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The catchment sediment budget as a management tool

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ABSTRACT

There is increasing recognition that fine sediment represents an important diffuse source pollutant in surface waters, due to its role in governing the transfer and fate of many substances, including nutrients, heavy metals, pesticides and other organic contaminants, and because of its impacts on aquatic ecology. Catchment management strategies therefore frequently need to include provision for the control of sediment mobilisation and delivery. The sediment budget concept provides a valuable framework for assisting the management and control of diffuse source sediment pollution and associated problems, by identifying the key sources and demonstrating the importance of intermediate stores and the likely impact of upstream mitigation strategies on downstream suspended sediment and sediment-associated contaminant fluxes. Accordingly, the utility of the sediment budget concept for catchment management is further discussed, by introducing examples from several contrasting river basins.

1. Introduction

Growing recognition of the important role of fine sediment in the transfer and fate of nutrients and contaminants through both terrestrial and aquatic systems (e.g. Kronvang et al., 2003; House, 2003; Collins et al., 2005; Owens et al., 2005; Carter et al., 2006; Horowitz et al., 2007), and in the degradation of aquatic habitats, including fish spawning gravels (e.g. Newcombe and Jensen, 1996; Acornley and Sear, 1999; Suttle et al., 2004), has emphasized its wider environmental and ecological significance as a diffuse source pollutant. Effective sediment control strategies are therefore a frequent requirement in catchment management plans, in order to reduce the associated problems.

The precise link between upstream erosion and sediment mobilisation and downstream sediment yield and contaminant transfer involves many uncertainties, due to sediment retention and both short- and longer-term storage at intermediate locations, such as the foot of slopes and the river channel and its floodplain. The proportion of the sediment mobilised within a catchment that is intercepted and stored during transfer or delivery through the catchment will frequently exceed the proportion exported (Slaymaker, 1982; Phillips, 1987; Trimble, 1995). From a management perspective, it is therefore essential to consider the sediment system in its entirety, as opposed to focussing on the downstream fluxes. The sediment budget concept provides an effective basis for representing the key components of the sediment delivery system within a catchment and for assembling the necessary data to elucidate, understand and predict catchment sediment delivery (Swanson et al., 1982; Reid and Dunne, 1996; Renwick et al., 2005; Owens, 2005; Rommens et al., 2006). However, despite its clear utility for catchment management and in the design and implementation of measures for mitigating sediment-related diffuse source pollution, few practitioners are familiar with the concept, the various approaches that can be used to construct a sediment budget or indeed examples of their application (Reid and Trustrum, 2002). There is substantial scope for policy makers and catchment managers to make greater use of the sediment budget concept as a practical framework for targeting

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mitigation strategies (e.g. Wilkinson et al., 2005). Equally, the budgeting approach offers a useful means of improving our understanding of catchment response to different land use scenarios and management programmes, as well as longer-term climate change (Walling, 1995; Summer et al., 1996; Wasson et al., 1998).

2. The sediment budget concept

As a concept, the sediment budget approach was first applied over 40 years ago (e.g. Rapp, 1960) and it is readily applicable at the catchment scale, which is now widely adopted as the most appropriate spatial unit for characterising and managing diffuse source sediment problems. Based on a mass balance of sources, sinks and outputs, the sediment budget of a catchment provides an effective means of addressing the need for an holistic understanding of the interaction and linkages between sediment mobilisation, transport, storage and yield (Dietrich and Dunne, 1978; Slaymaker, 2003). The utility of the concept in relation to catchment management lies in the identification of the key sources, stores and transfer pathways and thus the sensitivity of a catchment to perturbations in either intrinsic or extrinsic controls. The sediment delivery ratio, which expresses the ratio of the sediment output or sediment yield from the catchment to the total sediment mobilisation within the catchment, provides a valuable measure of the importance of storage and thus of the overall catchment response. What is now widely recognised to be a classic example of the value of applying a sediment budget approach in a management context, is provided by the work of Trimble (1983) in the 360 km^2 Coon Creek catchment in Wisconsin, USA. This work provides a clear example of how the sediment budget approach can help improve understanding of catchment response to mitigation programmes. Sediment budgets for this catchment were established for two periods, 1853–1938 and 1938–1975, using a range of morphological, and sedimentological evidence, coupled with available prediction techniques (see Fig. 1). During the first period, poor land management caused severe soil erosion, although, as the budget indicates, a major proportion of the mobilised sediment was stored within the basin and only ca. 5% of the mobilised sediment was transported out of the basin. During the subsequent period 1938–1975, the widespread application of soil conservation measures resulted in soil erosion rates being reduced by ca. 25%. However, the sediment yield at the catchment outlet remained essentially the same, due to the low proportion of the sediment mobilised by soil erosion previously reaching the catchment outlet and the remobilisation of sediment stored in the tributary and upper main valleys during the second period. Thus although the application of soil conservation measures considerably reduced on-site problems of soil degradation, they had negligible impact on downstream sediment loads and associated water quality problems. From the latter perspective, the implementation of improved land management and soil conservation measures within the catchment could be seen as having been of very limited benefit.

Walling (2006) has highlighted a paradox associated with the application of the sediment budget approach, whereby,

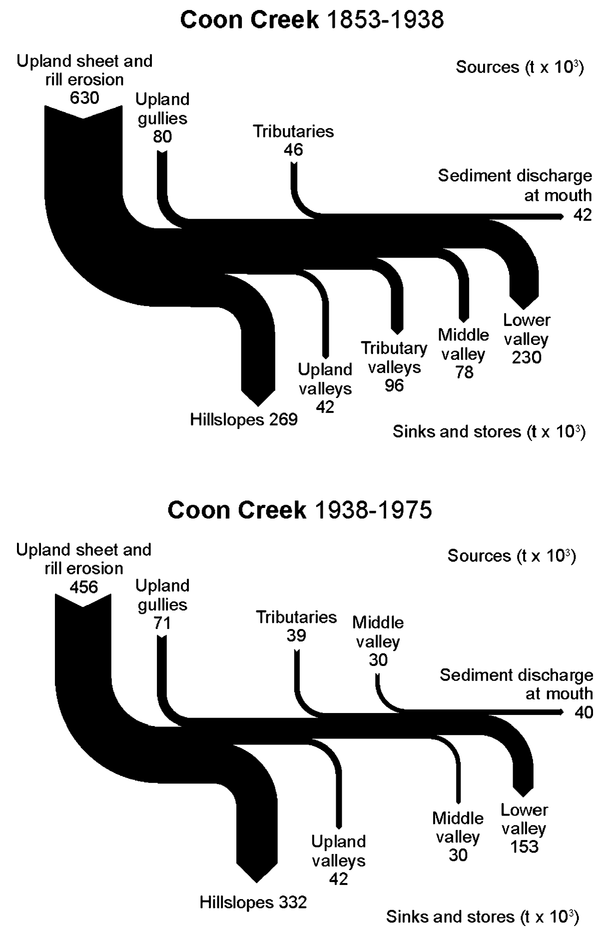

Fig. 1 – The sediment budget for Coon Creek, Wisconsin, USA for the periods 1853–1938 ands 1938–1975 (based on data presented by Trimble, 1983).

despite its obvious utility, it has proved difficult to assemble the necessary information to establish a reliable sediment budget for a catchment and the approach has therefore not been widely applied to support catchment management. In the case of the sediment budget for Coon Creek presented above, the aim was to highlight key differences between the two periods and the budget was based primarily on broadscale generalisations of the catchment behaviour, rather than measurements of the processes involved. In most studies aimed at establishing the contemporary sediment budget of a catchment, with a view to assessing the efficacy of potential mitigation measures in reducing downstream sediment fluxes, there will be a need for more detailed information on the sources, sinks and fluxes involved. Sediment mobilisation, transport and storage are characterised by appreciable spatial and temporal variability (Walling, 1998) and it is necessary to take account of this variability when constructing a sediment budget.

There is no widely accepted or generally applicable procedure for establishing a comprehensive sediment budget for a catchment, because it has proved difficult to adapt traditional measurement techniques to address the spatial and temporal variability associated with the operation of sediment mobilisation and transfer processes at the catchment scale. Traditional techniques, including the use of erosion pins, profilometers and photogrammetry to document erosion rates, and the use of sediment traps or post-event surveys to document sediment storage, possess many logistical and operational limitations as well cost constraints (Collins and Walling, 2004). The potential for coupling recent advances in sediment tracing technique with more traditional monitoring techniques has, however, provided new opportunities to assemble the information required for sediment budget construction (Walling, 2003, 2004, 2006; Walling et al., 2001, 2006).

3. Sediment budget construction

The demand for more holistic information to underpin sediment management and control strategies has strengthened the need for new approaches to assembling the data required to construct reliable catchment sediment budgets. One important development in this context has been the use of fallout radionuclides as sediment tracers (Walling, 2004). Because such fallout radionuclides are commonly rapidly and strongly adsorbed by soil particles upon reaching the catchment surface as fallout, their subsequent redistribution proves a means of tracing sediment mobilisation, transfer and deposition (Ritchie and McHenry, 1990; Zapata, 2002). Assessment of the post-fallout redistribution of the radionuclides offers a basis for documenting time-integrated rates and patterns of sediment redistribution and storage within the catchment system. The majority of studies employing fallout radionuclides to trace sediment mobilisation and delivery have been based upon measurements of caesium-137 (^{137}Cs) activities and inventories. Caesium-137 is an artificial fallout radionuclide produced by the testing of thermonuclear weapons, during the period extending from the mid-1950s to the early 1960s. Upon release into the stratosphere, ^{137}Cs was distributed globally and deposited as fallout, with the magnitude of the latter reflecting annual precipitation and location with respect to weapons testing (Walling, 2002). Although ^{137}Cs fallout declined to near zero by the late 1970s, its relatively long half-life (30.2 years) ensures that detectable amounts remain in soils and sediment 40 years after the main period of fallout in the late 1950s and the 1960s. By establishing the current distribution of ^{137}Cs in the landscape, it is possible to assess soil and sediment redistribution during the period elapsed since the time of the main period of fallout and the time of sampling. Collection of soil cores, measuring their ^{137}Cs content using gamma spectrometry and comparing their inventories with the corresponding estimate for an undisturbed reference site experiencing neither erosion nor deposition, using appropriate conversion models (e.g. Walling and He, 1999), provides a means of documenting medium-term (i.e. ca. 50-year) rates of gross erosion, deposition and net soil loss (e.g. Walling et al., 1999a; Collins et al., 2001). Similarly, the ^{137}Cs inventories measured in floodplain cores can be compared with those of a nearby reference site to estimate mean annual sedimentation rates (Walling and He, 1997). The ^{137}Cs approach has a number of key advantages relative to more conventional measurement techniques, including the need for only a single site visit, the potential for retrospective documentation of medium-term (~50 years) rates of soil and sediment redistribution using a limited number of contemporary measurements and the provision of point estimates of erosion and deposition, which can be used to elucidate spatial patterns and which can be extrapolated to provide catchment scale information (Walling and Collins, 2000).

Another tracing technique capable of providing useful information to assist in constructing catchment sediment budgets is the fingerprinting approach. Sediment source fingerprinting can generate valuable information on the relative importance of individual potential sources contributing to the downstream suspended sediment flux of a river. Such information is clearly of considerable value both for providing information on the linkages between upstream sediment sources and downstream sediment yield required to construct a sediment budget and more directly for targeting sediment control measures and thus optimising the effectiveness of such work in reducing downstream sediment fluxes. Although the source fingerprinting technique has been successfully deployed to investigate spatial sediment sources, classified in terms of discrete geological zones (Collins et al., 1998) or tributary sub-catchments (Collins et al., 1996), information on individual source types e.g. surface soils supporting different land use and eroding channel banks (Collins et al., 1997; Walling et al., 1999b; Motha et al., 2004) is commonly of greater value in a management context. The fingerprinting approach is founded upon the link between the geochemical properties of sediment and those if its sources. On the assumption that the potential sediment sources can be reliably distinguished by their geochemical properties or 'fingerprints', the provenance of the sediment can be established by comparing its properties with those of the sources, using a numerical mixing model coupled with uncertainty analysis.

In the absence of a well-defined single procedure for assembling the information required to establish a sediment budget, ongoing work by the authors has focused on developing and testing an integrated approach, which combines a number of complementary techniques, including both sediment tracing and more traditional monitoring. These techniques include the use of fallout radionuclides to estimate soil redistribution and floodplain deposition rates, sediment fingerprinting to establish sediment sources, more traditional sampling techniques to document storage of fine sediment on the channel bed and continuous monitoring using turbidity sensors to quantify the suspended sediment flux at the catchment outlet (Walling and Collins, 2000; Walling et al., 2001, 2002, 2006).

4. Examples of sediment budgets and their utility for sediment management

The sediment budget provides a sensitive indicator of the sediment response of a catchment (Phillips, 1991; Nagle et al., 1999; Walling, 1999) and an effective means of targeting mitigation measures to optimise their effectiveness in reducing the downstream sediment flux and assessing their likely impact on that flux. To demonstrate this utility, it is useful to

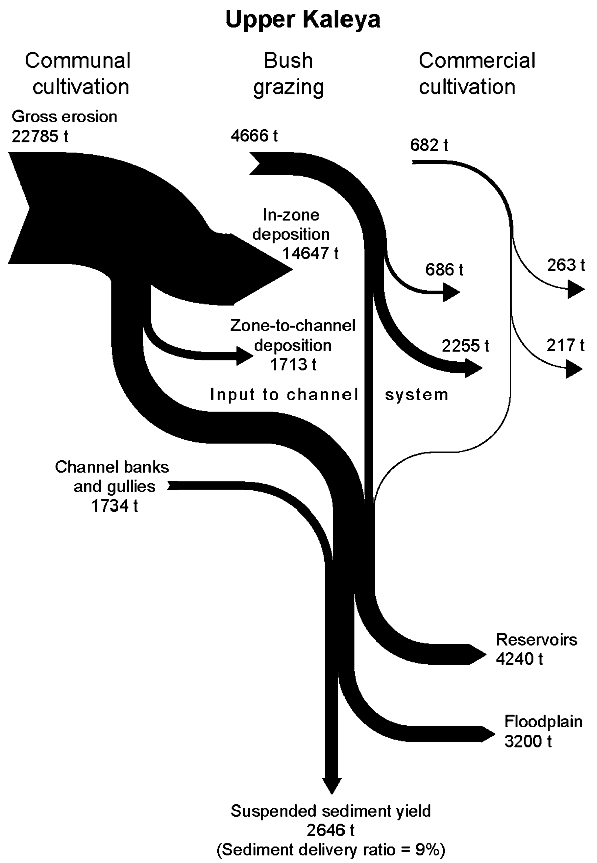

Fig. 2 – The sediment budget of the upper Kaleya catchment, southern Zambia (based on Walling et al., 2001).

present several examples of sediment budgets and their potential use in supporting catchment management.

Walling et al. (2001) used the integrated approach outlined above to establish the sediment budget for the 63 km^2 upper Kaleya catchment in southern Zambia (Fig. 2). The budget indicated that areas of communal cultivation (76%) and bush grazing (16%) were the most important sediment sources within the catchment, although a significant proportion of this sediment was deposited during transfer to the river channel. Sediment storage in local reservoirs and on the floodplain bordering the main river channel was also shown to be appreciable. As a result, the overall sediment delivery ratio was estimated to be only 9%, indicating that implementation of mitigation strategies to control soil erosion and sediment mobilisation within the catchment would not necessarily result in a major reduction in the sediment flux at the catchment outlet and that there would be a need for careful management of the main sediment stores, to reduce the risk of remobilisation of sediment from these stores. In addition, the sediment budget highlighted the need for any sediment control strategy to include provision for the protection of eroding channel banks and gullies, since these contributed ca. 17% of the annual suspended sediment load measured at the catchment outlet and this source is directly connected to the channel system, with little or no opportunity for depositional losses during transfer from the source to the channel system.

Walling et al. (2002) again used a similar integrated approach to assemble the information used to establish the sediment budgets for the Rosemaund (1.5 km^2) and Lower Smisby (3.6 km^2) catchments in central England (Fig. 3). The overall sediment delivery ratios for these catchments were higher than those of the upper Kaleya catchment at 17% and 20%, respectively, indicating that the sediment yields of these smaller catchments are likely to be more sensitive to land use change or sediment mitigation programmes. A significant

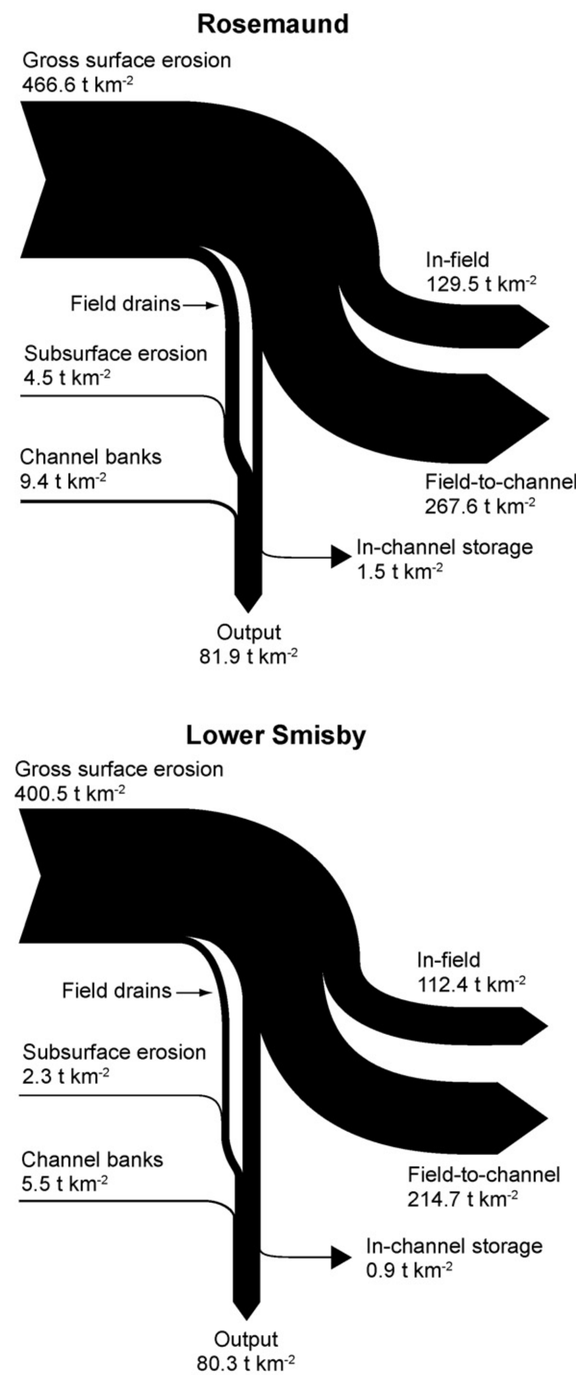

Fig. 3 – Sediment budgets for the Belmont and Lower Smisby catchments in central England (based on Walling et al., 2002).

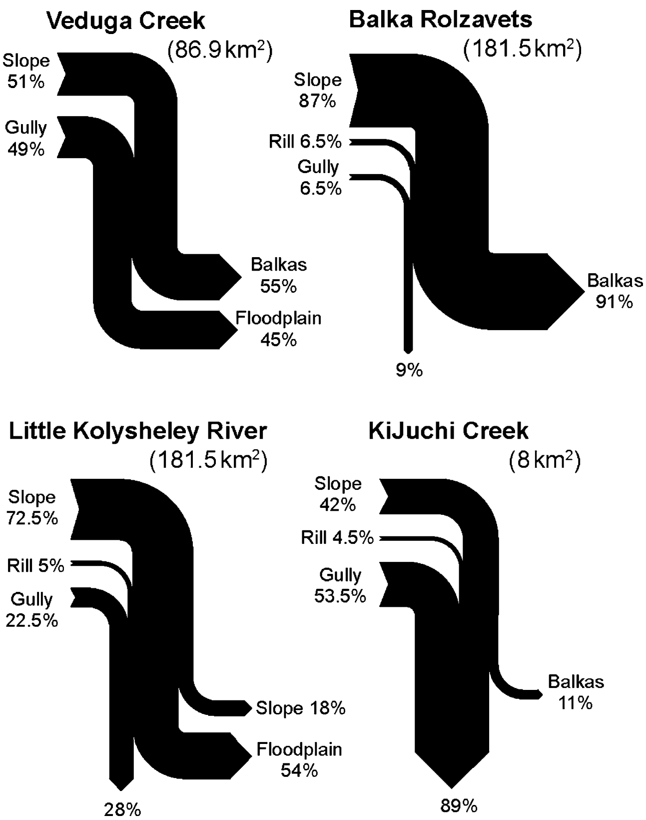

Fig. 4 – Sediment budgets for four catchments on the Russian Plain (based on data presented by Golosov et al., 1992).

proportion of sediment mobilised on local fields is, nevertheless, subsequently stored either within the fields or between the fields and the river channel. Failure to recognise these stores and the potential for remobilisation could result in an over-optimistic assessment of the scope for reducing the downstream sediment fluxes. Equally, the sediment budgets of these two catchments highlighted the need to manage sediment transfers via artificial drains, which serve to increase connectivity of the catchment surface to the watercourses and promote the rapid delivery of sediment to the catchment outlets during storm events.

The sediment budgets for a number of small and medium-sized river basins on the Russian Plain were reported by Golosov et al. (1992). In this case, the information used to construct the budgets included both field monitoring and sediment tracing as well as interpretation of soil profiles and the use of prediction equations to estimate rates of soil loss. The budgets established for four of the catchments, which are presented in Fig. 4, emphasise the wide range of sediment delivery ratios (0–89%) associated with this landscape. Accordingly, whereas it could be expected that changes in land use and erosion rates would not be readily reflected by the sediment flux at the outlet of the Veduga Creek catchment, the suspended sediment yield of Kijuchi Creek could be expected to be much more sensitive to such changes. The results from these four catchments emphasise the need to recognise the potential variability of catchment sediment budgets within even a relatively small region and thus variation in the effectiveness of improved management and mitigation measures in reducing the sediment fluxes at their outlets.

As a final example, Fig. 5 presents the sediment budgets established by Walling et al. (2006) for the Pang (166 km^2) and Lambourn (234 km^2) catchments in southern England using a combination of fallout radionuclide measurements, sediment source fingerprinting, and measurements of sediment flux at the catchment outlet and fine sediment storage on the channel bed. Both catchments are underlain by chalk, and the very low sediment yields are consistent with the low sediment yields commonly associated with chalk catchments. However, the sediment budgets emphasise that, although the sediment yields of these two catchments are very low,

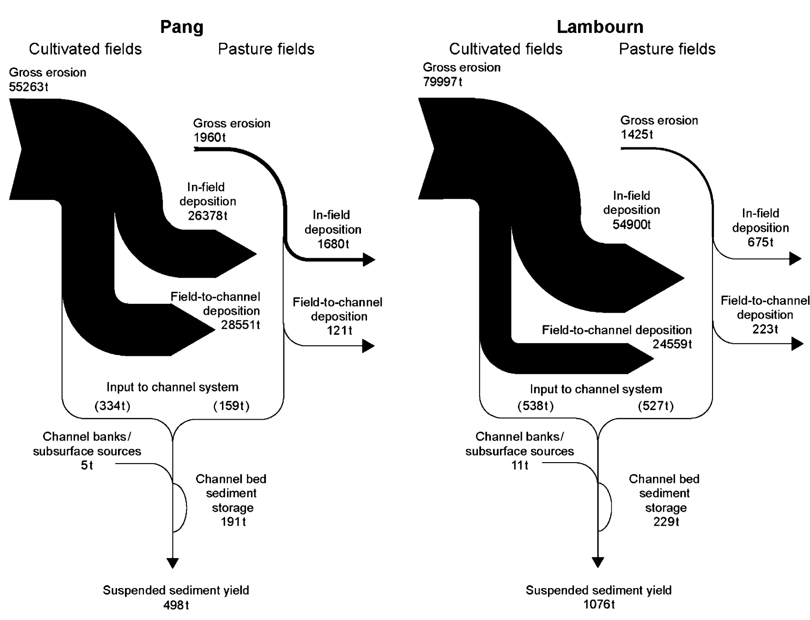

Fig. 5 – Sediment budgets for the Pang and Lambourn catchments, southern England (after Walling et al., 2006).

substantial amounts of sediment are mobilised by erosion within the catchments, but only a very small proportion of this reaches the catchment outlets. The budgets underscore the importance of cultivated fields as a sediment source and again highlight the importance of conveyance losses during the transfer of sediment from the slopes to the channel system, with 51% of the sediment mobilised from cultivated fields in the Pang catchment and 31% in the Lambourn catchment being sequestered between the fields and the river channel. The measurements of storage of fine sediment on the channel bed also emphasise the importance of this temporary store in the transfer of sediment through the channel system to the catchment outlet. The estimates of the magnitude of this store represent the mean storage on the channel bed during the year and the values indicated are of the order of 20% (Lambourn) and 40% (Pang) of the annual sediment flux at the catchment outlets. Since there will be frequent remobilisation and replenishment of this store, a substantial proportion of the sediment flux at the catchment outlet will have passed through this temporary store. Overall, the low sediment delivery ratios (ca. 1%) for both catchments indicate that their downstream sediment fluxes are unlikely to be sensitive to mitigation strategies targeting soil erosion and sediment mobilisation in fields. If, however, land use change or climate change was to cause a reduction in the in-field or field-to-river conveyance losses, appreciable additional quantities of sediment could be delivered to the watercourses, causing harm to the unique aquatic habitats supported by these chalk systems with their abundance of benthic invertebrates including nymphs, caddis larvae, stoneflies and white-clawed crayfish. Under current environmental conditions, eroding channel banks and subsurface sources are of minimal importance as a sediment source and do not require targeted mitigation in the Pang and Lambourn catchments.

The above examples serve to emphasise that it is important for policy makers and catchment managers to recognise that the sediment yields of many catchments appear to be characterised by a lack of sensitivity to land use change and mitigation programmes (Walling, 1999). This reflects, at least in part, the sediment delivery ratio, in that those catchments with a low sediment delivery ratio are likely to exhibit an enhanced buffering capacity and delayed response to improved management. The potential for remobilisation of stored sediment to offset, or at least delay, the downstream effects of a reduction in sediment mobilisation from the primary sediment sources within a catchment must also be recognised, introducing the need to raise awareness amongst stakeholders that any projected catchment response to sediment mitigation programmes could be delayed, at least in the short-term.

5. Conclusion

The importance of fine sediment as a diffuse source pollutant means that there is increasing recognition of the need to include provision for sediment control within catchment management strategies. However, it is important that the design of sediment control strategies should be founded on a holistic understanding of the sediment dynamics of the catchment concerned. A sediment budget fulfils that need, by providing key information on the sources, sinks and transfers involved. Focussing attention on an individual component of the sediment delivery system, without appropriate understanding of the overall sediment budget, may result in an incorrect assessment of the potential benefits of sediment mitigation programmes. It is suggested that the sediment budget concept should be more widely adopted and utilised as a practical framework to support the design and implementation of sediment control programmes aimed at reducing diffuse source pollution by fine sediment. Assembling the information required to establish a sediment budget is, however, likely to prove a demanding task in terms of the resources required, and may as a result constrain the use of the approach. However, the establishment of sediment budgets for representative catchment types within a region, so that the resulting typology of sediment mobilisation and delivery can be used to inform the design and implementation of sediment management and control strategies more generally, may provide an effective way forward.

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