Review Articles

Conceptual Models and Budgets for Sediment Management at the River Basin Scale

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Abstract

Background, Aims and Scope. Sediment management in river basins has tended to deal with local issues associated with either excessive amounts of sediment (both clean and contaminated) or sediment deficit. With sediment management increasingly needing to address both sediment quantity and sediment quality issues, it is becoming increasingly apparent that for sediment management to be effective the river basin represents the most appropriate scale for consideration. Although local and site-specific sediment issues are still likely to be the main scales at which interventions are made, they need to be placed within a broader context and with full appreciation and consideration of their impacts within the river basin. This paper describes some of the reasons why the river basin scale represents the most appropriate scale for sediment management, while recognizing the needs for site-specific interventions. It also describes the development of conceptual river basin models (CRBM) for sediment.

Main Features. A CRBM should identify, in a conceptual framework, the relevant key environments (subsystems) within a river basin and the interrelationships between the environments. From a sediment perspective, key information includes the identification of sources of sediment (and associated contaminants and nutrients), the pathways of sediment and contaminants within and between the various environments, and the role of storage elements. Additional information that informs the CRBM includes, the assessment of sediment fluxes (including storage), the residence time of sediment storage, and information on exchanges between sediment and contaminants, although such information is often not available at the scale of the river basin. An example of a CRBM for sediment for a hypothetical river basin and examples of several sediment budgets (for basins in USA and Zambia, and for Europe) are presented which are based on data and information on sediment sources, fluxes and storage. These are discussed and some of the advantages and disadvantages for sediment management decision-making are described.

Conclusion and Recommendation. Conceptual frameworks and models for sediment offer considerable potential for certain stages of the management process. They are, however, only part of a much larger decision-making process, which involves, amongst other things, stakeholder participation, evaluation of the appropriate legislation and guidelines, and the use of risk assessment and societal cost-benefit analysis.

Keywords: Conceptual river basin model; contaminated sediment; geomorphology; river basin; sediment budgets; sediment fluxes; sediment management; sediment sources; sediment storage; systems

1 Introduction

For over a century, hydrologists and geomorphologists have recognised that the movements of water and sediment are controlled by processes which themselves operate within the context of a river (or drainage) basin. In consequence, the river basin has long been regarded as the fundamental unit of study in hydrology and fluvial geomorphology (Chorley 1969, Gregory and Walling 1973) and as an important functional unit for landscape ecology (Bormann and Likens 1969). As water and sediment move from higher to lower elevations under the influence of gravity, the topography (and other characteristics) of the Earth's surface dictates the direction and rate of water and sediment transfers. Ultimately, water inputs from precipitation are routed through the river basin to the oceans (**Fig. 1**), and under most situations sediment movements are linked to this routing of water. It is estimated that the annual discharge of water and sediment (mainly suspended) to the global oceans are of the order of 35×10^3 km^3 and 20×10^9 t, respectively (Milliman and Syvitski 1992, Farnsworth and Milliman 2003). For Europe, Owens and Batalla (2003) have tentatively estimated the annual flux of sediment towards the coastal zone (including that deposited in harbours etc) at ca. 0.7×10^9 t.

It is important to recognise, however, that not all water and sediment fluxes are contained within a river basin, as: groundwater flows do not necessarily adhere to basin surface boundaries; as evaporation and transpiration return water to the atmosphere (see Fig. 1); as atmospheric dust and chemicals are often derived from outside the basin; and as society is increasingly transferring water and sediment *between* river basins. Indeed, these transfers and the net loss of water, sediment and energy at the basin outlet (i.e. discharged to the oceans) mean that a river basin is an 'open system' (Chorley 1962). However, it is clear that the river basin represents a meaningful and convenient unit and scale for considering water and sediment movement on the surface of the Earth. In recognition of this, water management, particularly in terms of water quantity, increasingly operates at the river basin or 'watershed' scale.

The management of sediment in rivers has a long history but until recently has tended to deal with local issues, usually associated with either (a) excessive amounts of sediment in rivers, reservoirs and harbours and associated removal and dredging activities or (b) issues of sediment deficit and the effects of this on habitats (including river banks, floodplains and deltas) and building structures (Owens et

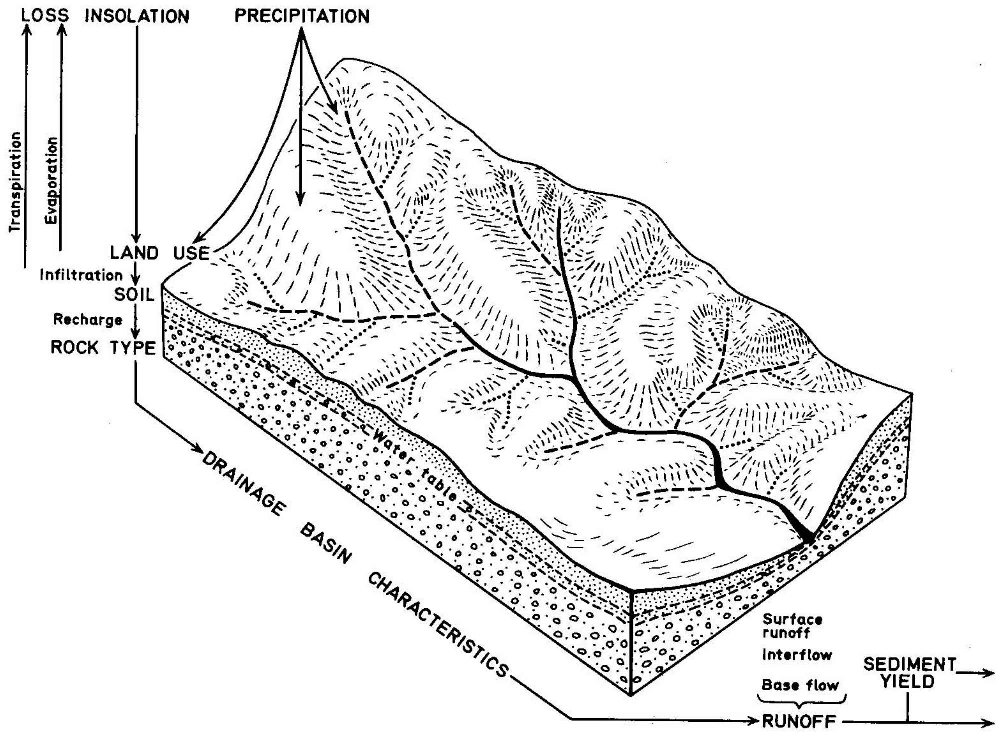

Fig. 1: A schematic representation of a drainage basin illustrating the way in which drainage basin characteristics influence the transformation of input of precipitation into output of runoff and sediment (from Gregory and Walling 1973, reproduced with permission of Arnold Publishers and the authors)

al. 2005). This is not to say that the amount of sediment has been 'naturally' excessive or deficient, but excessive or deficient in terms of its socio-economic impacts, such as navigation, reservoir operation, fishing and destruction of habitable land. For example, the increased transportation costs (e.g. reduced loads of goods in ships etc) associated with excessive sediment in Indiana Harbor ship canal in the USA have been estimated at US$12.4 million annually (USEPA 2004). Similarly, the city of Hamburg, Germany, spends ca. 30 million Euros each year to dredge and treat between 2 and 5 x 10^6 m^3 of sediment (much of it contaminated) in the port (Netzband et al. 2002). It is estimated that the cost of sediment related problems in urban drainage systems in the UK is of the order of 100 million Euros each year (CIRIA 1986, cited in Ellis 1996).

Recently, in many countries, such sediment management has also had to consider the issues of sediment quality and the introduction of guidelines and legislation associated with the removal and disposal of contaminated sediment, especially in estuarine and marine environments (Köthe 2003, Owens et al. 2004, 2005). In particular, the introduction of the EU Water Framework Directive (WFD, 2000/60/EC) now requires that issues of water quality and ecological status are addressed within a set timeframe. Although sediment quality is addressed only to a very limited extent within the WFD, it is clear that water quality and ecological status are closely linked to sediment quality, and that ultimately sediment fluxes and management will need to be addressed within the WFD or associated legislation (Förstner 2002, Brils 2004).

With sediment management needing to consider and address both sediment quantity and sediment quality issues, it is becoming increasingly apparent that for sediment management to be effective - environmentally, socially and economically – the river basin represents the most appropriate scale for consideration. Although local and site-specific sediment issues are still likely to be the main scales at which interventions are made (i.e. dredging of a particular river reach), they need to be placed within a broader context and with full appreciation and consideration of their impacts within the river basin, here defined to include the near-coastal zone.

2 Why Manage Sediment at the River Basin Scale?

There are several reasons why the river basin scale approach is required and these are considered below. Firstly, decision-making needs to be placed within the context of the river basin because a local intervention will in most cases impact other parts of the river basin. As described above, a river basin operates and functions as an open system with interconnected subsystems. By altering one subsystem (such as through climate change or widespread land use change) or part of a subsystem (such as construction of a dam at a particular point in a river), there will, by definition, be impacts on other parts of the *system*. For example, it is well documented that the construction of dams and impoundments, for hydro-electric power generation, irrigation and flood control, result in the trapping of a significant quantity of sediment in reservoirs and other features (Syvitski 2003, Vörösmarty et al. 2003, Walling and Fang 2003, Owens 2005). In turn, the reduction in the supply of sediment to downstream reaches has important environmental impacts including the loss of fish habitats, wetlands and saltmarshes and the regression of deltas (Owens et al. 2005). For example, downstream from the Hoover dam, on the Colorado River, USA, the riverbed had degraded by 7.5 m within 13 years of dam closure, and erosion had affected 120 km of the river during that period (Williams and Wolman 1984). There are also important socio-economic impacts in downstream reaches including the undermining of bridges and other structures (Kondolf 1997). Batalla (2003) provides a good review of the impacts of sediment deficit downstream of dams and areas of in-stream gravel mining for northeastern Spain. Leopold (1997) describes the situation downstream of the Aswan dam, where 15–19% of the habitable land of the Nile delta could be gone within 60 years due to subsidence resulting from a lack of sediment deposition, which in turn could displace 15% of the population of Egypt.

Secondly, most large river basins throughout the world are highly populated and/or modified by human activities (such as deforestation) and thus there are many users and uses of sediment within a basin. These range from the extraction of river sands and gravels as a construction material for industry, the use of fertile floodplains for agriculture and urban development, to the utilization of channel bed gravels for fish spawning. **Fig. 2** provides a schematic representation of some of these uses and users. This means that site-specific interventions will have impacts that will likely affect other users and uses of sediment within a river basin. It is, therefore, necessary to consider all users and uses of sediment within a river basin and to develop ways to consider and evaluate these needs, including involving stakeholders in the decision-making process (for further details see Gerrits and Edelenbos 2004). Again, the river basin represents the most meaningful unit and scale for consideration because it is the scale at which the users and uses of sediment (and water) are most connected (i.e. because the size and topography of the river basin controls the sources, pathways and fluxes of water and sediment) as well as the scale which is most appropriate for decision-making.

Thirdly, the river basin represents an appropriate scale for management because in many cases source control will be the optimal long-term solution: environmentally, socially and economically. Most sources of sediment are derived from diffuse sources (described later). In addition, in developed countries such as Canada, USA and most countries in Europe, many of the point sources of contaminated sediment are being brought under control, and in consequence diffuse sources of contaminated sediment are increasing in relative importance. Many diffuse sources of sediment (both clean and contaminated) operate across large areas and may be dispersed throughout all or most of a river basin, such as those sources associated with agricultural land (see sections below). The contribution from individual diffuse sources may be minimal but collectively they can be significant. The controlling of diffuse sources necessitates a river basin scale approach in order to: identify all or most of the sources of the sediment and contaminants; for conducting meaningful risk assessment and evaluation; and to be able to implement remediation and mitigation options that are appropriate for controlling diffuse sources spread over a large area, for example, implementing appropriate land use and land management measures.

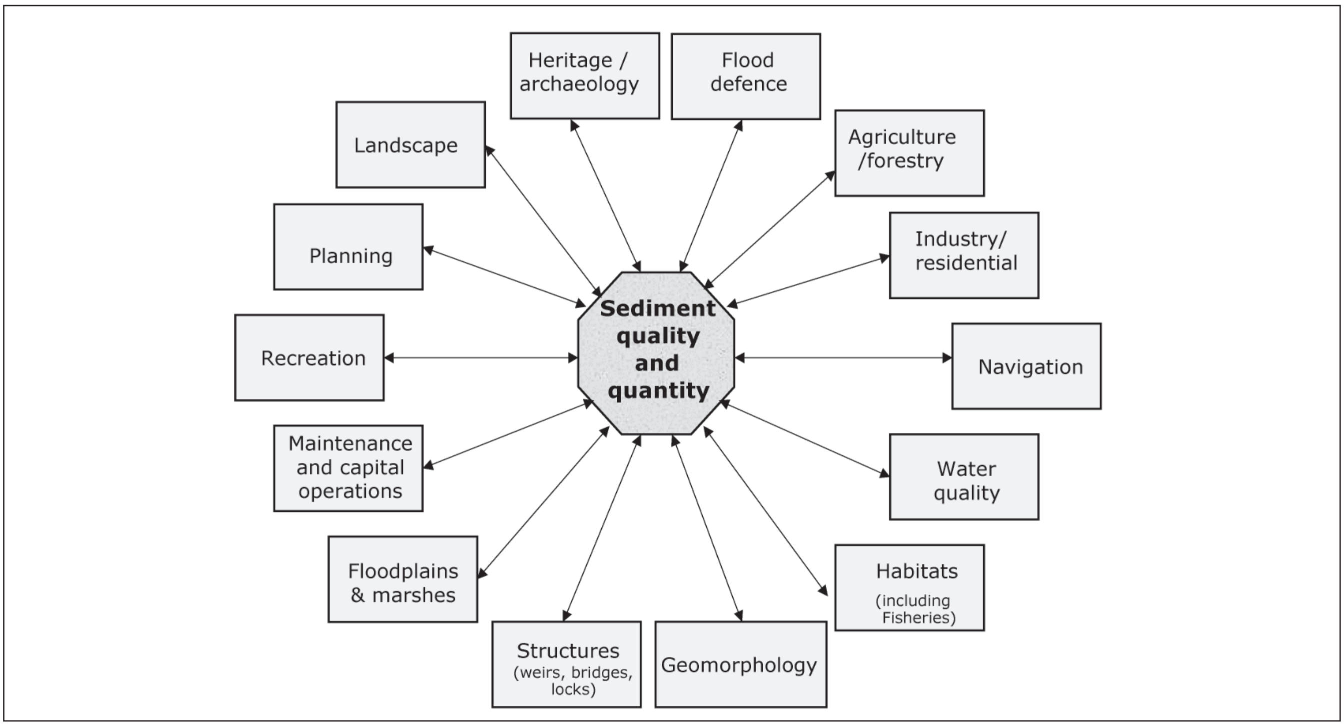

Fig. 2: Schematic representation of some of the main influences and impacts on sediment within a river basin (from Owens et al. 2004)

3 Conceptual Mapping and Modelling of the River Basin

By considering the river basin as the prime morphological unit and scale for effective sediment management, one of the most important requirements in the early stages of the planning and decision-making processes for sediment management is the establishment of a conceptual river basin model (CRBM) appropriate for sediment (also see Apitz and White 2003, Heise et al. 2004). The CRBM concept stems from hydrological and ecological theory and has been used for water management for many decades. Conceptual mapping and modelling at the river basin scale has developed over the last 40 years due to the need to understand the behaviour of complex environmental systems (cf. Crawford and Linsley 1966, Douglas 1974). The CRBM should be part of an overall river basin management plan (RBMP). In the broadest sense, a CRBM should identify, in a conceptual framework, the relevant key environments (subsystems) within a river basin and the interrelationships between the environments. From a sediment perspective, key information includes the identification of sources of sediment (and associated contaminants and nutrients), the pathways of sediment and contaminants within and between the various environments, and the role of storage elements. Additional information that informs the CRBM includes, the quantification of sediment fluxes (including storage), the residence time of sediment storage, and information on exchanges between sediment and contaminants, although such information is often not available at the scale of the river basin.

3.1 Environments within a river basin

Examples of the environments within a river basin that are relevant for sediment management include:

- atmosphere;
- land (i.e. soils);
- river channels;
- lakes and reservoirs;
- floodplains;
- the groundwater zone;
- estuaries and harbours; and
- the coastal zone.

The atmosphere is relevant as it provides inputs of water, sediment (i.e. atmospheric dust) and chemicals to the river basin, although its limits are not bounded by the basin and it primarily provides allochthonous material that is derived from outside the basin (such as precipitation) (see Fig. 1). Similarly, the groundwater and coastal zones are also relevant environments and have both autochthonous (derived from within) and allochthonous (derived from outside) components. Thus, for example sediment in estuaries is derived from both the upstream river basin and from the coast (e.g. beaches and cliffs) and ocean. In addition, both groundwater and coastal zones have a much closer connection, as compared to the atmosphere, with the concept of a river basin as defined by the EU Water Framework Directive (WFD). In reality, all of the environments listed above represent important components of the river basin system and should be included within a CRBM, at least at an initial stage. During the decision-making process, some of these environments may not be relevant to a particular sediment-related issue or problem, and may then be disregarded. It is, however, important that the decision to disregard from further consideration is based on an initial evaluation of their role within the overall functioning of the river basin system.

Some of the environments listed above can be considered primarily to represent sources of sediment and associated contaminants (such as the atmosphere, soils etc), while others tend to represent intermediate storage elements (such as floodplains, lakes etc). It is useful to recognise that typically >80% of the surface area of a river basin is *land*, and <20% is open surface water (rivers, lakes, reservoirs etc) and this obviously has important implications for the management of water and sediment. Indeed, it is becoming increasingly clear that both the quantity and the quality of water and sediment in rivers, lakes, estuaries and the coastal zone is very much dependent on activities that occur on the land. In particular, forestry and agricultural practices greatly influence not only the amount of sediment delivered to rivers and lakes but also the quality of the sediment through the application of fertilisers and manures to land, for example. It can be argued that the linkage between activities on the land and the chemical and ecological quality of surface waters and groundwaters has not been recognised and addressed sufficiently within most of the existing water legislation, such as the WFD in the EU. Recommendations established under the EU Thematic Strategy for Soil Protection (Blum 2003, Van-Camp et al. 2004) may help to redress this problem.

3.2 Identification of sediment and contaminant sources

Sediment and associated contaminant sources may take one of two general forms:

- point sources and
- non-point (or diffuse) sources

and each of these types poses specific problems regarding identification and management. Point sources of sediment and contaminants are those sources originating from a single location, and as such are often readily identified. Furthermore, such sources are generally more easily controlled and monitored. Non-point (diffuse) sources of sediment and contaminants are those originating from a wide area. As a result, the identification, and in particular the control, of these sources presents much more of a challenge to sediment management. However, given the high level of success in controlling point sources of contaminants, these non-point sources are now recognised as requiring the most effort for identification and control.

Table 1 lists the main sources of sediment and associated contaminants. Generally, most of the *sediment* transported in rivers (above the tidal limit) is derived from diffuse sources such as from the erosion of agricultural and forested land, erosion of channel banks, landslides and dust derived from the road network (defined here as a diffuse source of sediment in terms of its wide spatial location and the measures needed for control) (Owens et al. 2000, Carter et al. 2003).

Table 1: Examples of sources of sediment and associated contaminants to river basins (from Owens et al. 2004)

Material	Sources
Sediment (organic and inorganic)	Erosion from rural, agricultural and forested land, channel banks, urban road dust, STW solids, construction sites, geological mines, atmospheric deposition, inputs from tidal areas and coastal zone
Metals (Ag, As, Cd, Cu, Co, Cr, Hg, Ni, Pb, Sb, Sn, Zn)	Geology, mining, industry, acid rock drainage, sewage treatment, urban runoff
Nutrients (P, N)	Agricultural and urban runoff, wastewater and sewage treatment
Organic compounds (pesticides, herbicides, hydrocarbons)	Agriculture, industry, sewage, landfill, urban runoff
Xenobiotica and antibiotics	Sewage treatment works, industry, agriculture
Radionuclides (^{137}Cs, ^{129}I, ^{239}Pu, ^{230}Th, ^{99}Tc).	Nuclear power industry, military, geology, agriculture (secondary source)

Some of these diffuse sources (such as landslides, channel bank erosion) supply sediment that is essentially 'clean' in that there are no or only limited amounts of potentially detrimental chemicals attached to the sediment. Other diffuse sources (such as agricultural land and the urban road network) supply sediment that may be contaminated with excessive amounts of nutrients (e.g. phosphorus), fertilizers, metals etc.

Point sources of *sediment* include in-stream gravel mining, which although usually associated with sediment removal (and thus a net loss to the river channel system), is often an important source of resuspended coarse- and fine-grained sediment as a result of the highly disruptive processes involved (for example see Owens et al. 2005). Other point sources of sediment include discharges from sewage treatment works (STWs) and combined sewer overflows (both of which can discharge significant quantities of mainly organic sediment), industrial point discharges, construction sites and geological mines. Again, some of these point sources (e.g. in-stream gravel mining) are likely to supply predominantly 'clean' sediment while others (e.g. STWs and industrial point discharges) will supply contaminated sediment.

Many of the *contaminants* listed in Table 1 are, however, usually derived from point sources such as STWs, industrial point discharges and mining activities. Often these contaminants are discharged from point sources to rivers in solution, and subsequently sorb onto the sediment in the water column. Owens and Walling (2002), for example, measured marked increases in the phosphorus content of suspended sediment collected downstream of a large STW in England due to sorption of dissolved phosphorus onto suspended sediment that was passing the outflow pipe (**Fig. 3**).

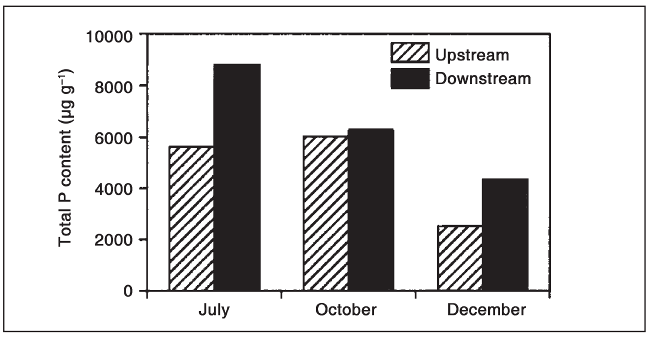

Fig. 3: Phosphorus content of suspended sediment samples collected immediately upstream and downstream of a large STW, River Aire, England. There were no significant sources of sediment or phosphorus between the two sampling sites (based on data in Owens and Walling 2002)

In summary, sediment management (and river basin management in general) needs to recognize that the identification and mapping of the sources of sediment and associated contaminants at the scale of the river basin is complex, in that:

- sediments and contaminants may be derived from many different sources (both point and diffuse);
- sediment from these sources may be 'clean' or contaminated; and
- contaminants may be delivered in different forms (sediment-associated and in solution).

In consequence, river basin sediment management plans need to be developed accordingly, and the use of conceptual river basin models for sediment can greatly assist this process.

3.3 Identification of pathways

Related to the identification of the main sediment and contaminant sources (in terms of type and spatial location) is the need to determine the pathways by which these are delivered to, and through, the river basin. **Fig. 4** provides a conceptual model which identifies the main pathways by

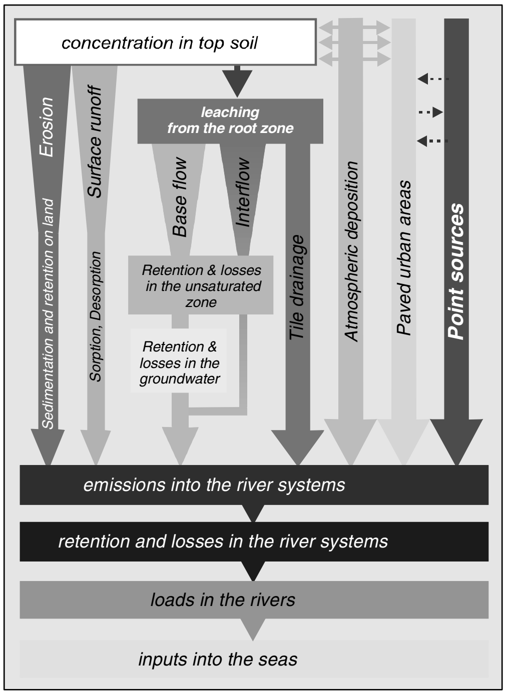

Fig. 4: Conceptual model of the main pathways that relate to sediments and associated contaminants (from Behrendt et al. 2000, Vink 2002)

which sediment and contaminants are delivered to rivers. The dominant pathway(s) will depend upon a variety of factors, including land use, soil type, climate and topography. In the case of agricultural land, for example, soil erosion and overland flow will often represent the dominant processes and pathways by which many diffuse sources of sediment and contaminants (such as phosphorus, fertilisers and pathogens) are delivered to rivers and lakes. Owens et al. (2000) used sediment fingerprinting techniques to determine that 61% of the sediment load of the River Tweed in Scotland was derived from topsoil, mainly from pasture and arable land: the remainder was derived from channel bank and subsoil (i.e. gully erosion) sources. Recent research has, however, demonstrated the importance of subsurface pathways, such as tile drains, in delivering sediment and contaminants to rivers in agricultural areas. For example, Chapman et al. (2001) determined that land drains contributed >50% of the catchment suspended sediment yield and a significant proportion of the phosphorus load over a two year period for a small experimental catchment in England.

In urbanized river basins, the urban road network may provide an important pathway by which sediment and contaminants are delivered to rivers. Carter et al. (2003) determined that 20% of the sediment load of the River Aire in England was transported to the river from the road network. This study also demonstrated that this pathway changed in importance over time in response to the connectivity between the road network and the river system, with limited contribution during dry conditions and maximum contribution during rain events. The road network (small rural roads, farm tracks etc) may also play an important role is delivering sediment and contaminants in agricultural river basins, and may also act as an important secondary source of sediment (Gruszowski et al. 2003).

Identification of the pathways by which sediment and contaminants are delivered to waters is particularly useful from a management perspective because it helps to develop mitigation options and thus prevent potential sediment and contaminant sources becoming a threat to a river or lake. The success in the control of point source discharges from STWs and industrial facilities is a good example of how the understanding and identification of source-pathway-receptor linkages has resulted in improved water and sediment quality. Identifying the pathways by which diffuse sources of sediment and contaminants are delivered to surface waters is inherently more difficult from a management perspective. However, recent developments in the use of geographical information systems and the improved resolution of digital terrain models has enabled water and sediment pathways from land to waters to be mapped and appropriate mitigation options to be employed (such as the strategic placement of buffer features) through the identification of high-risk areas.

3.4 Identification of storage elements

There are many environments within a river basin (such as channels, floodplains, lakes, harbours etc) where sediment and contaminants are deposited and stored, and these stores operate at a variety of different time scales, ranging from hours to thousands of years. Thus sediment storage on the bed of a river is often of the order of days or months (i.e. until the next high flow event remobilizes the sediment). Owens et al. (1999), for example, estimated that the channel bed storage of fine-grained sediment within the main channel system of the River Tweed, Scotland, during a single low-flow sampling period was of the order of 4% of the annual sediment load delivered to the channel. This value represents an instantaneous measure of storage and it is estimated that on other occasions storage would be less due to resuspension. In a similar study for the River Ouse in England, Walling et al. (1998) estimate instantaneous channel bed storage of ca. 10%. In some environments, such as those with ephemeral channels (such as Mediterranean regions), channel bed storage may be more significant and may occur over a period of months to years.

Sediment and contaminant storage on floodplains, on the other hand, is often of the order of decades to thousands of years (i.e. until it is reworked by bank erosion due to lateral channel migration). **Table 2** presents estimates of the long-term storage of sediment and contaminants (metals and phosphorus) on the floodplains of two large river basins in England. Estimates of the mean annual conveyance loss to floodplain storage range between ca. 10 and 45% of the flux delivered to the river system, and the timescale associated with this storage is likely to be of the order of hundreds to thousands of years. Similarly, Middelkoop and Asselman (1994) combined an assessment of the mass of fine-grained sediment deposited along a 100 km reach of the floodplain of the River Waal in the Netherlands during a 40-year flood with information on the suspended sediment load of the river to estimate that about 19% of the total suspended sediment load transported into that reach during that event was deposited on the floodplain.

Table 2: Estimates of the deposition and conveyance losses of sediment and associated contaminants on the floodplains bordering the main channels of the Rivers Swale (1,346 km^2) and Aire (1,002 km^2), Yorkshire, UK (from Walling and Owens 2003)

Material	Mean annual river load (t year^{-1})		Mean annual floodplain deposition flux (t year^{-1})		Mean annual conveyance loss to floodplain storage (%)	
	River Swale	River Aire	River Swale	River Aire	River Swale	River Aire
Suspended sediment	45,158	18,462	16,894	8,604	27	32
Cr	1.17	2.51	0.33	0.25	22	9
Cu	3.66	2.76	0.86	0.38	19	12
Pb	29.40	3.66	24.49	1.30	45	26
Zn	32.51	9.99	17.50	2.43	35	20
Total-P	62.54	120.21	9.83	11.48	14	9

Another important area where sediment and associated contaminants are deposited and stored in river basins is reservoirs and lakes. Values of sediment storage in reservoirs and lakes for individual river basins vary considerably depending on a variety of factors such as the number and size of lakes/reservoirs. The scale of storage is, however, illustrated by the work of Vörösmarty et al. (2003) who estimate that ca. 25–30% of the global sediment flux to the oceans is retained in 45,000 registered reservoirs throughout the world.

3.5 An example of a conceptual river basin model for sediment

Once we have identified the main environments within a river basin, the sources and storage elements of sediment and contaminants, and the pathways and processes that control the movement of sediment and contaminants within the river basin, it is then possible to establish a CRBM for sediment. **Fig. 5** provides a good example of a CRBM for sediment and is based on the work of Meybeck et al. (2004) within the EUROCAT project (Salomons 2004). It illustrates conceptually (i.e. there are no actual estimates of the contribution of the sources, of material fluxes, or of estimates of storage rates) the sources, transfer pathways and storage elements (sinks) for sediment and contaminants within a hypothetical river basin. It contains both those elements expected in a natural system (e.g. natural soil erosion) and those elements expected in a system modified by human activities (e.g. mining, enhanced soil erosion). While the model initially appears complex, it enables the interactions and transfers of sediment and associated contaminants to be identified at a river basin scale. Such a model, subsequently allows the manager or regulator to identify the implications of a particular management option or intervention, whether local or basin scale. It may also identify the part(s) of the system where further, more detailed information is required.

3.6 Examples of river basin sediment budgets

The conceptual mapping and modelling of sediment and associated contaminant transfers within a river basin should represent an important initial requirement for sediment management at the river basin scale. However, the usefulness of the exercise is increased substantially during a subsequent stage whereby absolute values are assigned to components of the CRBM, either through assembling appropriate existing data or through a specific programme of measurement and monitoring. The development and application of numerical models may also be useful at this stage of the decision-making process, because they may enable a limited amount of data to be extrapolated across larger spatial units and because they enable potential management scenarios to be tested and evaluated.

Fig. 6 and **Fig. 7** provide two examples where a CRBM for sediment has been developed through assembling data on sediment sources, pathways and sediment fluxes to construct a sediment budget (for more information on the sediment budget concept see Trimble 1983, Slaymaker 2003) at the river basin scale. Based on the information obtained it is

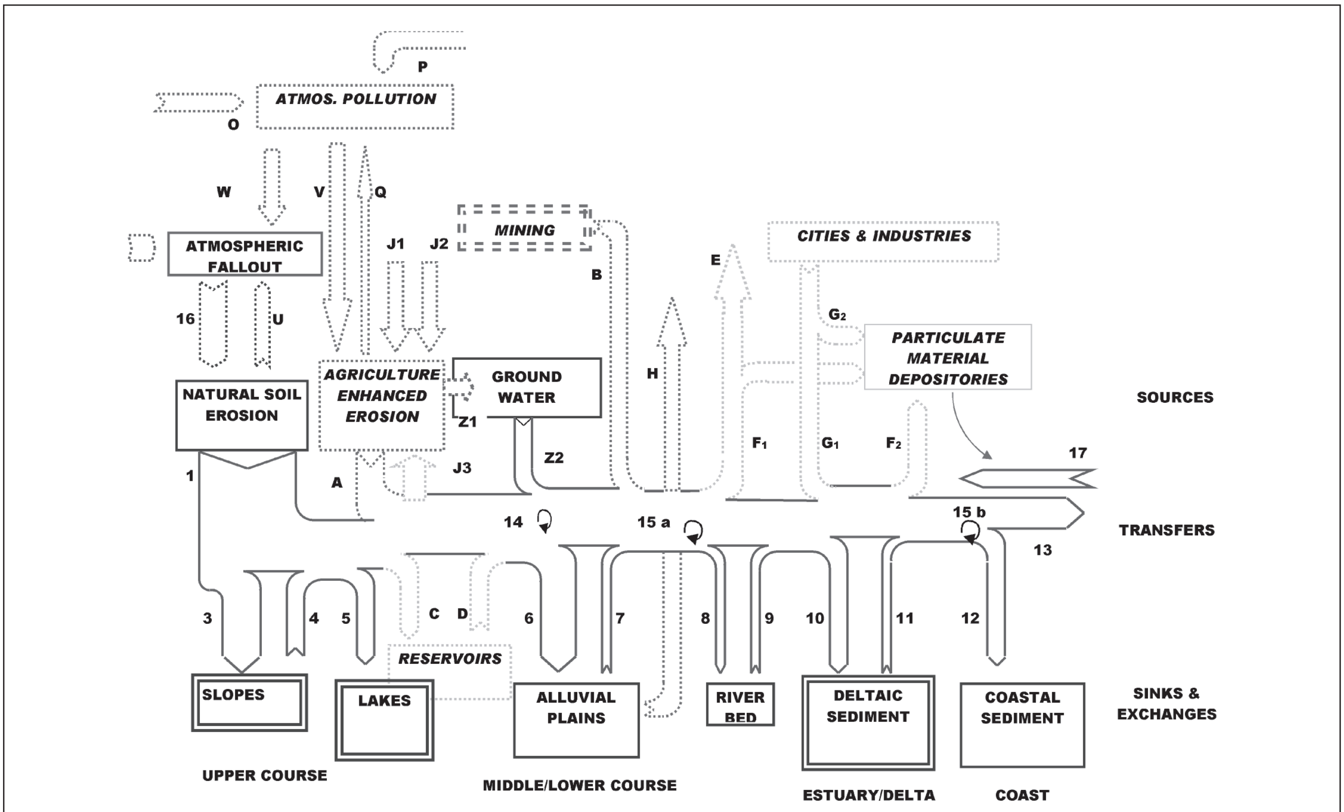

Fig. 5: Conceptual model of material fluxes (especially sediment and contaminants) in a river basin: 1 to 17 represent fluxes in a natural system and A to Q represent additional fluxes generated by society (from Meybeck et al. 2004, reproduced with permission of the author)

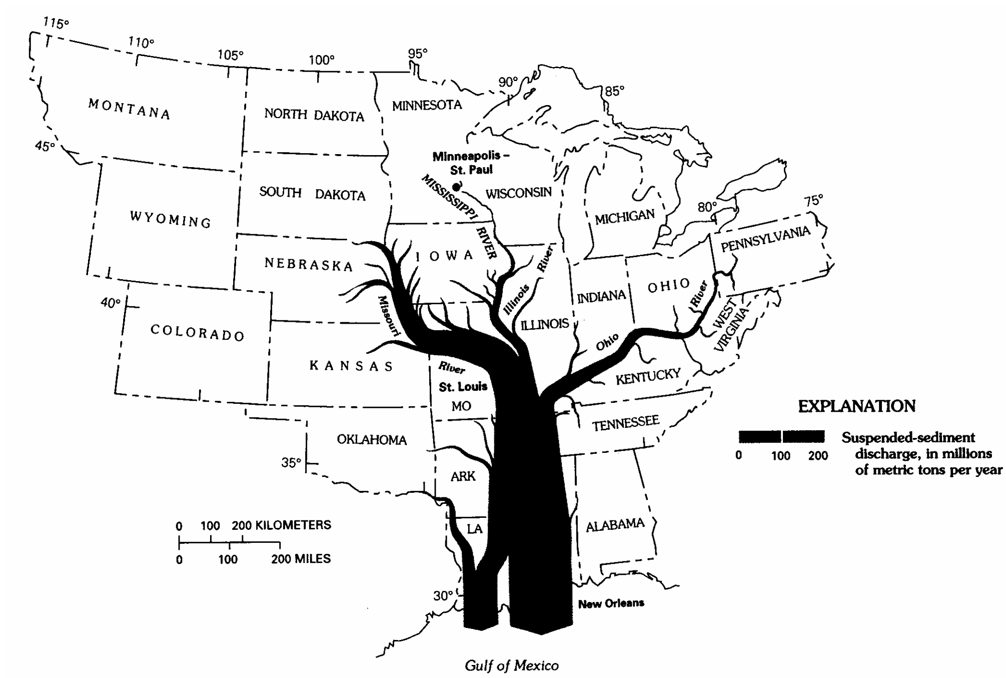

Fig. 6: Sediment fluxes in the Mississippi River, USA (from Meade 1995)

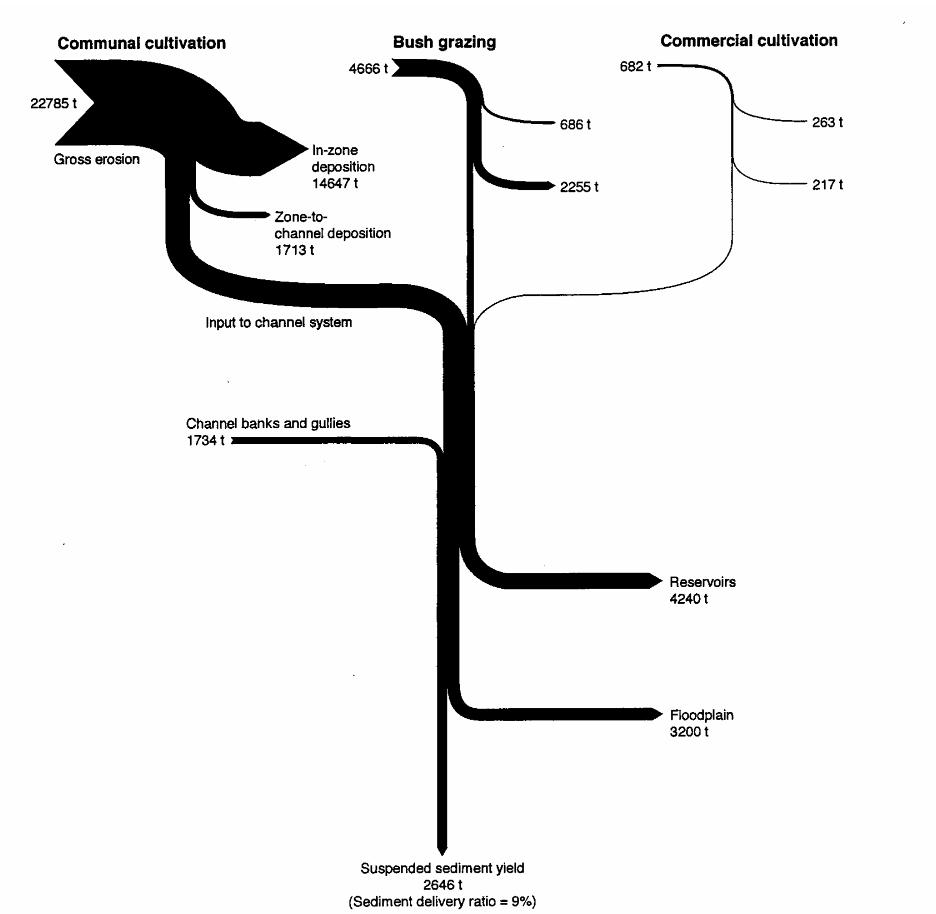

Fig. 7: The suspended sediment budget for the upper Kaleya catchment, Zambia (from Walling et al. 2001, reproduced with permission of John Wiley and Sons Ltd.)

possible to identify where management options can be best directed and targeted, although some of the limitations of the approach are also discussed below. From an inspection of the contemporary sediment budget for the Mississippi River, USA (see Fig. 6), based on the work of Meade (1995) and co-workers, it appears that measures to reduce sediment fluxes through the downstream reaches of the river system and delivery to the Gulf of Mexico should be directed towards sediment delivery and transport in the Missouri River, as opposed to the Ohio River. While the sediment budget for the Mississippi River illustrated in Fig. 6 helps to identify where to target management in a cost-effective way (i.e. targeting rivers with high sediment loads as opposed to attempting to manage all rivers equally), such a simplified picture does not provide an understanding of the cause of the problem and, as such, offers limited advice for management options to control the source of the sediment being delivered to the rivers. In the case of the Mississippi River basin, the contemporary sediment budget does not include important information on sediment sources, pathways and storage. A detailed evaluation of these has shown that sediment fluxes in the Missouri and Arkansas Rivers have decreased dramatically over the last few decades due to storage within large reservoirs. Conversely, sediment loads in the Ohio River system have increased by five- to 10-fold due to clearance of virgin forest and subsequent erosion on agricultural land (Meade 1995). Thus while the Missouri River represents the dominant source of sediment to the main stem of the Mississippi River, a more detailed evaluation of sediment sources, pathways and sinks suggests that management efforts should also be directed at the Ohio River due to increased delivery and transport of sediment and associated contaminants (Meade 1995). In addition, there may be a need to evaluate whether the storage of sediment in reservoirs along the Missouri River is causing detrimental effects in terms of sediment deficit (as compared to under more natural conditions) to downstream aquatic habitats and the coastal zone.

A more detailed sediment budget for a small basin in Zambia, based on the work of Walling et al. (2001), is presented in Fig. 7. This budget presents detailed information on the main sediment sources according to the three main land uses in the Kaleya basin, in addition to estimates of sediment fluxes, sediment storage (within-field, floodplain and reservoir) and the downstream sediment yield. Some important information for management can be obtained from this sediment budget model. For example, the erosion rates and sediment delivery to the channel system are greatest for the land under communal cultivation. As such, it would appear that sediment management efforts may be best targeted towards controlling soil erosion and sediment delivery in areas of communal cultivation, which occupy ca. 70% of the basin. However, because of in-field storage, the sediment delivery ratio (the proportion of the eroded sediment which actually reaches the channel) for this land use is relatively low. Thus any soil conservation programme on the communal land would have limited impacts on the amount of sediment delivered to the channel, and the costs of this programme would therefore need to be evaluated in light of the impacts in the river. Conversely, although bank erosion only supplies a limited amount of sediment to the channel, because this material is introduced directly into the channel (i.e. the sediment delivery ratio is effectively 100%) it is an important source of the sediment transported in the lower reaches of the river. Simple measures to reduce accelerated bank erosion (due to cattle poaching for example) may, therefore, be a cost-effective solution to reduce sediment transport in the river. Also of note is the importance of reservoirs in the lower reaches in trapping sediment and the effect this has on downstream sediment fluxes.

Another, contrasting (in terms of scale and level of detail) type of CRBM for sediment is presented in **Fig. 8** which shows a sediment budget for Europe (including existing and new Member States and countries likely to join the EU in the near future; see Owens and Batalla (2003) for further de-

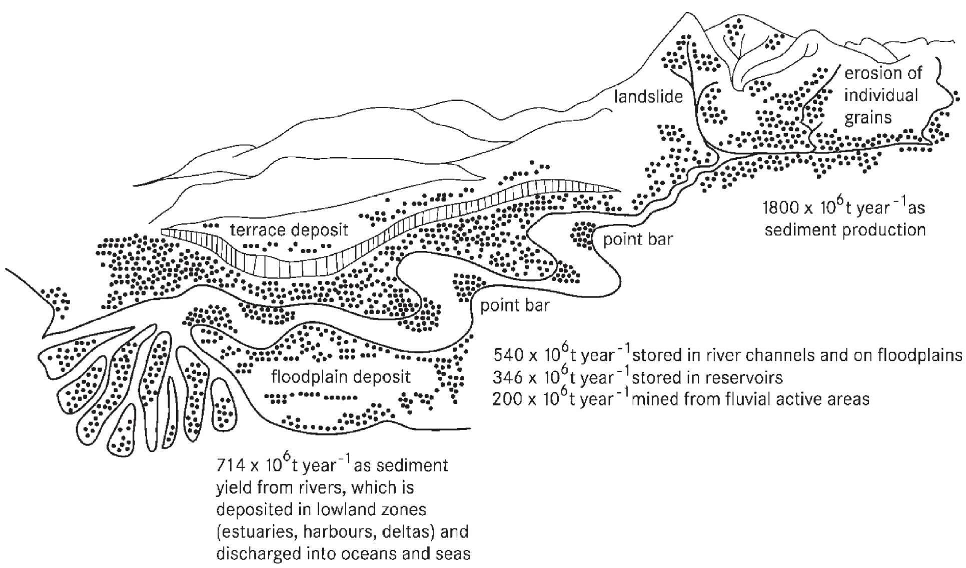

Fig. 8: An approximate sediment budget for Europe (from Owens and Batalla 2003: the base map is from a diagram by G.M. Kondolf and reproduced with permission of the author)

tails) based on existing data. Although fairly crude, it helps to illustrate the magnitude of sediment production (mainly through soil erosion and bank erosion) and sediment transfers to the coastal zone, and as such informs decision-making by identifying if there is a need for management in the first place (i.e. are the fluxes large enough to be of concern) and then, if so, where the management should be targeted (i.e. at the source, transport or delivery stage). This sediment budget is presently undergoing further refinement.

3.7 Water-sediment-contaminant interactions: some additional considerations

There are several important aspects of sediment and contaminant behaviour that need further consideration if CRBMs for sediment (including sediment budgets) are to be informative and effective for understanding sediment and contaminant sources, fluxes and storage, and thus for making sediment management decisions. These include:

- the magnitude and frequency of hydrologic and geomorphic processes, and in particular sediment fluxes (Wolman and Miller 1960);
- historical changes in sediment and contaminant fluxes (Owens and Walling 2003);
- sediment-contaminant interactions (Petticrew et al. 2003, Förstner 2004); and
- the role of flocculation in sediment-contaminant transport and deposition (Petticrew and Droppo 2000, Droppo 2001).

It is important to recognise that most fluxes of sediment and associated contaminants occur in a relatively short period of time with basin scale fluxes often likened to a jerky conveyor belt (Owens et al. 1999) or the theory of traffic flow (Apitz and White 2003). Most diffuse sources and pathways, for example, are only activated during certain periods of time, and are usually driven by rainfall events. Typically, >90% of the sediment flux in most rivers occurs in <10% of the time and it is the big rainfall and flood events that usually cause most erosion, sediment transport in rivers and floodplain deposition. While a CRBM for sediment is able to demonstrate the main sources, pathways and sinks of sediment and contaminants, it is also necessary to establish the magnitude and frequency of the processes which connect the sources-pathways-sinks. Efforts to continuously manage a particular dominant sediment-contaminant pathway may not be cost effective if that pathway is only active occasionally. Instead, resources may be better tailored to those periods when the pathway is active.

The examples presented above (see Figs. 5, 6, 7 and 8) only provide a snap-shot of the sediment system. A better understanding of the system is obtained if information on historical changes in sediment behaviour and dynamics is obtained. This can be achieved through long-term monitoring of sediment fluxes (Owens and Collins 2005), through the reconstruction of sediment dynamics using sediment archive records (e.g. Owens and Walling 2003), and through the use of erosion and sediment transport models (Summer and Walling 2002). Such a temporal perspective is particularly important given present and anticipated changes in climate and land use, and the effects these may have on sediment-contaminant dynamics in river basins (Salomons 2004, Owens 2005): there may be little use in adopting a particular management strategy if an important sediment source were to change in importance because of climate change.

For models and budgets of sediment-contaminant dynamics and behaviour in river basins, of particular importance are the interactions between sediment and associated contaminants, such as chemical speciation, sorption-desorption effects, the influence of particle size and bioavailability. There has been much research on these issue (for example see Salomons and Förstner 1984, Hites and Eisenreich 1987, Evans et al. 1997, Förstner 2004), and as such it is beyond the scope of this paper to discuss these interactions in detail. It is, however, important for developing and using frameworks and models for sediment management to take full consideration of sediment-contaminant interactions and how these interactions may affect sediment-contaminant fluxes and behaviour. Conversely, it is important to recognise and evaluate how management interventions may influence sediment-contaminant interactions.

An example of sediment-contaminant interactions worthy of particular mention, but that to date has tended to be ignored from a sediment-contaminant management perspective, is the role of sediment flocculation in river systems. It is becoming increasingly evident from scientific research that in reality much of the fine-grained suspended load transported in rivers, lakes and estuaries is not transported as individual discrete particles, but instead is transported as flocculated or composite particles. While this phenomena has long been recognised in estuarine and marine environments (e.g. Fowler and Knauer 1986), research in the last decade or so has demonstrated that much of the cohesive, fine sediment load of freshwater systems is also transported as 'flocs' (Droppo and Ongley 1994, Droppo, 2001). By definition, flocculated material is larger than the primary constituent particles and tends to be less dense that equivalent-sized material due to the incorporation of water, organic material and gases within the floc. In turn, the transport and settling behaviour, and the ability to sorb and transport contaminants, can be noticeably different than for primary, discrete particles (Petticrew and Droppo 2000, Droppo et al. 2005). Thus, sediment and associated contaminant deposition in a reservoir or on a floodplain, for example, may be greater than expected if the sediment is flocculated.

4 Summary

The previous sections have described some of the reasons why sediment should be managed at the river basin scale and, in terms of a CRBM, have identified some of the important considerations and requirements for sediment management at the river basin scale. In particular, at an early stage in the sediment management process it is necessary to identify and evaluate the:

- various uses and users that interact with sediment in a river basin;
- various environments within a river basin;
- sources of the sediment and associated contaminants; and
- pathways, storage and fluxes of sediment and contaminants between these environments.

Examples of a conceptual model of sediment sources and pathways and of sediment budgets have been presented. While these models and budgets can be of considerable use during the early stages of the decision-making process, particularly in terms of understanding the sediment-contaminant system and interactions at the basin scale, the examples also illustrate some potential weaknesses which must be considered and evaluated. Finally, some additional issues that relate to water-sediment-contaminant interactions, have been described briefly. These issues have relevance to the development of river basin scale sediment models and budgets, and for sediment management at this scale.

Conceptual models and budgets for sediment offer considerable potential for certain stages of the management process. They are, however, only part of a much larger decision-making process, which involves, amongst other things, stakeholder participation, evaluation of the appropriate legislation and guidelines, and the use of risk assessment and societal cost-benefit analysis.

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