflected in vegetation distribution, complicating the modelling of flooding and sedimentation. While empirical estimates of flood plain sedimentation are needed for a great many rivers, generalization of these results by modelling will be the only way to reach widely useful conclusions. The hydraulic roughness of flood plains is a key variable in any model, and Asselmann *et al.* (2002) have applied laser altimetry to aid the mapping of roughness. They demonstrate that this technique, when calibrated by ground observations, can be used to map hydraulic roughness caused by vegetation. But this technique is labour intensive and is likely to be applied sparingly. Other techniques will be needed for widespread use.

One of the most commonly used methods for empirically determining sedimentation rates on flood plains relies upon the fallout radionuclide ^{137}Cs. Van Wijngaarden *et al.* (2002) have used this technique, along with the ^{206}Pb/^{207}Pb ratio, to estimate ages at various depths in the flood plain of the River Meuse in The Netherlands. They have developed a scanning device for measuring the ^{137}Cs content of cores, speeding up the analyses and thereby allowing more cores to be analysed. This is necessary given the spatial variability of sedimentation, as demonstrated by Foster *et al.* (2002a), van Wijngaarden *et al.* (2002) also show the utility of lead isotope ratios, determined by pollution from leaded petrol. The two techniques give essentially the same sedimentation rates, showing that the possible effect of delay between ^{137}Cs and Pb fallout and inclusion in flood plain sediments is small and not a serious constraint on these techniques as chronometers. The reason for this conclusion is that the delay, if present, is likely to be different for the two techniques. Agreement of results is therefore heartening, but surprising given that some of both the Cs and Pb must have been attached to particles that had been labelled upstream. It would therefore be useful to compare the total ^{137}Cs and Pb isotope inventory in the sediment with the direct atmospheric input in this area. These two quantities should be identical if upstream sources of Cs and Pb are trivial. Measurement of ^{137}Cs in modern sediment would therefore be useful, and if the surface concentrations in the flood plain are indicative, there is ~7 Bq kg^{-1} of ^{137}Cs being deposited today. This contradicts the notion of zero delay and zero ^{137}Cs-labelled sediment from upstream. These issues need clarification.

Another empirical investigation by Walling & Owens (2002) uses ^{137}Cs to estimate flood plain sediment accretion along the River Swale, Yorkshire, UK. In addition, P and heavy metal deposition was measured for modern floods. By comparing accretion rates of both sediment and pollutants with measured transport rates in the river, losses to flood plains have been calculated. Flood plain deposition accounts for 27% of the suspended sediment input to the main channel, and between 14 and 46% of the sediment-associated contaminants. The range of values for the contaminants reflects the proximity of sources to the flood plains. High losses occur closest to the source.

The loss of 27% of sediment in the River Swale is compared with 39% in the River Ouse and 47% in the River Tweed in Scotland and 39–71% in the Brahmaputra River. These values, and others that can be deduced from average annual sediment budgets, support the idea that flood plain sedimentation is quantitatively important and is likely to be the most significant cause of delays.

The absence of a paper demonstrating the power of small-sample optically stimulated luminescence dating to determine sedimentation rates on flood plains, and in other bodies of sediment, is disappointing. Major advances are likely in the near future using this technique.

Transport in rivers

The transport, or flow, of sediment in catchments can be estimated by measuring changes in storages because transport is equal to change in storage. But this measurement can be very difficult, and prone to large errors. Therefore, the direct measurement of sediment flux in rivers is preferable, although it is also a very difficult matter.

The estimation of bed-load transport has been the most difficult to make. Hicks *et al.* (2002) used digital photogrammetry, airborne laser scanning, and ground survey of a braided reach of the Waimakariri River, in New Zealand, to investigate morphological change of the bed. Insights into morphological change and processes are provided, of a kind not previously available. The potential to use these techniques to investigate bed load transport seems obvious, particularly to compare the estimate based upon remote sensing with an existing estimate of transport rate based on ground survey. It is only by innovative approaches to this problem that we can break free of the "rule-of-thumb": bed load is 10% of the total load.

For many rivers in the world, remote sensing combined with key ground observations can provide the starting point for quantitative analysis. Gupta & Ping (2002) demonstrate this approach for the Mekong River, showing the untapped value of archived satellite images. So much has been promised by remote sensing, and the failure to realize the promise is partly the result of geomorphologists failing to recognize the values of the archives.

At the other end of the analytical spectrum are mathematical models of river sediment transport and morphological change. Cao & Carling (2002), in a very important paper, raise fundamental questions about computational models, of the coupled flow–sediment–morphology system. It is stimulating to find expert modellers prepared to conclude what many have intuitively felt: "model calibration can be subjective, verification is impossible and validation does not necessarily establish model truth." This conclusion is profoundly important for the users of model output and for those who would couple together complicated models. Cao & Carling (2002) observe that considerable expertise, physical insight and experience are needed to both use these models and understand their output.

The healthy relationship between empiricism and modelling will be with us for some time to come, having survived the recent exaggerated claims for modelling. That empiricism is alive and well is demonstrated in the paper by Gölz (2002); why else would 28 000 t of gravel be tipped into the Rhine? River-bed degradation downstream of weirs and dams is common, and artificial bed-load replacement is important in many rivers to overcome the problem. To optimize bed-load management, the fate of added bed load needs to be known.

The granite gravel added to the river was traced, and mixing and dispersion determined. While this is a very particular study of bed load, it has provided insights into both processes and patterns of dispersion that might also apply to natural settings such as a point input of coarse debris from a landslide.

The transit time of sediment in a river is an important aspect of catchment dynamics, and is of practical importance because of, for example, the likely delay between ameliorative catchment management, through soil conservation measures, and a response in sediment transport rate. Transit times can be calculated from budgets, by dividing the long-term average input rate by the output rate. For example, in the 130 km^2 Jerrabomberra Creek catchment near Canberra in Australia, suspended sediment has an average transit time in the main channel of ~10 years, and bed load takes an average of 100 years to move through the main channel (Wasson *et al.*, 1998).

Wallbrink *et al.* (2002) use the mass balance of ^{210}Pb and ^{137}Cs in eroding soil and river sediments to calculate sediment residence times in the Brisbane and Logan rivers in southeast Queensland, Australia. For <10 μm sediment, the maximum residence time is 21 years in the Brisbane River (catchment area of 10 060 km^2) and 9 years in the Logan River (catchment area of 2435 km^2). These estimates are dependant upon the assumptions used in the calculation, particularly the thickness of the "active layer" of sediment in the river beds. Ranges of residence times from 0 to 21 and 0 to 9 years result. For these estimates to be more useful, firm evidence of the thickness of the "active layer" is required.

While these estimates of in-channel residence times are highly uncertain, they suggest decadal delays between soil conservation and detectable changes in river sediment transport rates. Here is a significant clue that monitoring to detect effectiveness of catchment management will need to be long term.

Sediment sources

A quantum of sediment at any point in a catchment is usually a mixture of material from various sources; unless it is the result of a single input like that simulated by Gölz (2002). These sources may be spatially distinct, where different tributaries drain rocks and soils of very different character and erodibility, and/or may be acted upon by different processes, such as sheet erosion or landsliding. The physico-chemical properties of spatially different sources, and of topsoils *vs* subsoils, can be used as fingerprints (e.g. Olley et al., 1993; Kelly & Nater, 2000). The properties of sediment sampled downstream can be compared with the fingerprints and be used, under certain circumstances, to estimate the proportionate contribution from various sources. This a very useful tool to identify catchment management priorities and is being used to understand the differences in source types and dominance in various geomorphic regions of the globe.

Small *et al.* (2002) recognize the following problems with the approach: inherent variability of source properties; the number and distribution of sources; the discriminating power of different tracers; numerical issues with unmixing models; nonlinear additivity, tracer transformation, and tracer enrichment. A Bayesian statistical framework is employed by these authors to investigate two issues: source contributions and source variability. Given the importance of tracers in sediment budget construction, especially where high quality instrumental monitoring is not available, this study is welcome.

SEDIMENT BUDGET

The two papers on whole sediment budgets use very different approaches. Foster *et al.* (2002b) combine environmental history, analysis of lake sediment, chronometry, tracers, and geochemistry. De Boer & Ali adopt entirely a modelling approach.

Foster *et al.* (2002b), from an analysis of changes in lake sedimentation history, infer periods of catchment disturbance. But here we encounter the problem of delays once again. Without knowledge of the transit times of sediment in a catchment, how can a record of change in a lake be interpreted in terms of catchment disturbance? Foster *et al.* (2002b) working in a catchment of only 2.5 km^2, are not likely to be troubled by this problem, but studies in large catchments will be. Interestingly, Foster *et al.* (2002b) interpret ^{137}Cs and ^{210}Pb, in the lake sediments, as both chronometers and sediment source tracers, an inappropriate approach in many settings.

The paper by De Boer & Ali (2002) is very interesting. Based on a simple cellular model of a catchment in which there is no distinction made between hillslope and channels, the model indicates that total sediment yield varies over more than three orders of magnitude for rainstorms of the same magnitude. According to the model results, these variations in yield are not the result of external factors. They reflect the recent sediment dynamics of the catchment. So yield is an emergent property of the interactions between the many components of the catchment and is not a simple function of disturbance.

Foster *et al.* (2002b) by contrast, assume that variations in yield, as measured in a lake, are a direct function of catchment disturbance. Therefore, a ^{137}Cs peak in a core is interpreted as a result of topsoil erosion following ditch construction. The conclusion of De Boer & Ali (2002) that yield variation is a function of the history of sediment dynamics is consistent with Trimble's (1999) conclusions. There is no straightforward relationship between rainfall magnitude and sediment yield in such a catchment. This echoes a conclusion by van Wijngaarden *et al.* (2002) that there is no correlation between flood plain sedimentation rate and the magnitude of river sediment flux. Hydraulic factors are involved in explaining this lack of relationship, calling into question the use of flood plain records to reconstruct river sediment fluxes.

CONCLUDING REMARKS

The availability of chronometers, source tracers, and computer models opens new opportunities to investigate the temporal dynamics of catchment sediment budgets. New remote sensing techniques, and the combination of old techniques in new ways provides new insights. But as we explore temporal dynamics, new paradoxes are found; or at least suspected. Delays are pervasive, so that yield change may be massively out of phase with triggering disturbances and there is no correlation between yield and rainfall and runoff. Models of such a system, which are only appropriate for years rather than decades, will be unable to provide insights into important catchment dynamics. Systems models that incorporate long-term scales are essential. Moreover, the usual method by which lake or reservoir sedimentary records are interpreted in terms of overall catchment change, as if transit time of sediment is instantaneous, will need careful reconsideration.

Spatial variability is as important and techniques are rapidly evolving to examine this issue at a wide range of scales. Remote sensing for reconnaissance and detailed examination of a river reach can now be used to examine temporal dynamics as well. The spatial dependence of temporal change is a key research topic for the future.

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