Tools in Fluvial Geomorphology

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Sediment Budgets as an Organizing Framework in Fluvial Geomorphology

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16.1 INTRODUCTION

A river's character is strongly influenced by the amount and timing of the water and sediment provided to it, and a change in sediment or water supply usually provokes a change in the river. When a river's character changes, the activities the river had supported are often disrupted. Applied fluvial geomorphology is largely devoted to understanding and designing strategies for coexisting with changing fluvial systems. To do so, it is usually necessary to understand the river's sediment regime. Theoretical fluvial geomorphology focuses on understanding the mechanics of fluvial processes and the evolution of fluvial landforms. Whenever a fluvial feature changes form, there has been a local imbalance in the movement of sediment to and from the site. In this case, too, an understanding of the sediment regime is usually central to addressing the questions posed.

Both theoretical and applied fluvial geomorphologists address questions of how changes in catchment conditions affect channels, how long the effects will last, and what the sequence of responses will be. Answers to these questions require an understanding of how a river collects, transports, and deposits sediment, and sediment budgets are tools for building that understanding.

Sediment budgets provide frameworks for organizing and interpreting information about sediment regimes, they identify the information needed to address particular questions, and they assist in comparing conditions across catchments and displaying likely outcomes of management options. Magnitudes of a budget's components can be compared in order to establish management priorities or design efficient sediment control or monitoring strategies.

Previous chapters describe a rich array of tools for answering questions concerning rivers, but with an array of choices comes the challenge of identifying the tools appropriate for particular applications. Preliminary sediment budgets can provide information to guide selection of the analytical tools needed for more detailed analyses, and the framework provided by simple, qualitative sediment budgets can aid interpretation of results of the more detailed studies. For other applications, more sophisticated sediment budgets are themselves the strategy for addressing the problems posed. This chapter discusses the nature of sediment budgets, provides examples of how they have been used, and describes an approach for designing and constructing useful budgets.

The Sediment Budget Defined

A sediment budget describes the input, transport, storage, and export of sediment from a geomorphic system. That system can be anything from an individual hillslope segment to the Amazon Basin, from a channel reach to a mountain range. Sediment budgets can be designed to describe the magnitude of a process or response rate, its location, and its timing, or to explore the influences contributing to a morphologic change. They can be used to compare the likely outcomes of different land-management options or climatic changes, or to evaluate the significance and implications of climatic, tectonic, or land-use changes that have already occurred. Sediment budgets provide a framework for organizing both qualitative information about process interactions and quantitative information about process rates. Budgets can take many forms, describe many scales, and incorporate varied levels of precision. The most commonly used sediment budgets take the form of flowcharts that describe relationships between sediment sources and transport processes; these have been the starting point for many geomorphological studies. At the other extreme, long-term monitoring projects have provided precise measurements of particular budget components (e.g., Caine and Swanson 1989).

Whether qualitative or quantitative, all sediment budgets are conceptually underlain by a basic continuity equation for sediment:

$$\text{sediment input to a landscape element} = \text{sediment output} + \text{change in sediment storage}$$

where all terms are expressed as quantities per unit time. The basic equation can be refined in many ways: changes in grain size can be accounted for by constructing equations for different size classes, for example, and specific processes can be identified.

Given the various forms sediment budgets may take and the variety of problems to which they can be applied (Table 16.1), it is clearly not useful to think of sediment budgeting as a singular tool to be applied using a uniform protocol. Instead, sediment budgeting represents a general approach to geomorphic problem solving, and the methods most useful for each budget depend on the intended application for that budget.

History and Applications

Geomorphologists have long used the concept that imbalances between sediment supply and transport capacity cause aggradation and degradation, and by the late 1800s sediment production and transport rates were being measured. Hill (1896), for example, integrated the results of landslide surveys in New Zealand to demonstrate that landslides could influence landscape evolution. Two decades later, Gilbert (1917) incorporated a sediment budget into his analysis of the effects of sediment from hydraulic mining in the Sierra Nevada on navigation in San Francisco Bay.

In 1960s the idea of systematically quantifying the balance between sediment inputs, transport rates, and storage changes began to spread widely through geomorphology. Many methods for quantifying components of sediment regimes had been developed by then, and long-term monitoring and air-photo records were becoming available. At first, quantification of sediment budgets simply involved systematic accounting of process measurements. For example, Jäckli (1957) and Rapp (1960) accumulated measurements of rock material transfers in two European mountain ranges. Leopold *et al.* (1966) measured sediment inputs and some aspects of particle movement and storage in an ephemeral stream in New Mexico.

Sediment budgeting soon proved useful for analyzing the landscape-scale effects of land use. Both Haggett (1961) in Brazil and Trimble (1977) in the Southern Appalachian Mountains of the US found large disparities between landscape-averaged estimates of soil erosion following colonization and the subsequent amounts of fluvial sediment transport in neighboring lowlands. Both authors interpreted the disparities to indicate that huge volumes of sediment must be stored on footslopes and valley floors, and that the storage elements would continue to contribute fluvial sediment long after hillslopes restabilize. These studies emphasized the connections between sediment fluxes through various landscape elements and highlighted the importance of studying changes in sediment storage. Trimble (1983) then retrospectively quantified changes in hillslope-derived sediment input, valley-floor sediment storage, and sediment yield of a catchment in Wisconsin as land was first converted to agricultural use, soil conservation measures were then implemented, and forest eventually reclaimed parts of the catchment.

Field-based monitoring studies began to be coupled with modeling to interpret, extend, and generalize results, and increasingly sophisticated tools were developed to extend the spatial and temporal scales of process measurements. As methodological and conceptual difficulties were surmounted, the organizing power of the sediment budget concept became more evident, and the approach is now widely applied to quantify landform evolution under both natural and modified conditions (Table 16.1).

Sediment budgets play a key role in basic and applied geomorphological studies over a wide range of scales and levels of complexity. For example, Flemings and Jordan (1989) used a model of mountain building, isostasy, and crustal flexure to analyze the partitioning of sediment between an evolving orogen, the adjacent sedimentary basin, and export downstream. Burbank (1992) documented the large-scale sediment budget of deposition in the Ganges foreland basin to identify controls on uplift of the Himalayas.

Table 16.1 Examples of sediment budgets used to address issues in fluvial geomorphology. Explanation of symbols provided at the end of the table

Reference	Problem addressed	Why	Precision	Regime	Time	Method
		PNF	QNS	DESY	AELS	MFACSH
Spatial focus: catchment response						
Gellis *et al.* (2001)	Prioritize subbasins for rehabilitation by erosion potential	.N.	..S	.E..	...S	.FA...
Hovius *et al.* (1997)	Proportion of sediment yield from landslides	.N.	.N.	.E..	A...	.FA...
Page *et al.* (1994)	Sediment contribution to lake from cyclone	.N.	.N.	DESY	.E..	.FA.S.
Pearce and Watson (1986)	Effects of earthquakes on sediment input and transport	P..	.N.	.ESY	.E..	.FA...
Phillips (1986)	Evaluate effectiveness of soil conservation strategies	..F	.N.	DESY	..L.	.F
Phillips (1991)	Influence of upper-basin sediment on lower basin	PN.	.N.	DESY	..L.	.F
Reneau and Dietrich (1991)	Relation between hillslope erosion and sediment yield	P..	.N.	.E.Y	A...	.F..SH
Roberts and Church (1986)	Effects of logging on sediment input and channel form	.N.	.N.	.ES.	..L.	.FA...
Smith and Swanson (1987)	Sediment routing after tephra deposition by an eruption	.N.	.N.	.ES.	.E.S	MF....
Springer *et al.* (2001)	Effect of storm	.N.	.N.	.ESY	.E..	.F....
Wasson *et al.* (1998)	Effects of land use on sediment yield	P..	.N.	.ESY	...S	.FA.SH
Spatial focus: channel system response						
Abernethy and Rutherfurd (1998)	Use distribution of bank erosion types to plan restoration	.NF	Q.S	DE..	...S	.F.C..
Benda (1990)	Effect of debris flows on downstream channel form	.N.	.N.	DESY	...S	.FA...
Brizga and Finlayson (1994)	Is upstream land use causing downstream aggradation?	.N.	Q..	DES.	..L.	.FA..H
James (1999)	Extent of channel recovery from mining debris inputs	.NF	..S	DES.	..L.	MFA..H
Knighton (1991)	Effect of mining on downstream channels	P.F	.N.	DESY	..L.	.FA...
Le Pera and Sorriso-Valvo (2000)	Changes in sediment character along a channel	.N.	.N.	D...	...S	.F....
Liébault and Piégay (2001)	Effect of land-use change on form of downstream channel	.N.	.N.	.ES.	..L.	.FACS.
Madej and Ozaki (1996)	Extent of channel recovery from the 1964 flood	P..	.N.	DESY	.E..	MFA...
Marron (1992)	Downstream distribution of introduced mining debris	P..	.N.	DES.	..L.	.FA.S.
Marutani *et al.* (1999)	Significance of temporary sediment storage	P..	.N.	.ESY	...S	.FA...

(*Continues*)

Table 16.1 (*Continued*)

Reference	Problem addressed	Why	Precision	Regime	Time	Method
		PNF	QNS	DESY	AELS	MFACSH
Trimble (1983)	Effects of land use on downstream conditions	P..	.N.	DESY	..L.	.F.C..
Trimble (1993)	Develop strategy for catchment rehabilitation	..F	..S	DESY	..L.	.F.C...
Spatial focus: response of a particular reach						
Brooks and Brierley (1997)	What caused the channel form to change?	P..	Q..	.ES.	..L.	.F..S.
Collins and Dunne (1989)	Effect of gravel mining on channel form	P..	.N.	.ES.	..L.	.FAC.H
Davis *et al.* (2000)	Basis for designing appropriate gravel harvest rate	.N.	..S	DES.	...S	.F.C.H
Dunne *et al.* (1998)	Exchanges of sediment between channel and floodplain	.N.	.N.	DESY	A...	MFAC..
Gilbert (1917)	Will hydraulic mining debris affect shipping channels?	..F	.N.	.ESY	..L.	.F.C..
Kesel *et al.* (1992)	Describe original sediment regime in lower Mississippi River	P..	.N.	.ESY	A...	.....H
McLean *et al.* (1999)	Variation of particle transport modes through a reach	.N.	.N.	D.SY	A...	M.....
Nakamura *et al.* (1997)	Effect of channelization on a wetland	P..	.N.	D.S.	..L.	MFA...
Parker (1988)	Suspended sediment budget for channel reach	.N.	.N.	DESY	...S	M.....
Pitlick and Van Steeter (1998)	River management strategies to improve fish habitat	..F	.N.	DES.	..L.	MF.C..
ten Brinke *et al.* (1998)	Extent of sand deposition during floods	.N.	.N.	D.S.	.E..	.FA...
Van Steeter and Pitlick (1998)	Effect of dams on channel form	PN.	.N.	DES.	..L.	M.A..H
Walling *et al.* (1998)	Extent of deposition of suspended sediment load	.N.	.N.	..S.	...S	MF..S.
Wathen and Hoey (1998)	Behavior of sediment wave and effects on channel form	.N.	.N.	DES.	.E..	MFA...
Wiele *et al.* (1996)	Distribution of sands introduced by tributary	.N.	.N.	DES.	.E..	MFAC..
Wilcock *et al.* (1996)	What dam release regime will most benefit bed material?	..F	.N.	.ES7.	A...	...C..
Wohl and Cenderelli (2000)	Effect of sediment release on downstream conditions	.N.	.N.	DESY	.E..	MF....
Spatial focus: specific land use, landform, etc.						
Harvey (1992)	Factors controlling a gully's form and evolution	PNF	.N.	DESY	A...	MFA...
Megahan *et al.* (1986)	Sediment input during forest road construction	.N.	.N.	.E.Y	..L.	M.....

(*Continues*)

Table 16.1 (*Continued*)

Reference	Problem addressed	Why	Precision	Regime	Time	Method
		PNF	QNS	DESY	AELS	MFACSH
Page and Trustrum (1997)	Effect of land-use changes on lake sedimentation	P..	.N.	...Y	A.L.	....S.

Explanation of symbols used:

Why: purpose

P	Past	Explain how a condition developed
N	Present	Describe interactions within present system
F	Future	Forecast future forms, conditions, or outputs

Precision

Q	Qualitative	Depends primarily on qualitative results
N	Quantitative	Depends primarily on quantitative results
S	Semi-quantitative	Incidental quantification, rankings, etc.

Component of sediment regime

D	Distribution	Conclusions involve spatial distribution
E	Erosion	Erosion specifically evaluated
S	Storage	Sediment storage specifically evaluated
Y	Sediment yield	Yield specifically evaluated

Time considered

A	Average	Generalized, or long-term average
E	Particular event	Effect of a particular triggering event
L	Land-use activity	Timescale selected to evaluate land use
S	Specific period	Conclusions referenced to particular period

Method

M	Monitoring	Monitoring was carried out for the study
F	Field work	Field measurements or observations
A	Air photos	Air photos for measurement or interpretation
C	Modeling	(Includes use of published equations)
S	Stratigraphy	Analysis of datable deposits
H	Historical records	(Includes archived monitoring records)

Church and various colleagues (Church and Ryder 1972, Church and Slaymaker 1989, Church *et al.* 1999) illustrated the importance of lagged and indirect responses in erosion and sedimentation during and after glaciation. Questions about the response of rivers to perturbations such as land use (Trimble 1974), dam construction and gravel mining (Kondolf and Swanson 1993), volcanic eruptions (Lehre *et al.* 1983), and sea-level rise (Meade 1982, Allison *et al.* 1998) have also been explored by systematically accounting for input and output of sediment. Other studies have examined the exchange of sediment between channels and their floodplains (Marron 1992, Dunne *et al.* 1998) and between catchment hillslopes and floodplains (Marutani *et al.* 1999, Gomez *et al.* 1999), and have evaluated the imbalance between rates of sediment generation from bedrock and its export from drainage basins over various time periods (Clapp *et al.* 2000, 2001; Kirchner *et al.* 2001). Such studies provide information needed to motivate, plan, and interpret more detailed studies of sediment production and transport processes and their driving agents.

Because sediment influences many ecosystem and watershed processes, sediment budgeting can also be used to explore non-geomorphological issues. Graf (1994), Malmon (2002), and Malmon *et al.* (2002), for example, studied the migration of radionuclides through channels and floodplains of Los Alamos Canyon, New Mexico, paying particular attention to the disparate trajectories of coarse sediment that contains little contaminant and the more reactive fine sediment.

Sediment budgeting has long contributed to management of sediment-related problems. Studies have described the effects of logging on sediment regimes through long-term monitoring (Swanson *et al.* 1982) and field-based surrogate measures of process rates (Roberts and Church 1986). Other studies have quantified the effects of specific activities such as road construction (Megahan *et al.* 1986) and road use (Reid and Dunne 1984). Such studies aid erosion control efforts by identifying the most important influences on and sources of sediment production. Sediment budgets for river channels have been quantified to establish appropriate extraction rates for gravel (Collins and Dunne 1989, Davis *et al.* 2000). Sediment budgeting has also been used to design strategies for catchment-scale sediment control (Phillips 1986, Trimble 1993, Gellis *et al.* 2001) and riparian restoration (Abernethy and Rutherfurd 1998), and to plan reservoir releases to maintain habitat for particular species (Wilcock *et al.* 1996, Pitlick and Van Steeter 1998).

Sediment budgets are increasingly used to aid regulatory oversight of land-use activities. Under the US Clean Water Act, for example, "Total Maximum Daily Load" allocations and sediment control plans must be developed for non-point-source sediment in catchments found to be impaired by such sediment. To do so, the amount and sources of anthropogenic sediment must be determined. Sediment budgeting can also aid preparation of environmental impact assessments, which usually must predict the effects of planned projects on sediment production and on cumulative environmental impacts. Off-site cumulative impacts often result from changes in erosion, transport, or deposition of sediment.

16.2 BACKGROUND: THE SEDIMENT SYSTEM

A sediment system can be examined from many points of view, and each of these could be represented by a sediment budget. Which point of view is most useful depends on the intended application. To understand the variety of approaches possible, the components of a catchment's sediment production and transport system must first be reviewed.

Entire books have been written about specific aspects of the sediment system, and other chapters in this book discuss sediment transport (Chapters 13 and 15) and channel change (Chapters 10, 11, and 19). Here we briefly summarize concepts that are particularly relevant to sediment budgeting. Reid and Dunne (1996) provide more detailed descriptions of methods.

Hillslope Processes and Sediment Delivery to Streams

Sediment in a catchment originates from bedrock, atmospheric deposition, and biological activity. Bedrock becomes sediment through physical and chemical weathering, during which some of the original material is removed by dissolution. Heimsath *et al.* (1997) have defined the "soil production rate" as the rate per unit area at which soil material is converted from bedrock; Small *et al.* (1999) refer to this quantity as the "regolith production rate".

As weathering progresses, a particle may remain in place as saprolite or be dislodged (eroded) and transported downslope as colluvium. Erosion rates are generally described as a net loss of sediment per unit area, while transport rates represent the discharge of sediment per unit width of hillslope or through a channel cross section. Net erosion occurs only where transport into an area is less than transport out. Rates are reported in terms of either volume or mass, but values reported by mass can be compared more readily.

Ordinarily, a sequence of disparate hillslope processes (Table 16.2) moves a sediment particle downslope until it is finally delivered to a channel. The rate of sediment production to stream channels has been defined as the rate of colluvial sediment transport across a line corresponding to the streambank (Reid and Dunne 1996)—note that the words "production" and "delivery" can refer to transfer between any landscape elements, so the context for the usage must be considered if confusion is to be avoided.

Table 16.2 Examples of methods used to evaluate erosion, colluvial sediment transport, and primary sediment production to channels. Additional methods, including direct monitoring, are usually available. The major controlling variables are listed in parentheses after the process name to aid stratification and facilitate use of data from analogous sites. Expected accuracies are estimated for typical conditions; an expected accuracy of *H* indicates that the estimated value is expected to be between 0.6 and 1.6 times the actual value; *M*, 0.4–2.5 times; and *L*, less than 0.4 to more than 2.5 times. Accuracies can be increased through more detailed work or long-term monitoring or decreased through use of reconnaissance methods. References are selected to provide further information about a process, demonstrate methods for evaluating it, or illustrate its incorporation into a sediment budget

Examples of analysis methods by process	Sample references
Dissolution (controlling variables: topography, climate, bedrock, soil depth, vegetation)	
Monitor discharge and concentration of non-organically derived solutes in outflow and precipitation. May be able to develop relation between concentrations and specific conductivity, which is readily monitored. Define relation between concentration and discharge—this may vary seasonally and by solute. Apply this relation to the annual hydrograph to calculate a year's total non-organic solute yield, and subtract solute input from precipitation (expected accuracy: *H*)	Chapters 12 and 20; Janda (1971), Lewis and Grant (1979), Saunders and Young (1983), Clayton and Megahan (1986), Caine and Thurman (1990), Small *et al.* (1999), Hodson *et al.* (2000)
Soil creep (gradient, climate, soil type, soil depth, vegetation)	
Difficult to monitor accurately; few measurements exist. Method 1: apply values of creep rate measured at similar sites, and multiply estimated creep discharge per unit width by the length of colluvial streambank (*L*). Method 2: sediment production from creep transport is by way of other processes such as bank erosion and streambank landslides, so assess these processes instead (*M*)	Saunders and Young (1983), Auzet and Ambroise (1996), Reid and Dunne (1996), Clarke *et al.* (1999)
Burrowing (gradient, species, soil type, vegetation)	
Production is by transport of burrow tailings across streambanks; measure deposit volumes and consider the seasonal distribution of burrowing (*H*). Delivery by overland flow may be important. Must know burrow patterns to assess on-slope transport; these vary by species (*L*)	Chapter 20; Thorn (1978), Meentemeyer *et al.* (1998), Gabet (2000)
Tree-throw (gradient, storm size, vegetation type and age)	
Identify fall modes (i.e., breakage or tree-throw) for each vegetation type, and use age of associated vegetation to identify fall-age diagnostics (e.g., time to shedding of twigs or loss of bark). Field sample to estimate delivery ratios and number of contributing rootwads by age per unit channel length (*H*). For transport rate, sample frequency per unit area, rootwad volumes (less root volume), and displacement of mounds from scars (*H*). Consider history of wind storms	Chapters 10 and 20; Santantonio *et al.* (1977), Schaetzl *et al.* (1989), Norman *et al.* (1995), Small (1997), Reid and Hilton (1998)
Earthflows (gradient, seasonal rainfall, bedrock, vegetation)	
Map visible flows on air photos; less visible flows require fieldwork. Delivery is by bank erosion, gully erosion, and streambank landslides. Method 1: use methods described below to assess rates of delivery processes (*M*). Method 2: estimate surface velocity near toe by measuring displacement of survey markers or features visible on sequential air photos, assume a characteristic velocity profile (or measure it using inclinometer tubes), and apply the resulting unit discharge to the measured flow cross section at the streambank (*H*). Also assess gully erosion if present (see below)	Chapters 6, 10, and 20; Van Asch and Van Genuchten (1990), Zhang *et al.* (1991a,b, 1993), Nolan and Janda (1995), Swanston *et al.* (1995)

(*Continues*)

Table 16.2 (*Continued*)

Examples of analysis methods by process	Sample references
Deep-seated slides (gradient, seasonal rainfall, bedrock, vegetation)	
Map and date using sequential aerial photos; field sample to measure sediment delivery (compare scar and deposit volumes), evaluate slide not visible on photos, and date small scars from vegetation ages. Assess as for earthflows if movement is chronic or intermittent; if removal of deposits is intermittent, evaluate temporary storage. May be able to define relationships between scar area and volume and between topographic setting and delivery ratio. Calculate production as frequency × volume × delivery ratio for each land stratum. Consider abnormally wet or dry seasons when interpreting average rates (*H*)	Chapters 6, 10, and 20; Chandler and Brunsden (1995), Ibsen and Brunsden (1996), Mantovani *et al.* (1996), Wiles *et al.* (1996), Corominas and Moya (1999), Fantucci and Sorriso-Valvo (1999)
Shallow slides (gradient, landform, storm rainfall, bedrock, vegetation, earthquakes)	
Map and date using sequential aerial photos; field sample to measure sediment delivery (compare scar and deposit volumes), evaluate slides not visible on photos, and date small scars using vegetation ages. May be able to define relationships between scar area and volume and between topographic setting and delivery ratio. Calculate production as frequency × volume × delivery ratio for each land stratum. Consider storm history when interpreting average rates (*H*)	Chapters 6, 9, 10, and 20; Roberts amd Church 1986, Page *et al.* (1994), Mantovani *et al.* (1996), Reid and Dunne (1996), Hovius *et al.* (1997), Reid (1998), Corominas and Moya (1999)
Rockfalls and rock slides (gradient, weather, bedrock exposure, bedrock type, earthquakes)	
Map and date large falls using sequential aerial photos; older falls might be dated using vegetation ages or lichenometry. More diffuse falls might be assessed by measuring volumes accumulated on a datable surface such as a snowpack, or from repeated ground-based stereophotography of rock faces. Consider proximity to stream to estimate delivery; blocks may be too large for transport (*H*)	Chapters 6, 10, and 20; Bull *et al.* (1994), Wieczorek and Jäger (1996), André (1997), Matsuoka and Sakai (1999)
Streambank slides (gradient, flow distribution, channel size and form, bedrock, vegetation)	
Assess most inner-gorge and valley-wall failures as for shallow slides (*H*). If undercut valley walls are long-term sources, assess wall retreat using air photos or vegetation (*H*). Small failures in alluvium and colluvium can often be analyzed with other bank erosion processes. Otherwise, identify characteristic failure sizes and temporal and spatial patterns of failure along channels of different kinds; consider recent storm history when estimating average rates (*H*)	Chapters 7, 10, 11, and 20; Thorne and Tovey (1981), Kelsey *et al.* (1995), Couper and Maddock (2001)
Debris flow erosion (hillslope gradient, storm rainfall, channel gradient, bedrock, vegetation)	
Under steady state, only erosion of colluvium and bedrock is primary; otherwise, also evaluate remobilization of channel deposits. Map and date visible scars using air photos; measure widths in the field if obscured by trees. Identify other flows in the field from debris deposits and date using vegetation. Determine characteristic erosion depths from scarp heights and from depths of soil and channel deposits at analogous sites. Consider storm history when interpreting average rates (*H*)	Chapters 6, 7, 10, 11, and 20; Benda (1990), van Steijn (1996), Yoshida *et al.* (1997), Cenderelli and Kite (1998), Springer *et al.* (2001)

(*Continues*)

Table 16.2 (*Continued*)

Examples of analysis methods by process	Sample references
Primary streambank erosion (gradient, peak-flow size, channel size, soil type, vegetation)	
Under steady state, only colluvial and bedrock erosion is primary; otherwise, also evaluate erosion of alluvium because it alters the distribution of stored sediment. Stratify by channel type. Estimate bank retreat rates in large channels with visible banks using sequential air photos and field measurements of bank height (*H*). Otherwise, field sample to estimate proportion of banks eroding (i.e., without vegetation). Rates are often difficult to assess without monitoring, but might be estimated from datable vegetation, scarp depths, or deposit volumes (*M*). Estimates have also been made by applying an estimated creep discharge to the susceptible bank area (*L*)	Chapters 4, 6, 7, 10, 11, and 20; Roberts and Church (1986), Kesel *et al.* (1992), Trimble (1994), Reid and Dunne (1996), Zonge *et al.* (1996), Barker *et al.* (1997), Stott (1997), Dunne *et al.* (1998), Cohen and Brierley (2000), Prosser *et al.* (2000), Couper and Maddock (2001)
Primary channel erosion (channel gradient, peakflow size, channel size, bedrock)	
Under steady state, only colluvial and bedrock erosion is primary. Long-term, steady-state channel lowering is of the same order as the mean hillslope lowering rate, but channel area is small relative to hillslope area so production from this source is relatively small. Where steady state cannot be assumed, incision of alluvium must also be evaluated (Table 16.3). Most reliably assessed by dating terrace surfaces to calculate incision rate since the surfaces were formed (*H*)	Chapters 4, 7, 9–11, and 20; Clayton (1997), Seidl *et al.* (1997), Trimble (1997), Ward and Carter (1999), Reneau (2000)
Tunnel erosion (gradient, landform, soil type)	
Examine channel heads to ascertain presence of tunnels (soil pipes); identify upslope extent by trenching or observing collapse features. Sediment delivery is most reliably assessed by monitoring effluent from multiple tunnels (*M*). Otherwise, measure deposit volumes on hillslopes (ascertain that their presence does not indicate an atypical feature) and apply to the full distribution of tunnels (*L*), or apply published measurements from analogous features (*L*)	Chapters 12, 15, and 20; Jones (1987), Ziemer (1992), Garland and Humphrey (1992), Page *et al.* (1994), García-Ruiz *et al.* (1997), Terajima *et al.* (1997)
Gullying (gradient, catchment area, peakflow size, channel size, soil type, vegetation, compaction)	
Map and date gullies in open terrain using sequential air photos; use field measurements to identify relations between length or area and volume, and use these to estimate volume changes through time (*H*). Otherwise, field sample for distribution, frequency, size, and age. Date using associated vegetation, eye-witness accounts, or age of causal features. Estimate sediment production through time from retreat rate and volume–length relationships (*H*)	Chapters 2–4, 6, 9, 10, and 20; Swanson *et al.* (1989), Harvey (1992), Archibold *et al.* (1996), DeRose *et al.* (1998), Nachtergaele and Poesen (1999), Vandekerckhove *et al.* (2000)
Rilling (gradient, slope length, storm rainfall, soil type, vegetation, compaction)	
Assess distribution considering controlling variables and season. Monitor or field sample rill dimensions before and after wet season or storms of different sizes, or through year. Estimate delivery ratio from size distribution and volume of deposits (compare to soil texture), or from sediment concentration measurements. If using an erosion equation, test by comparing predictions and measurements (*H*)	Chapters 12, 15, 17, and 20; Collins and Dunne (1986), Smith and Swanson (1987), Harvey (1992), Slattery *et al.* (1994), Flanagan and Nearing (1995), Morgan *et al.* (1998)

(*Continues*)

Table 16.2 (*Continued*)

Examples of analysis methods by process	Sample references
Sheet and rainsplash erosion (gradient, slope length, storm rainfall, soil type, vegetation, compaction)	
Define distribution by controlling variables and season. Field sample root exposure on datable plants or monitor erosion pins (*H*). These measurements combine effects of sheet, rainsplash, dry ravel, and wind erosion, so use the spatial and temporal distribution of each to interpret results. If using an erosion equation, test by comparing predictions and measurements (even short-term data will indicate whether results are approximately correct). Estimate delivery ratio from size distribution and volume of deposits (compare to soil texture), or from sediment concentration measurements; erosion equation results should be checked against field evidence (*H*). Surface erosion can also be quantified by sampling runoff from small, definable catchments (*H*)	Chapters 12, 15, 17, and 20; Wischmeier and Smith (1978), Carrara and Carroll (1979), Trimble (1983), Reid and Dunne (1984), Collins and Dunne (1986), Smith and Swanson (1987), Flanagan and Nearing (1995), Quine *et al.* (1997), Renard *et al.* (1997), Morgan *et al.* (1998), Brazier *et al.* (2000), Yanda (2000)
Wind erosion (storm size, soil moisture, soil type, vegetation)	
Define distribution by controlling variables and season. Measure root exposure on datable plants or monitor erosion pins (*H*). These measurements combine effects of sheet, rainsplash, dry ravel, and wind erosion, so consider their spatial and temporal distributions to interpret results. If using an erosion equation, compare predictions and measurements. Estimate delivery ratio from intersection of travel paths with streams, or calculate input from measured aerial deposition (*M*)	Chapters 17 and 20; Skidmore and Woodruff (1968), Potter *et al.* (1990), Leys and McTainsh (1996), Phillips *et al.* (1999), Borówka and Rotnicki (2001), Goossens *et al.* (2001)
Dry ravel (gradient, soil moisture, soil type, temperature, vegetation)	
Define distribution by controlling variables and season. Measure root exposure on datable plants or monitor erosion pins or accumulation in troughs. Such measurements combine effects of sheet, rainsplash, dry ravel, and wind erosion, so consider their spatial and temporal distributions to interpret results. Compare grain sizes of deposits and sources to estimate delivery (*H*)	Chapter 20; Megahan *et al.* (1983)
Construction, tillage, engineering, etc. (gradient, type of project, soil type, bedrock)	
Only direct mechanical displacement of sediment is considered here; secondary processes are considered above. Aerial photos, maps, plans, interviews with equipment operators, and field observations can indicate distribution and timing of effects and location of displaced material with respect to streams (*H*). Estimate tillage transport from topographic discontinuities at field edges, and delivery by applying the resulting rate to adjacent streams or assessing bank erosion there (*H*)	Chapter 20; Riley (1990), Vandaele *et al.* (1996), Quine *et al.* (1997), Phillips *et al.* (1999)
Deposition on hillslopes and swales (gradient, landform, soil type, vegetation, sediment input)	
For non-discrete processes, field sample accumulation depths around datable plants or structures, or measure seasonal accumulations atop leaf litter (*H*). Stratigraphic dating methods can be used for long-term accumulations (*H*). For discrete processes, measure volumes of deposits and date using sequential aerial photographs or ages of associated plants (*H*)	Chapters 2, 3, 6, 9, 10, and 20; Megahan *et al.* (1986), Page *et al.* (1994), Vandaele *et al.* (1996), Phillips *et al.* (1999), Beuselinck *et al.* (2000)

In an accounting of primary sediment input, any particle can be delivered to the stream system only once. For example, soil creep often moves sediment to the base of a slope, where bank erosion carves away the encroaching sediment. In this case, sediment delivery is evaluated as either the rate of streambank erosion or the soil creep discharge at the channel margin, but these rates cannot be summed because both processes involve the same particles. Similarly, sediment production cannot be calculated by summing rates of landsliding and soil creep where creep transports colluvium to bedrock hollows that are episodically evacuated by landslides (Reneau and Dietrich 1991, Dunne 2000). A portion of the sediment derived from colluvium may be deposited downstream and later reenter the channel through erosion of alluvium. Such re-entry (described in Table 16.3) represents remobilization from temporary storage rather than primary sediment delivery. In contrast, sediment introduced by channel incision into bedrock represents primary sediment delivery (Table 16.2).

Colluvial transport processes are of two kinds. "Chronic" processes include transport by rainsplash, soil creep, sheetwash, wind, and other mechanisms that recur frequently at the same sites. "Discrete" processes, in contrast, are events that can be counted, such as landslides and tree-throws. Table 16.2 describes methods for measuring a selection of process rates and attributes and lists examples of studies that have evaluated or are relevant to assessment of each process. Other methods are also available, including direct, long-term monitoring for most processes listed.

Chronic processes are usually evaluated by determining average rates and applying those to the areas affected. For example, the rate of sheetwash erosion on rangelands might be estimated from measurements of root exposure around datable vegetation, by monitoring surface lowering around erosion pins, or by modeling using the USLE (Wischmeier and Smith 1978, Renard *et al.* 1997) or WEPP (Flanagan and Nearing 1995). The estimated rate would then be assumed to apply throughout the area of similar land-use activity, topography, and soil type. Only part of the eroded sediment is delivered to channels, however, and this amount varies with conditions in and around the eroding sites. The delivery ratio can be estimated for different site types using methods such as monitoring sediment transport in overland flow during a few storms, applying erosion models, or comparing the grain size of deposits to that of the eroding material. Sediment production rates are then calculated by multiplying erosion rates by sediment delivery ratios for each site type and applying these values to the distribution of site types present.

Rates of discrete processes, such as landslides, usually are evaluated by applying the measured spatial and temporal frequency of events to the area susceptible. Shallow landslide scars, for example, ordinarily are counted on sequential air photos to determine the number of slides per unit area per unit time. Fieldwork is usually necessary to define a relationship between scar area and scar volume and to determine the proportion of the landslide debris characteristically delivered to streams, and is also useful for estimating the frequency of landslides too small to detect on photos. Because shallow landslides are generally triggered by infrequent, large storms, the dependence of areal landslide density on the magnitude of triggering events may need to be defined to determine whether the sampling period is long enough to estimate average rates validly (e.g., Figure 16.1). For many applications, only the relative rates between different land uses or landforms need be known, and results from a single major storm often can provide this information.

Analysis of other process rates generally follows similar patterns (Table 16.2). The success of each rate analysis depends on:

1. having a well-defined objective that identifies the information required;
2. using a sampling design that permits valid characterization of the process;
3. recognizing the area and time period over which the estimate applies.

Wherever possible, rates should be estimated using multiple methods and should be checked for consistency; this is particularly important if rates are to be modeled mathematically in areas or under conditions for which the model has not been adequately tested.

Sediment Transport in Channels

Changes in hillslope sediment transport rates arouse particular concern when sediment reaches a channel, and so can affect off-site conditions. Sediment entering a channel either is transported downstream or alters channel morphology where it enters. Such alterations modify the channel bed and the sediment transport rate through the reach, and may even change the dominant transport mode. For example, long-term sediment accumulation in first-order steepland channels can convert them into unchanneled swales (zero-order basins), and eventually deepen the fill enough to

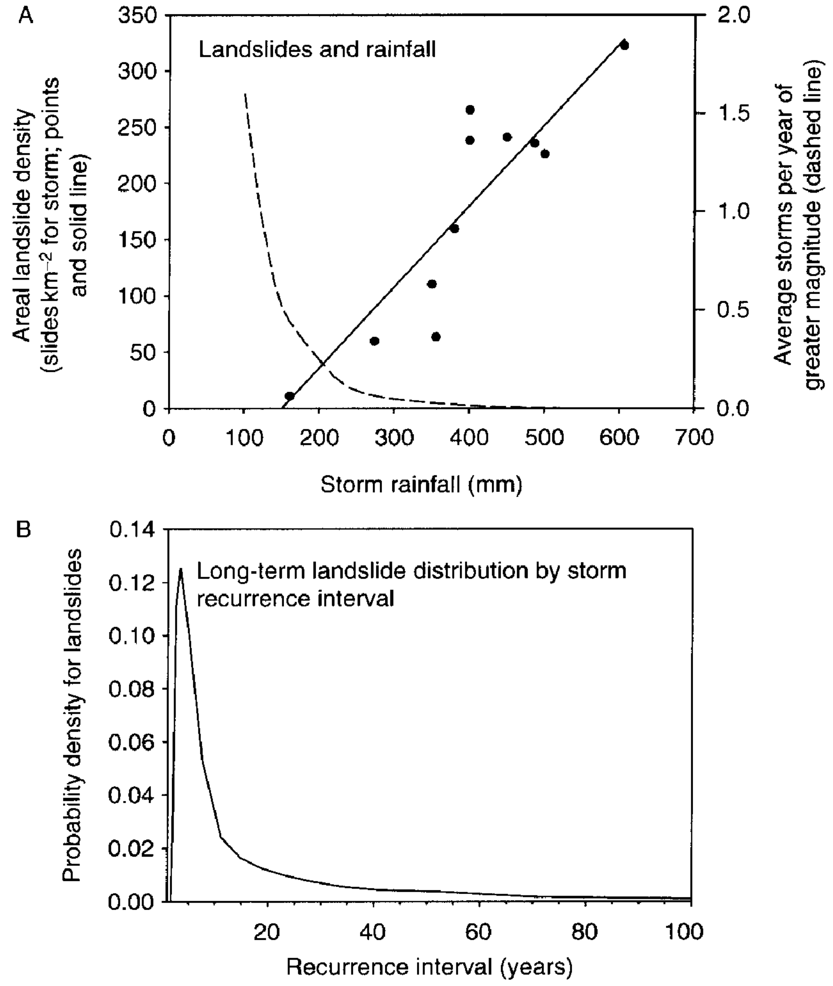

Figure 16.1 Assessing the long-term distribution of landslides as a function of storm recurrence interval for colluvial landslides on the Te Arai land system under the Waipaoa Station rainfall regime, North Island, New Zealand. (A) Areal landslide density and storm frequency as a function of storm rainfall. (B) Long-term distribution of landslide sediment inputs as a function of storm recurrence interval

generate shallow landslides (Dietrich *et al.* 1982); sediment transport shifts from fluvial, to soil creep, to landsliding. In other cases, channel flows gradually remove newly introduced sediment, leaving only the largest clasts to weather in place. How rapidly the sediment is removed depends on characteristics of both the sediment input and the channel.

Streams transport sediment in three ways. The largest grains are rolled or jostled along the bed as "bedload", while the smallest particles are continually suspended in the flow (washload). Intermediate grains are entrained repeatedly by eddies and move predominantly as suspended load. These intermediate sizes return to the bed when flow slows and are referred to as the "bed material suspended load"; most sediment in the streambed represents size fractions moved as bedload (especially in gravel-bed channels) or bed material suspended load (in sand-bed channels). The transport mode for a particular grain varies with flow and with channel characteristics (e.g., McLean *et al.* 1999).

Travel times for different components of the sediment load vary widely. Washload can exit a 1500-km^2 catchment during the same storm that eroded the sediment from a headwater hillslope, while bedload may require many decades to move the same distance. Matisoff *et al.* (2002b) have demonstrated that concentrations of the isotopes ^{7}Be, ^{137}Cs, and ^{210}Pb on suspended sediment can be used to measure the speeds and distances of fine sediment transport in single events.

The most accurate estimates of sediment transport rates in channels are provided by well-designed and maintained monitoring stations with records long enough to produce representative results. However, most sediment budgets must be constructed too rapidly to allow determination of transport rates by monitoring if records do not already exist (Table 16.3). Instead, rates ordinarily are estimated using

Table 16.3 Examples of methods used to evaluate sediment transport and storage in channels, erosion of alluvial sediment, and sediment yield. Additional methods, including direct monitoring, are usually available. The major controlling variables are listed in parentheses after the process name to aid stratification and facilitate use of data from analogous sites. Expected accuracies are estimated for typical conditions; an expected accuracy of *H* indicates that the estimated value is expected to be between 0.6 and 1.6 times the actual value; *M*, 0.4–2.5 times; and *L*, less than 0.4 to more than 2.5 times. Accuracies can be increased through more detailed work or long-term monitoring or decreased through use of reconnaissance methods. References are selected to provide further information about a process, demonstrate methods for evaluating it, or illustrate its incorporation into a sediment budget

Examples of analysis methods by process	Sample references
Bedload (controlling variables: channel gradient and form, flow distribution, grain size, sediment input, bedrock)	
Where the coarse load is trapped in a lake or low-gradient reach, estimate transport by measuring changes in depositional landforms through time using bathymetric measurements or air photos (*H*). Otherwise, bedload transport equations are usually applied. Equations must be carefully selected to be appropriate for the conditions being assessed (*M*). Bedload sampling data are available for a few stations, but records are usually sparse and short.	Chapters 7, 11–15, 17, 18, and 20; Collins and Dunne (1989), Wilcock *et al.* (1996), Reid and Dunne (1996), McLean and Church (1999), Ham and Church (2000)
Suspended load (channel gradient and form, flow distribution, grain size, sediment input, bedrock)	
Measure suspended sediment concentrations over a range of flows to define a sediment rating curve and apply the resulting curve to annual hydrographs (*H*). Sediment transport equations for suspendible bed material load are useful if input-dependent washload is not large (*M*).	Chapters 7, 12, 15, 17, 18, and 20; Walling and Webb (1982), Reid and Dunne (1984, 1996), Parker (1988), McLean *et al.* (1999), Asselman (2000), Singer and Dunne (2001)
Sediment attrition (transport rate, grain size, rock type)	
Tumbling-mill experiments can indicate grain size changes per unit travel distance (*H*). If different lithologies are present, use changes in relative abundance to estimate relative breakdown rates (*H*). Compare sediment stored for different lengths to assess importance of dissolution (*M*)	Chapters 13 and 20; Collins and Dunne (1989), Le Pera and Sorriso-Valvo (2000)
Bed aggradation (channel gradient and form, flow distribution, grain size, sediment load)	
Land surveys or surveys for bridge planning can be repeated; local residents can describe recent changes; and engulfed artifacts, woody debris, or plants can indicate the extent and timing of aggradation, as can changes in flood severity. Long-term gauging data can document changes in bed elevation. Recently aggraded bed material often is finer grained and can sometimes be probed to determine the depth of a buried gravel armor layer. Comparison of geometry in aggraded and non-aggraded channels can indicate the magnitude and distribution of changes. Establish timing from personal accounts, vegetation ages, and comparison of sequential air photos. Estimate bar aggradation rates by multiplying the areas of bars deposited by average bar heights. (*H* to *M*)	Chapters 4, 7, 10, 11, 13 and 20; Smith and Swanson (1987), Collins and Dunne (1989), Benda (1990), Knighton (1991), Madej and Ozaki (1996), Wiele *et al.* (1996), Brooks and Brierley (1997), Heritage *et al.* (1998), Wathen and Hoey (1998), Lisle and Hilton (1999), James (1999), Sloan *et al.* (2001)

(Continues)

Table 16.3 (*Continued*)

Examples of analysis methods by process	Sample references
Bank and floodplain aggradation (*channel gradient and form, flow history, grain size, sediment load, vegetation*)	
Measure deposit depths around datable plants or structures, or date deposits using methods described in other chapters (*H*). Data from sediment traps or erosion pins can indicate relation between deposition and flood size, as can post-flood observations of deposition atop litter layers; data from large floods are needed to estimate long-term rates (*H*). Many methods for assessing bed aggradation can be applied to banks. Several-decade-long cores can be dated with ^{137}Cs concentration profiles; profiles of ^{210}Pb attached to clay particles can provide longer ($\sim$100 years) records; and ^{14}C dating produces records dating back thousands of years. Standard stratigraphic methods can be used to correlate cores at different locations.	Chapters 2, 3, 6, 7, 9–12, 14, 15, and 20; Marron (1992), Nakamura *et al.* (1995), Asselman and Middelkoop (1998), ten Brinke *et al.* (1998), Walling *et al.* (1998), Walling and He (1998), Goodbred and Kuehl (1998), Gomez *et al.* (1999), Rumsby (2000), Lecce and Pavlowsky (2001), Steiger *et al.* (2001)
Channel erosion of alluvial sediments (*channel gradient and form, flow distribution, grain size, sediment load, bedrock*)	
Compare channel geometry to that of unaffected channels (*H*). Land surveys or cross sections surveyed for bridge planning can be resurveyed if available. Calculate river-bed elevation trends at gauging stations from low-flow stage records and flow-depth measurements. Residents can describe recent changes, and undercut vegetation or exposed bridge piers may provide data. Timing is usually established from personal accounts or comparison of sequential air photos. Evaluate erosion rates from shifting of large channels by multiplying the areas of bank eroded by the average bank height. (*H* to *M*).	Chapters 4, 7, 10, 11, and 20; Dunne (1977), Collins and Dunne (1989), Booth (1990), Erskine *et al.* (1992), James (1997, 1999), Heritage *et al.* (1998), Knighton (1999), Wohl and Cenderelli (2000), Gonzalez (2001), Liébault and Piégay (2001)
Sediment yield (*catchment size, flow distribution, sediment input, bedrock, vegetation, topography*)	
Where catchments drain into lakes or ponds, yield can be estimated from rates of lake sedimentation if the trap efficiency is known and the bathymetry has been monitored or can be reconstructed (*H*). Measurements or calculations of sediment transport at the mouth of a catchment provide an estimate of yield (*H* to *M*). Nearby catchments with similar characteristics are expected to have similar sediment yields (*M*).	Chapters 2, 9, 11, 14, and 20; Brune (1953), Megahan *et al.* (1986), Evans (1997), Hill *et al.* (1997), Page and Trustrum (1997), Wilby *et al.* (1997), Lloyd *et al.* (1998), Evans and Church (2000), Verstraeten and Poesen (2000), Cisternas *et al.* (2001)

transport equations, as described in Chapter 15, or by measuring the volume of sediment deposited in an effective sediment trap over a known time (e.g., Ham and Church 2000, Davis *et al.* 2000).

Transport equations can provide useful estimates of non-washload components if equations are selected that are calibrated over the range of conditions appropriate for the application. Reid and Dunne (1996) tabulate published comparisons between predicted and observed results and identify the equations that appear to be most reliable for various bed materials and channel sizes. Results are usually more accurate for sand-bedded than for gravel-bedded channels, but even the most reliable equations generally are accurate only within a factor of 2. Because washload is influenced more by sediment availability than by flow properties, transport equations are not useful if this component of the load is important. Instead, short-term monitoring results can be used to produce sediment rating curves, which can then be combined with calculated or measured hydrographs to estimate total suspended sediment loads. As with any monitoring-based method, errors are introduced if the monitoring period is unrepresentative or if estimates are made by extrapolation beyond the conditions measured. However, if applied carefully, the method is the best available for predictions of washload, and probably of all suspended load. Although most frequently used for larger catchments, the approach can also be applied to small, ephemeral drainages such as road-surface catchments (e.g., Reid and Dunne 1984).

During transport, sediment grains are subject to fracture, abrasion, weathering, and dissolution, contributing to widely observed downstream decreases in grain size and, often, shifts in particle composition (e.g., Le Pera and Sorriso-Valvo 2000). Downstream fining is also influenced by size-dependent transport, so attrition rates are not directly calculable from downstream size trends. Minimum attrition rates for particular lithologies can sometimes be estimated by evaluating downstream trends in the proportions of clasts of different lithologies. Where source materials differ greatly in durability, such compositional surveys are needed to identify the major sources for downstream bed materials; relative input rates do not necessarily reflect relative influence on downstream bed composition (Dietrich and Dunne 1978). Breakdown rates have also been estimated by measuring changes in clast size distribution as a function of "travel distance" in rock tumblers that have been modified to provide realistic rates of particle interaction (Kuenen 1956, Collins and Dunne 1989).

Different components of the sediment load influence downstream environments in different ways during transport. High suspended loads complicate water purification procedures and strongly influence aquatic ecosystems by limiting photosynthesis, decreasing the ability of visually feeding organisms to find their prey, abrading gill tissues, and disrupting behavior. The severity of such impacts depends on both the magnitude and duration of exposure (Newcombe and Jensen 1996). A variety of aquatic organisms inhabit the bed surface and interstices within the bed material of a stream, and this community is disrupted when bed material moves. Excessive scour can destroy the eggs of salmonids and other species that nest within gravel stream beds; this may occur where increased sediment loads contribute to a fining of the bed material, or where in-stream mining modifies bar morphology, thereby increasing the susceptibility to scouring as high flows rearrange the destabilized bars (Harvey and Lisle 1999).

Channel and Floodplain Sediment Storage

Periods of significant sediment transport in small to medium channels are interspersed with much longer periods of low transport, during which most of the transportable sediment is held in temporary storage in the channel bed, bars, and floodplains. Durations of temporary storage vary by depositional feature and by location in a catchment. Small amounts of even washload size material can be trapped within the bed material during transport or can infiltrate the bed as flows recede, and fine sediment that is decanted overbank can settle quickly onto the floodplain. Storage within floodplains is favored in rivers with high concentrations of particularly fine-grained sediment (Gomez *et al.* 1999) and frequent, sustained overbank flows (Dunne *et al.* 1998). Sediment deposited on floodplains generally remains until eroded by channel migration, so the residence time in storage is greater where channel migration is slow (Malmon *et al.* 2002).

Silt and sand are also deposited on stream banks. Residence times can be very long if banks are well vegetated and sediment is remobilized only by bank erosion. Elsewhere, as flow recedes, slumping and rilling can redistribute some of the newly deposited sediment back into the channel. Silt and sand can accumulate to aggrade stream beds if sediment loads are particularly high or transport capacity is perennially or seasonally low (e.g., Knighton 1999). Where aggradation is triggered by an altered balance between input and transport capacity, pools commonly fill first (e.g., Lisle and Hilton 1999, Wohl and Cenderelli 2000).

Gravel is most frequently deposited within the bank-full channel. These deposits can become incorporated into the floodplain as a channel migrates. However, unless the channel is aggrading, most coarse sediment temporarily resides in bars until the next bed-mobilizing flow occurs and moves the clasts farther downstream (Hassan *et al.* 1991). Widespread increases in inputs of coarse sediment to a channel network can produce temporary waveforms of gravel that can be either mobile or stationary (Jacobson and Gran 1999, Lisle *et al.* 2001).

Ponds, lakes, and reservoirs interrupt sediment transport. Coarser sediments are often trapped in these environments, while some finer sediment may remain in suspension long enough to emerge with the outflow. The trap efficiency for sediment depends on the ratio between the inflow rate and the volume of the impoundment (Brune 1953). In small ponds, trap efficiency can vary significantly over short periods (Verstraeten and Poesen 2000). Alluvial fans and major breaks in slope along a channel profile can also serve as long-term sediment sinks (e.g., McLean *et al.* 1999). At such sites, where transport capacity decreases and channels are not confined, bars accumulate rapidly, with associated rapid channel shifting or braiding (e.g., Dunne 1988).

No landscape is unchanging, but many change slowly enough that "steady-state" rates of sediment production and deposition can be assumed over moderate timescales. Over the long-term, the evolution of landforms would need to be considered (e.g., progressive erosion may decrease the hillslope gradient to the point that the average erosion rate decreases), while over a shorter period, weather patterns would need consideration (e.g., 10-year-old flood deposits may provide a temporary sediment source). On average, though, if no areas of chronic aggradation or incision exist downstream, sediment contributed to a stream system under steady-state conditions roughly balances the sediment exported from the catchment.

In catchments with rapidly evolving landforms or changing conditions, or over short periods for which seasonal and inter-annual variations are important, this simplified view must be expanded to account for changes in sediment storage (Trimble 1977). A large storm or anthropogenic alteration of vegetation cover, channel morphology, or flow regime can trigger major changes in sediment input, transport, and storage. A change in any of these components provokes compensating changes in the others, which themselves provoke additional changes. Long periods may be required for re-equilibration of the system, and different portions may respond out of phase with one another (e.g., Womack and Schumm 1977, Trimble 1983, Madej and Ozaki 1996). Under these conditions, both input to and output from channel storage need to be evaluated. Evaluation methods for erosion from storage are similar to those for erosion of hillslope materials (Table 16.3); results produce estimates of alluvial sediment input due to incision or changes in channel form. Rates of aggradation on streambeds, banks, and floodplains can be assessed using stratigraphic and dating methods described in previous chapters and in Table 16.3.

Sediment input and transport rates also vary over long periods as landforms evolve and climatic and tectonic conditions change. Many landscapes include landforms deposited by processes that are no longer active, and these forms now interact with the current process regime. Streams may be eroding into glacial outwash terraces, for example, or Pleistocene landslide deposits may locally constrict valleys. In such cases, the average erosion rate for this sediment is not balanced by an equivalent rate of deposition (e.g., Church and Slaymaker 1989), and the remobilized sediment effectively constitutes a new sediment input to the modern channel.

Where there has been a change in sediment transport rates or sediment input, channel form often changes through infilling, incision, or altered rates and modes of channel migration. If channel form changes, flood frequency also changes, and valley-bottom structures and transportation networks may be affected. Altered channel form also strongly affects aquatic ecosystems by modifying the distribution and quality of habitat. Animals that spawn on streambeds are often particularly sensitive to accumulations of fine particles in or on the bed (Phillips 1986, Everest *et al.* 1987). Accelerated accumulation of bed material within gravel rivers can lead to pool filling that impairs recreational uses and fish rearing habitat. Estuaries commonly are sites of sediment accumulation, which can interfere with harbor use and impair coastal fisheries (e.g., Nichol *et al.* 2000).

Accelerated removal or impoundment of bed material can lead to the degradation and armoring of channel beds (Collins and Dunne 1990, Kondolf and Swanson 1993, Bravard *et al.* 1999, Liébault and Piégay 2001). Such degradation can undermine bridge piers and other in-channel structures.

The Catchment: Integrating the Sediment System

Different parts of a catchment participate in the sediment regime in different ways. Low-order channels are often the major conduits for sediment input both because they are most closely connected with hillslopes and because they account for most of the drainage density. Downstream, channels are often inset into their own deposits. These terraces and floodplains can prevent hillslope sediment from reaching the channel directly, and channels at these locations may simply rework sediment initially contributed from hillslopes upstream. Opportunities for deposition generally increase downstream as alluvial valleys widen and their gradients decrease.

The "sediment yield" is the rate of sediment output from a catchment. Because sediment yields vary with catchment size, comparisons between catchments are usually made in terms of sediment yield per unit area of catchment. Sediment yields per unit area frequently decrease downstream, both because average hillslope gradients decrease with increasing drainage area and because long-term aggradation is more likely downstream. The "sediment delivery ratio" for a catchment is the proportion of sediment eroded from hillslopes that is exported from the catchment. Early work within uniform physiographic regions of generally low relief (e.g., Maner 1958, Roehl 1962) indicated that the sediment delivery ratio is characteristically less than one and decreases with increasing drainage area. This pattern is consistent with a downstream increase in sediment diverted into long-term storage. Although the original relationships have not been widely tested, they have been used elsewhere to estimate catchment sediment yield from evaluations of hillslope sediment supply. This is probably not an accurate prediction for most basins, except in the crudest sense. More research is needed to verify and elucidate such generalized predictions of sediment delivery ratios. Milliman and Syvitski (1992) have demonstrated that such a negative relationship is detectable at the scale of whole continents, although its predictive power is low.

Long-term sediment yields, especially for small to moderate-sized catchments, are most readily evaluated using measurements of sedimentation in reservoirs or ponds (Table 16.3). Repeated bathymetric surveys allow calculation of infill volumes per unit time, and total yield can then be estimated if the sediment-trapping efficiency is known. In-stream monitoring of sediment discharge also can provide estimates of sediment yield.

Although logistical and sampling difficulties have precluded much comparison of catchment sediment yields to define their reproducibility and transferability, yields are generally expected to be similar for similar-sized catchments within an area of relatively uniform physiography, geology, climate, land use, and vegetation cover, unless large, discrete sediment sources are present. For example, Dunne and Ongweny (1976) used average values for the forested, cultivated, and grazed parts of a catchment, developed from a few gauged subcatchments, to identify major sources of sediment threatening the useful life of a reservoir. In this case, new sediment sampling surveys confirmed the calculations, which were based on decade-old measurements. Such an approach requires careful consideration of potential sources of variation between catchments.

Sediment yields are often estimated by summing sediment input rates from individual processes. Such calculations are expected to be reliable under steady-state conditions if long-term aggradation is accounted for. Where conditions have recently changed, however, differences in mobility for different grain sizes cause lags between a change in hillslope process rate, the response of the suspended sediment yield, and the response of the bedload yield.

Even under steady-state conditions, rates of sediment input and transport vary considerably through time at several scales. Climates with pronounced wet seasons generally have strong seasonal sediment inputs, and channels dominated by snowmelt are often highly predictable in the timing of high sediment loads. Seasonal land-use activities also influence the timing of sediment outputs (e.g., Collins *et al.* 1998). Year-to-year variation is imparted by variations in storm intensity and by occurrence of other events that can influence erosion rates, such as wildfires, earthquakes, droughts, and episodic land-use activities (e.g., Rice 1982).

The timing of sediment transport varies through a catchment. Many headwater channels cannot move clasts coarser than pebbles during ordinary floods, and gravel and cobbles often are effectively trapped by woody debris in forest streams. At these sites, bed material might be mobilized only when debris jams fail (Mosley 1981) or during particularly large floods or debris flows (Benda and Dunne 1987). Farther downstream, transport capacities are usually high enough to mobilize bed material during ordinary bank-full events. Still farther downstream, breakdown of clasts and sequestering of the larger clasts lead to fining of the sediment load, until the largest rivers often transport primarily sand. Sand can be transported even at relatively low flows, so some transport occurs nearly continuously.

16.3 DESIGNING A SEDIMENT BUDGET

Construction of a useful sediment budget requires assessment of those parts of the sediment regime that are relevant to the particular application. No two applications have exactly the same goals or setting, so there is no single codifiable method for constructing sediment budgets. Sediment budgets vary widely in scope, approach, and methods (Tables 16.1 and 16.4), and much of the art of budget construction lies in deciding which form of budget will be most effective for addressing the particular question posed. This flexibility can be a problem in settings where the adequacy of a result is judged by whether it was obtained using standard procedures or where procedural manuals are expected to compensate for uneven levels of expertise. In such settings, it is critical for sediment budget analysts to present a strong conceptual model of the sediment budget and to provide clear, well-documented explanations of the basis for the methods to be used.

Although by no means comprehensive, Table 16.4 lists a variety of options that can be selected for each of 11 attributes of a sediment budget. Selection of appropriate options requires that several basic questions be addressed during design of the budgeting strategy (Table 16.5).

Identifying the Study Objectives

The success of a sediment budget depends strongly on the investigator's skill in defining the focal question and identifying the information needed to answer that question. To do so, the overall purpose for the inquiry must be understood. Are results of the sediment budget to be used to explain the shape of a landform? To describe existing conditions? To identify the cause of an existing condition? To design a plan to modify an existing condition? To predict the outcome of future actions? To provide a basis for regulatory oversight? To better understand interactions between specific processes? A single inquiry may have multiple purposes, but careful definition of the primary purpose allows the overall strategy to be optimized for that goal.

If the budget is to be constructed as part of a broader project, it is important that the goals of and motivations for the project be understood. Such understanding often can improve the utility of the resulting budget, but it can also protect those constructing the budget if the project is controversial. If a particular outcome would be preferred by project managers or interest groups, the geomorphologists' professional integrity and reputation rest on their ability to maintain technical independence. Documen-

Table 16.4 Examples of options for sediment budget design. A particular sediment budget would be characterized by one or more options for each numbered attribute

1. *Purpose of budget*:

Explain landform
Explain change or impact
Describe effect of activity
Describe effect of event
Prioritize, plan remediation
Describe system
Compare systems
Predict system response

2. *Focal issue*:

Land-use activity
Land-use effects
Background
Particular event
Particular impact

3. *Form of results*:

Absolute amounts
Relative amounts
Description of interactions
Locations
Timing of response

4. *Spatial organization*:

Distributed by sites
Generalized by strata
Conceptual
Lumped
Hypothetical

5. *Temporal context*:

Reconstruct past
Describe present
Predict future

6. *Duration considered*:

Event-specific
Specified duration
Long-term average
Land-use activity
Synthetic average

7. *Precision*:

Qualitative
Order-of-magnitude
Precise

8. *Part of sediment regime*:

Weathering
Hillslope transport
Hillslope storage
Erosion
Delivery to channels
Channel storage
Channel transport
Sediment attrition
Sediment yield
Morphology

9. *Landscape element*:

Hillslopes
Catchment
Specific landform
Land-use activity site
Channel reach
Channel system
Particular process
Particular land-use sites
Administrative unit

10. *Material*:

All
Non-dissolved
Suspended sediment
Bedload
Sand
Gravel
Organic material

11. *Method*:

Modeling
Existing evidence
Inference
Analogy
Historical records
Air photos
Remote sensing
Stratigraphic analysis
Monitoring

Table 16.5 Questions useful for guiding design of sediment budgets

Technical questions

1 What is the overall goal of the study or project of which the sediment budget is to be a part?
2 What kinds of decisions or conclusions are expected to follow from the study's results?
3 What information is needed to make those decisions or conclusions?
4 Are approaches other than sediment budgeting capable of providing that information?
5 What is the minimum level of precision needed to make the decisions or conclusions?
6 What is the minimum portion of the sediment regime that must be understood to make the decisions or conclusions?
7 To what area must the results apply?
8 To what period must the understanding apply?

Logistical questions

9 How much time is available for the study?
10 How much funding is available for the study?

tation and procedures should be maintained at the highest standard in such cases, and rigorous, independent technical review should be sought and heeded. Such input is useful both during the initial steps of designing the investigation and after results are produced.

Once the primary goal is identified, it is useful to specify how sediment budget results would contribute to meeting that goal. This can be done by first identifying the kinds of conclusions or decisions to be made once results are available and then evaluating how different kinds of results might influence those decisions or conclusions. For example, if the ultimate goal of a project is to design effective measures to reduce turbidity in a trout stream, it will be necessary to decide which sediment sources to control and how to control them. For this application, sediment budget results might be used simply to identify and prioritize controllable sources of fine sediment. However, the budget could also be constructed to aid design of sediment control measures by evaluating the importance of various influences on those process rates and describing the distribution of processes throughout the catchment. The strategy used for budget construction would differ according to which of these applications is selected.

Necessary and Sufficient Precision

An evaluation of how the sediment budget results are to be used also leads to definition of the minimum level of precision required. If the result is intended to guide sediment control efforts, for example, a relative ranking of sediment sources based on order-of-magnitude estimates of input might be sufficient to achieve the purpose. In contrast, a study designed to describe the relation between sediment production and sediment yield as a function of catchment size would require more precise estimates. The necessary precision can be estimated by identifying the range in potential values for results that would not alter the decisions and conclusions to follow from the budget. If the range is wide, precision can be low.

Although many investigations would benefit from increased precision, for many other studies the attainable precision is higher than that actually needed to answer the relevant questions. Pursuit of unnecessary levels of precision in such cases represents an inappropriate allocation of effort and saps resources from other aspects of analysis where effort might be more usefully applied.

Components to be Analyzed

It is sometimes asserted that sediment budget construction is too complicated to be practical for most applications. This appearance of complexity may have arisen in part because some sediment budgets have been constructed for ill-defined purposes and so embrace greater complexity than the applications actually require. Most applications require exploration of only a portion of the overall sediment regime. Targeting of sediment sources for control, for example, requires assessment only of sediment input rates to channels, while evaluation of gravel-mining influences focuses instead on changes in sediment storage in and downstream of the affected reaches. If the intent of the budget is to determine the relative importance of a particular kind of source, it may be sufficient to evaluate the input rate from that source relative to the total sediment yield (e.g., Hovius *et al.* 1997).

Identification of the portion of the sediment regime requiring study is easiest once a conceptual model has been developed for the sediment system in the area. Such models have generally been in the form of flow charts (e.g., Dietrich and Dunne 1978, Reid and Dunne 1996) and tables (e.g., Kesel *et al.* 1992, Clapp *et al.* 2001), but underlying each of these is the continuity equation for sediment transport, which simply states that, for some time interval, input equals output plus the change in storage. Constructing the relevant continuity equation for a particular application is useful because it requires identification of relationships that need to be evaluated, discloses the implications of disregarding particular components of the budget, and identifies the information needed to balance the budget.

Different formulations of the equation are useful for different applications. Benda and Dunne (1997), for example, model the stochastic nature of sediment supply to reaches of channel throughout a network from landslides, debris flows, and soil creep. To do so, they use a version of the equation modified to apply to individual reaches of third or higher order at specific times:

$$Q_i(k,t) + I(k,t) - Q_o(k,t) = \Delta V(k,t)/\Delta t \quad (1)$$

The terms representing input (in $m^3\ year^{-1}$) into the channel segment k during year t are $Q_i(k,t)$, the fluvial transport (suspended and bed load) from upstream, and $I(k,t)$, the sum of sediment supplied to the channel segment during the year by the processes illustrated in Figure 16.2. $Q_o(k,t)$ is the corresponding export ($m^3\ year^{-1}$) from segment k during year t, and the final term represents the change in the volume of sediment (V, m^3) stored in segment k during year t (represented by Δt, year).

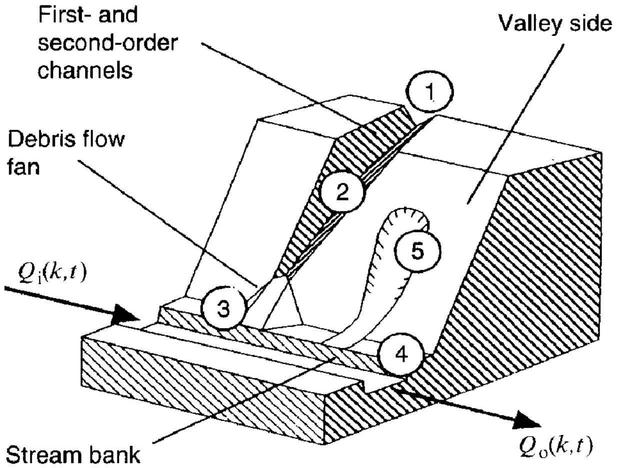

Figure 16.2 Conceptual model of the sediment budget of third- and higher-order channel segments in the Oregon Coast Range. Sediment input processes include: (1) shallow landsliding and debris flows in first- and second-order channels, (2) fluvial erosion and transport in first- and second-order channels, (3) bank erosion of debris flow fans and terraces, (4) soil creep along toeslopes of hillsides, and (5) landslides from streamside hollows. $Q_i(k,t)$ and $Q_o(k,t)$ represent the annual fluxes of sediment load into and out of the kth segment in year t. From Benda and Dunne (1997) (reproduced by permission of the American Geophysical Union)

For applications involving other kinds of information, the equation can be modified to specify the information required. For example, Dunne *et al.* (1998) examined interactions between the Amazon River and its floodplain (Figure 16.3), so the equation used to organize the study separated the term describing storage into four parts, including deposition on bars within and adjacent to the channel (D_{bar}), diffuse overbank deposition (D_{ovrbk}), deposition in floodplain channels attached to the main channel (D_{fpc}), and deposition on the bed and banks ($A_c\rho_b\Delta z/\Delta t$, where A_c and Δz are, respectively, the area and average elevation change of the channel bed and banks in the reach, ρ_b is the bulk density of the bed material, and Δt is the time interval of the computation):

$$Q_u + \sum_i Q_{trib_i} + E_{bk} = Q_d + D_{bar} + D_{ovrbk} + D_{fpc} + A_c\rho_b\frac{\Delta z}{\Delta t} + \varepsilon \quad (2)$$

Q_u, Q_d, and Q_{trib} are, respectively, the annual fluxes of suspended and bedload sediment at the upstream and downstream ends of each channel reach and from the i tributaries entering the reach, E_{bk} is bank erosion, and ε is the error; each term has units of $Mt\,year^{-1}$. This equation, too, was formulated to apply to particular reaches, but in this case the results define the average annual balance of sediment transport of each grain size for each reach.

Once the underlying equation is defined, flowcharts are useful for organizing specific information about processes. Preliminary information about major erosion and transport processes is usually available for a study area or for similar settings. This information can be used to identify potential sediment inputs,

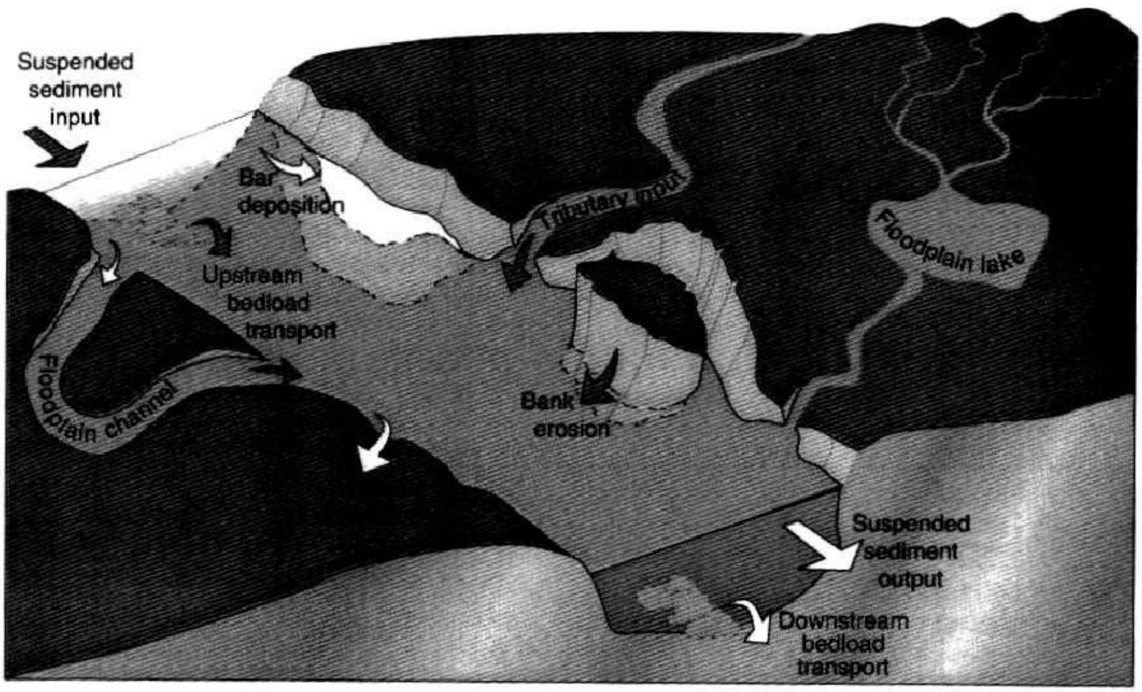

Figure 16.3 Components of the budget of channel-floodplain sediment exchanges for ~200-km-long reaches of the Amazon River, Brazil. Modified after Dunne *et al.* (1998) (reproduced by permission of the Geological Society of America)

outputs, and storage changes in the area and to diagram interactions between transport processes and storage elements, with primary focus on aspects of the sediment regime on which the study is to concentrate (e.g., Figure 16.4). If location is important, the flowchart can be organized to indicate spatial relationships (e.g., Figure 16.5). The conceptual model described by the flowchart then provides the framework for further analysis, always keeping in mind that the model is a hypothesis to be tested by field observations and analysis.

The preliminary flowchart can be used to identify which parts of the sediment regime need to be evaluated to meet the project's goals. If the analysis is intended to define the influence of a land-use activity on the sediment yield, the amount and kind of sediment produced by that activity would be evaluated relative to background and ambient sediment yields. In contrast, if localized channel aggradation is the focal concern, the amount of sediment contributed to the reach might be quantified and constraints on transport identified. If control of excess sedimentation is desired, a study might define the relative importance of sediment sources throughout the catchment. Sediment budgets can be constructed to describe the same sediment system from any of these perspectives, or from others relevant to other problems.

Spatial Scale of Analysis

The most useful spatial analysis strategy for a particular study depends on the kind of area to which results are to be applied. The relevant areas might be a particular catchment, a specific kind of landform found in a region, a particular channel reach, a hypothetical "typical" hillslope, or a politically defined district. Each of these areas requires a different strategy for spatial analysis.

If the budget is intended to explain conditions at a particular site, details of that site are critical to the problem. The location of tributary inputs in a channel reach, for example, may strongly influence the behavior of the reach. Similarly, for budgets developed to explore landform evolution, information concerning process rates must be distributed over that landform. Geographic information systems (GIS) are useful for constructing these spatially distributed sediment

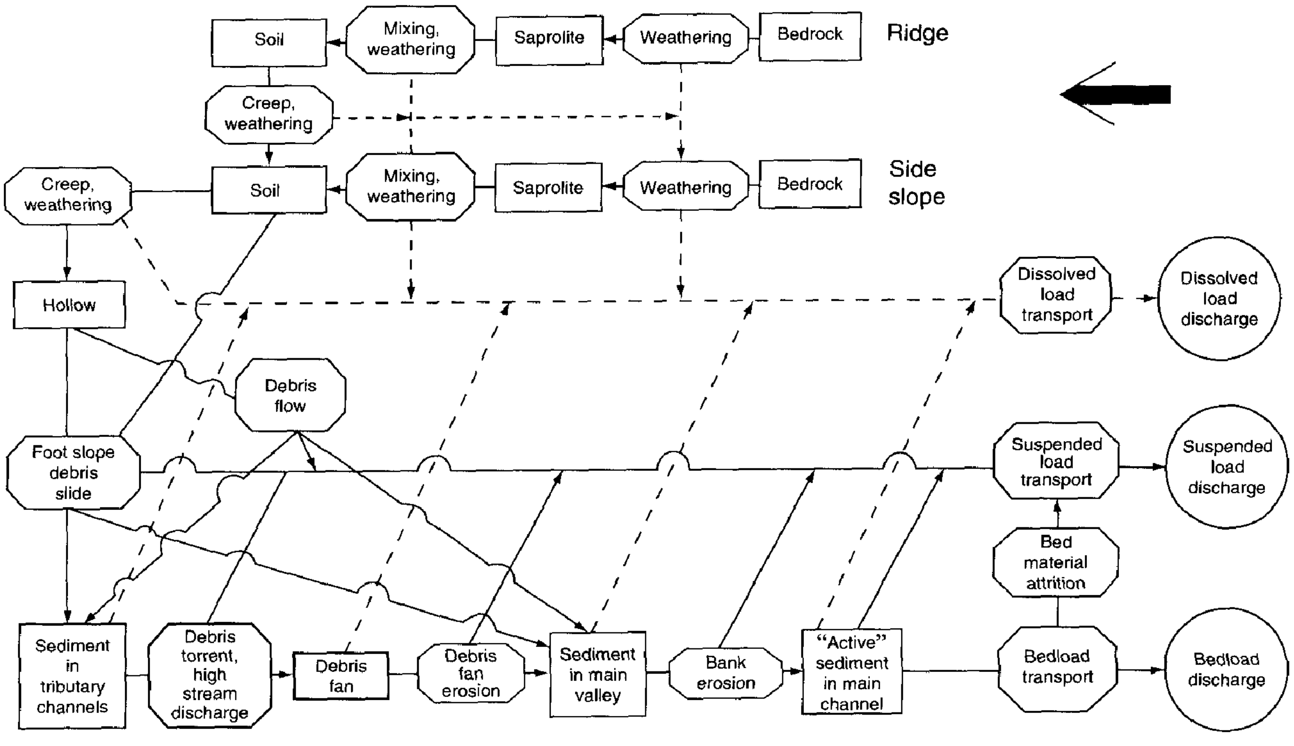

Figure 16.4 Conceptual model of the sediment budget of a small mountainous watershed in the Oregon Coast Range. Rectangles represent storage elements, octagons indicate transfer processes, and circles represent outputs. Solid lines indicate the transfer of sediment and dotted lines represent the migration of solutes. From Dietrich and Dunne (1978) (reproduced by permission of Borntraeger Publishers, http://www.schweizerart.de)

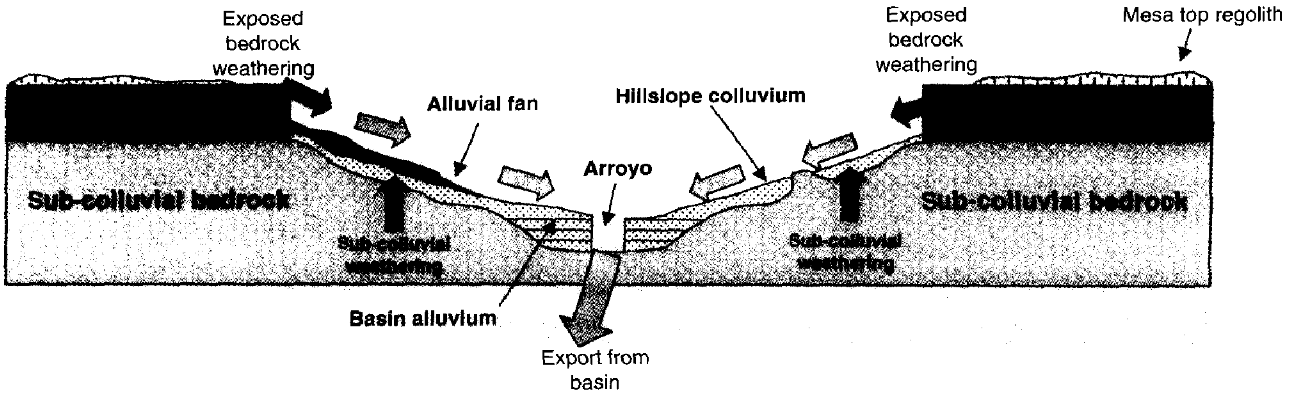

Figure 16.5 Schematic cross section of a small catchment in New Mexico showing the general flow paths of sediment from sources (weathering of bedrock outcrops and subcolluvial bedrock) to various temporary sediment "reservoirs" or "stores" (hillslope colluvium, alluvial fan, and valley-floor alluvium), and out of the basin. Black arrows represent mobilization by bedrock weathering. Gray arrows indicate sediment transport processes. The cross section is approximately 1 km across, and the relief is approximately 30 m. From Clapp *et al.* (2001) (reproduced by permission of Academic Press)

budgets. For many applications, this level of spatial specificity is unnecessary, and results can be presented as averages for particular land types, land uses, subcatchments, or entire catchments. Budgets can even be constructed for hypothetical settings, as is often useful when likely outcomes of different planning options are to be compared.

A preliminary evaluation of the likely spatial distribution of processes usually simplifies budget construction by allowing the study area to be "stratified" into areas that are likely to behave uniformly with respect to a particular process. This approach is useful for any scale of problem; even a sediment budget constructed for an individual gully relied on sampling of process rates on different site types within the gully (Reid 1989). Variables useful for stratification are generally those that control the rate or distribution of processes (Tables 16.2 and 16.3), and often include geologic substrate and vegetation type for hillslope processes and channel order and geologic substrate for channels. In practice, 3–20 stratification units for each process are usually sufficient to facilitate analysis without over-simplifying the problem, and a single stratification scheme is often applicable to multiple processes. Various methods have been used for stratification, ranging from visual delineations using aerial photographs to automated methods using GIS-based information or SPOT imagery (e.g., Giles 1998, Fernández *et al.* 1999). For most applications, statistically based sampling of conditions within stratification units is the most efficient approach to evaluating process rates and distribution; rarely are complete inventories necessary.

Stratification allows generalization of results across wider areas and estimates of values for particular parts of an area, and is useful for construction of budgets for hypothetical conditions. In each case, results are calculated according to the distribution of strata—which implicitly represents the distribution of controlling variables—in the area of interest.

Temporal Scale of Analysis

Appropriate temporal scales can be selected for sediment budgets by considering the intended applications and the timescales over which conditions change in the study area. A budget designed to examine the effects of land use on landsliding might evaluate landslide distribution after a single major storm on lands undergoing different uses. In contrast, a budget intended to estimate a long-term average would assess rates over a period long enough to either evaluate or average out year-to-year variations.

Budgets that evaluate changes in average sediment input relative to background conditions must consider two timescales, the first to assess long-term average natural rates, the second to provide an analogous estimate of current rates. Where current conditions are changing rapidly, as is the case where land-use patterns are shifting, definition of a "long-term average" for current conditions requires assessment of the hypothetical response of the current land-use pattern to the long-term average distribution of triggering events. If landslide rates are defined as a function of storm size, for example, landslide incidence can be evaluated for the distribution of storms expected over a 100-year period to calculate the average sediment input expected if current conditions were to be maintained for 100 years (Figure 16.1).

Comparison of current to background conditions requires estimates of process rates active under conditions no longer present. Where nearby catchments remain in a relatively pristine condition, sediment budgets for pristine and disturbed conditions can be compared directly. Comparisons are most useful for catchments of similar size, and the less-disturbed catchments tend to be small. Consequently, processes characteristic of downstream reaches often cannot be directly compared using this strategy.

More commonly, pristine examples are unavailable, and catchments or hillslopes undergoing different intensities of land use are examined instead. Analysis of trends along the gradient of land-use intensities can then allow inferences about predisturbance conditions. A gradient of hillslope conditions usually exists even where land use is uniformly distributed between catchments, so rates of hillslope processes usually can be compared even where comparison of downstream processes is not possible.

Past conditions and process rates in downstream channels usually must be evaluated using evidence left by those processes or from records and accounts of earlier conditions. Stratigraphic analysis of floodplain deposits can provide considerable information about disturbance-related changes in sediment regime and channel response (e.g., Lecce and Pavlowsky 2001). Where changes in land use are recent, interviews with long-term residents can provide valuable information about past conditions.

Budgets can also be designed to forecast future conditions. Because many erosion and sediment transport processes are strongly influenced by large, infrequent events, exact predictions usually are not possible. Instead, such budgets generally describe the likely outcome, given the expected distribution of events based on a probability analysis.

The nature of on-going changes also influences the temporal scale appropriate for a sediment budget. If a sediment system is recovering after a major event or adjusting to a land-use change, the budget generally would need to incorporate a broad enough temporal scale to evaluate the nature and progress of the system's response.

Selection of Analysis Methods

Examples of analysis methods are listed in Tables 16.2 and 16.3. The methods appropriate for a particular problem depend on the nature and context of the problem, but the choice is also influenced by logistical constraints. If answers are required quickly, analysis must depend largely on existing information, sequential aerial photographs, and field observations of evidence of past process rates. The depth of root exposure on datable vegetation might be measured to assess past surface erosion rates, for example, or isotope concentrations might be measured in sediment deposits to evaluate changes in deposition rate (Walling and He 1997, Panin *et al.* 2001, Matisoff *et al.* 2002a). If more time is available for the study, it may be useful to monitor process rates. Few studies employ only one method; different methods are used to evaluate different components of the budget or to provide multiple estimates for a single component.

Most sediment budget analyses use aerial photographs. Multiple photo sets spanning a 50-year period now exist for most locations, and some kinds of landscape changes can be documented by comparison of sequential sets. Landsliding rates can be estimated for periods spanned by aerial photographs by calculating the frequency of new scars, for example, and rates of migration can sometimes be measured for large channels. Some changes in channel form can be inferred from observed changes in riparian cover (Grant 1988). Aerial photographs are also useful for aiding landscape stratification and for planning fieldwork. Satellite imagery, now extending back for more than 30 years, can disclose alterations of land cover, changes in the position and form of large rivers, and broad patterns of variation across the landscape. Old maps and survey records, which can date from hundreds of years ago in Japan and Europe, can also indicate changes in land use and in channel location and character. Planning departments for cities, counties, and land-management agencies may have GIS coverage for some attributes in the area.

Useful information can also be provided by water quality reports, bridge surveys, flood zoning reports, reservoir surveys, and stream gauging records. Local experts can also be identified and interviewed; these people often know of relevant information that might be otherwise overlooked and usually can identify individuals who have observed recent changes. Affected landowners, for example, usually can provide detailed descriptions of recent channel changes.

Information is also useful from similar settings in other areas. In some cases, measured process rates can be transferred directly to other areas of similar character, but even where rates are not transferable, information on the nature of and interactions between processes may be transferred. When analogy is used to estimate process rates or interpret process interactions, similarities and differences between the study area and the measurement site need to be carefully evaluated.

Published equations and models can be used to evaluate some process rates, but use of any model or equation requires that the underlying assumptions be valid for the area in question and that appropriate data be available. No model or equation can be assumed valid for a particular application, so a model or equation should not be applied without understanding its assumptions and limitations and the conditions for which it was constructed. Results should be tested against those of other analytical methods.

Fieldwork is essential for refining the conceptual framework originally established for the budget and for checking aerial photographic interpretations. Evaluation of most chronic sediment sources requires fieldwork, and fieldwork often reveals unexpected measurement opportunities. Fieldwork also allows interviews with local observers and experts at the sites of interest; general recollections can become very specific in the presence of identifiable landmarks. Fieldwork is most useful if it is approached both with a prioritized list of tasks to be accomplished and with the willingness to abandon that list if more effective opportunities are found for answering the important questions. If possible, fieldwork should be scheduled for periods when important processes are likely to be active. Dry-season fieldwork, for example, is rarely useful for evaluating the distribution and significance of overland flow and sheet erosion.

Monitoring is sometimes useful during budget construction. Long-term average process rates can be defined through monitoring either if the monitoring duration is long enough to account for temporal variations in rate (e.g., Trimble 1999) or if monitoring produces a relationship between process rate and driving variables that allows the long-term rate to be calculated from a known distribution of driving variables (Reid and Dunne 1984, Clayton and Megahan 1986, Reid 1998). Short-term monitoring also can be useful for testing event-based modeling outputs. Comparison of modeled and monitored results for the range of sampled events indicates the level of confidence that can be placed on modeled results for unsampled events. Short-term monitoring can also reveal differences in process rates between particular site-types or treatments. For any of these applications, enough sites should be monitored to provide adequate confidence that results are characteristic of the relevant site-type during the monitoring period. Statistical analysis of preliminary results can identify the necessary sample size.

Integrating the Results

Sediment budgets commonly incorporate disparate kinds of information, and each information source usually represents a different temporal or spatial scale and a different level of data quality. The overall budget must reconcile these differences to produce an internally consistent, interpretable result.

Particular care must be taken to avoid mismatching timescales within a budget. Sediment budget results cannot be compared or components of a single budget combined if they represent different time periods. For example, sediment budgets commonly incorporate monitoring data, modeling results, and retrospective rate estimates. If a budget is to be checked by comparing results to 2 years of sediment yield measurements, each kind of information would need to be evaluated in such a way that results apply to that 2-year period. Such a comparison would require that travel times for sediment also be evaluated.

Differences in spatial analysis scales are usually accounted for by stratification. A single budget, for example, might include an air-photo inventory of road-related landslides throughout a catchment and modeled sheet erosion rates from road surfaces on two soil types. The sediment input for the entire catchment would be calculated in a different way for each source. Overall rates for both sources would vary through time as the road system developed, so inputs would be calculated per unit length of road. The average annual landslide delivery would be calculated as the total landslide delivery divided by the road-kilometer-years present during the period for which aerial photos are available. Sheet erosion would be calculated by applying the modeled rates for each soil type to the road-kilometer-years present for that soil type during the period of air-photo coverage. Results could then be combined to estimate either the total input from these sources over the period of air-photo coverage or the combined average rate per unit length of road per year.

In general, inventory data can be used directly after suitable spatial and temporal averaging, while information characterizing particular land strata or site types is applied according to the distribution of those site types. Data that are randomly sampled without regard to site type characterize the area as a whole and cannot be used to characterize portions of the sample area unless the random sampling disclosed relationships between rates and controlling variables. This pattern is also true for sampling through time. A process rate evaluated as a long-term average cannot be assumed to apply to a particular interval within the analysis period.

Auditing the Sediment Budget

An answer is not useful if it is not possible to determine whether it is likely to be true. Most sediment budgets represent a complex mix of calculations, mapping, measurements, and qualitative inferences, so standard methods of error analysis are rarely applicable. Instead, results usually are tested by comparing estimated to measured sediment yields, assessing the reliability of each of the methods used, or carrying out sensitivity analyses. The effectiveness of each approach depends on the kind of error present.

The most serious errors generally result from overlooking important processes, and this can be avoided only through careful fieldwork. It is useful to begin with a complete list of potential processes, identify the evidence needed to demonstrate their presence, and determine whether such evidence is present. Technical review sometimes can identify missing components if reviewers are familiar with similar areas. Occasionally, comparison of the summed components of the budget with a known output reveals an imbalance, but uncertainties in components are often large enough that a shortfall cannot be correctly diagnosed. Assessment of the reliability of component methods and sensitivity analysis are ineffective for addressing this problem.

Important errors also occur when decisions are founded on budget results that are mistakenly assumed to be precise and accurate. In many cases, a sensitivity analysis would have revealed the uncertainty in the budget, and decisions could have been tempered to reflect that uncertainty or further work done to decrease it.

Large errors in individual budget components have occurred when modeling results were relied on without field testing or when short-term rates were assumed to represent long-term averages. Each of these methods is inherently unreliable and can be identified through technical reviews. Where such methods are considered necessary, it is important that the associated uncertainty be evaluated and reported.

Problems have also arisen when a difficult-to-evaluate component was estimated by subtracting the other components from a measured total. This approach implicitly assumes that all components have been identified and that the cumulative error in the sum is small enough that the difference between the sum and the total is meaningful (Kondolf and Matthews 1991). If such an approach is used, a sensitivity analysis should be carried out to identify the potential error in the result, and the presence or absence of all potential budget components should be carefully verified.

Another problem is beginning to appear with increasing frequency as budgeting is more widely applied: profound errors can be introduced when those preparing the budget have insufficient understanding of geomorphological processes. In a recent example, half the estimated bank erosion along major tributaries in a severely impacted catchment was arbitrarily assumed to be "natural", and recently accelerated aggradation on banks and floodplains was simply ignored because rates varied between sites and because a hypothesized future increase in bank erosion was assumed to compensate for the increased aggradation. Problems arising from lack of expertise can be addressed through a careful technical review, although the problems would ideally be circumvented earlier by ensuring that those constructing the budget are qualified to do such work.

Sediment budgeting is increasingly used in support of land-management planning, and in this context there usually is considerable financial interest in the results. Technical review from independent experts is particularly important in this case. The credibility of the budget can then be evaluated on the basis of both the content of the reviews and how the reviews are received: if those preparing the budget fail to address issues raised by review, the budget is clearly inadequate.

Although no single approach to testing budget results can ensure that the result is accurate, each is useful. Where estimated and measured sediment yields agree, it is likely that the major components are not severely over- or under-estimated, although compensating errors can occur. Methods of "fingerprinting" deposited or transported sediments to identify their provenance (Collins *et al.* 1998, Hill *et al.* 1998) can be used to test portions of the overall budget. For any such test to be valid, clearly the estimates of sediment yield must be completely independent of analysis of budget components.

Even technically valid sediment budgets can be unsuccessful if the question addressed by the budget is not relevant to the underlying problem. Central to formulation of a useful question is development of a strong understanding of what the problem to be addressed actually is. For problems associated with land-use activities, identified technical problems are often mere symptoms of underlying social, political, or economic problems (Rossi 1998), and technical solutions that do not take into account the underlying causes will not be relevant or workable.

Assessing Uncertainty

The reliability of specific methods used in budget construction usually can be assessed from the performance of a method at other sites or from other knowledge of process rates. In some cases, reliability can be expressed as a confidence interval, while in others, only a maximum likely error can be estimated. If multiple methods are used to estimate the same budget component, discrepancies between methods indicate the maximum potential accuracy for the suite of methods used.

In some cases, formal error propagation analysis is possible for parts of a budget. The sediment budget for the Amazon River (Figure 16.3; Dunne *et al.* 1998), for example, was structured in such a way as to allow such analysis. Equation (2) was first simplified to

$$Q_{\mathrm{u}} + \sum_{i} Q_{\mathrm{trib}_i} - Q_{\mathrm{d}} = \frac{\Delta V}{\Delta t} + \varepsilon \qquad (3)$$

where Q_{u}, Q_{d}, and Q_{trib} are, respectively, the annual fluxes of suspended and bedload sediment at the upstream and downstream ends of each channel reach and from the i tributaries entering the reach, and $\Delta V/\Delta t$ represents the rate of change of the total volume of sediment in storage in the reach. Sediment rating curves and flow duration curves available for each station on the main channel and each tributary were then used to analyze error propagation for the fluvial transport terms, allowing the uncertainties in estimating $\Delta V/\Delta t$ to be evaluated. The standard errors of the $\Delta V/\Delta t$ terms for individual reaches were significantly different from zero for the sand fraction in many reaches where the geomorphic and hydrologic setting suggested that net erosion or deposition would occur. This was not generally the case for the larger silt–clay fraction, although subtle trends in the net storage of this fraction did correlate with the same geomorphic and hydrologic patterns. Also, the standard error of the storage estimate for the entire 2000-km-long floodplain reach (200 Mt year^{-1}) was significantly different from zero for both size fractions, and it agreed approximately with the storage of 500 Mt year^{-1} estimated by quantifying each term in Equation (2). However, the paucity of information available for specific storage fluxes prevented estimation of uncertainties for terms describing individual exchanges between the channel and the floodplain.

The various kinds of information used to construct a sediment budget ordinarily incorporate different kinds and levels of uncertainty, so a standard calculation of uncertainty usually is not possible for the overall result. Instead, the sensitivity of the result to likely levels of uncertainty in the budget components can be assessed by recalculating the result for their estimated ranges of uncertainty. For some components the uncertainty will be represented by a 95% confidence interval; for others it may reflect a maximum likely error or complete removal of the component from consideration. Such calculations can indicate which components of the budget require the most careful analysis.

It is often useful to distinguish between a result and the conclusions based on that result. For example, a result might be a tabulation of sediment input by process, while the conclusion drawn from the result might be that road-surface erosion is the most useful target for sediment control. It is then possible to identify how much of a change in the result would be necessary to cause modification of the conclusion. The range in the result over which the conclusion is not changed defines the operationally significant tolerance interval around the result. If the calculations leading to the result are routine enough to be amenable to Monte Carlo simulation, a method similar to that of generalized likelihood uncertainty estimation (Beven and Freer 2001) can be used to estimate the probability that the actual result supports the conclusion drawn (Reid and Page 2002, Figure 16.6).

16.4 EXAMPLES

Because of the wide variety of methods and strategies available for constructing sediment budgets, it is useful to examine several examples to illustrate how particular options were selected to address specific questions (Table 16.6). The first example represents a reconnaissance-level, order-of-magnitude budget, while the second incorporates more detailed analysis.

Evaluating Sediment Production from a Hurricane in Hawaii

Hurricane Iniki hit the 1325-km^2 island of Kauai, northernmost of the major Hawaiian Islands, in September 1992. Flooding has been a problem on the island in the past, and officials feared that changes caused by the hurricane would increase future flood danger. They needed to know how and where flood hazard was affected and how it could be reduced. One aspect of concern was decreased channel capacity due to aggradation from Iniki-related erosion. A sediment budget study was undertaken to determine whether significant aggradation was likely to identify the endangered areas and to plan hazard reduction measures (Reid and Smith 1992).

The impacts to be evaluated were those of the hurricane, so the budget had to be event-based (Table 16.7). Results did not need to be precise; comparison of the order-of-magnitude of sediment inputs to "normal" values would be sufficient to determine whether a problem is likely. Results needed to be spatially distributed because sites at risk had to be identified. However, vulnerable communities and structures are concentrated at the mouths of catchments, so spatial resolution by the 18 major catchments was adequate, and calculations within each catchment could be spatially generalized.

The relevant standard of comparison for this application ordinarily would be the volume of sediment that the rivers can remove without undergoing significant morphological change. If Iniki contributed more than this volume, channels might flood because of aggradation, while a lower sediment input would not cause aggradation. Aggradation was not a major problem before Iniki, and rainstorms with recurrence intervals of 100 years or less have triggered significant landsliding and produced sediment loads of at least the same order as an average year's sediment yield. We thus assumed that downstream aggradation would not occur if the hurricane contributed less than an average year's sediment load to a river. The standard of comparison then became the average annual sediment input in years without hurricanes. This standard is not well defined; no measurements exist of sediment yields on Kauai. Various estimates suggest that sediment yields range between 300 and 3000 t km^{-2} year^{-1}, and the distribution of old landslide scars suggests that years with intense storms have produced considerably higher yields.

Landslides were mapped by comparing 1:12 000 color infrared aerial photographs taken before and after the storm. Most landslides displaced only the

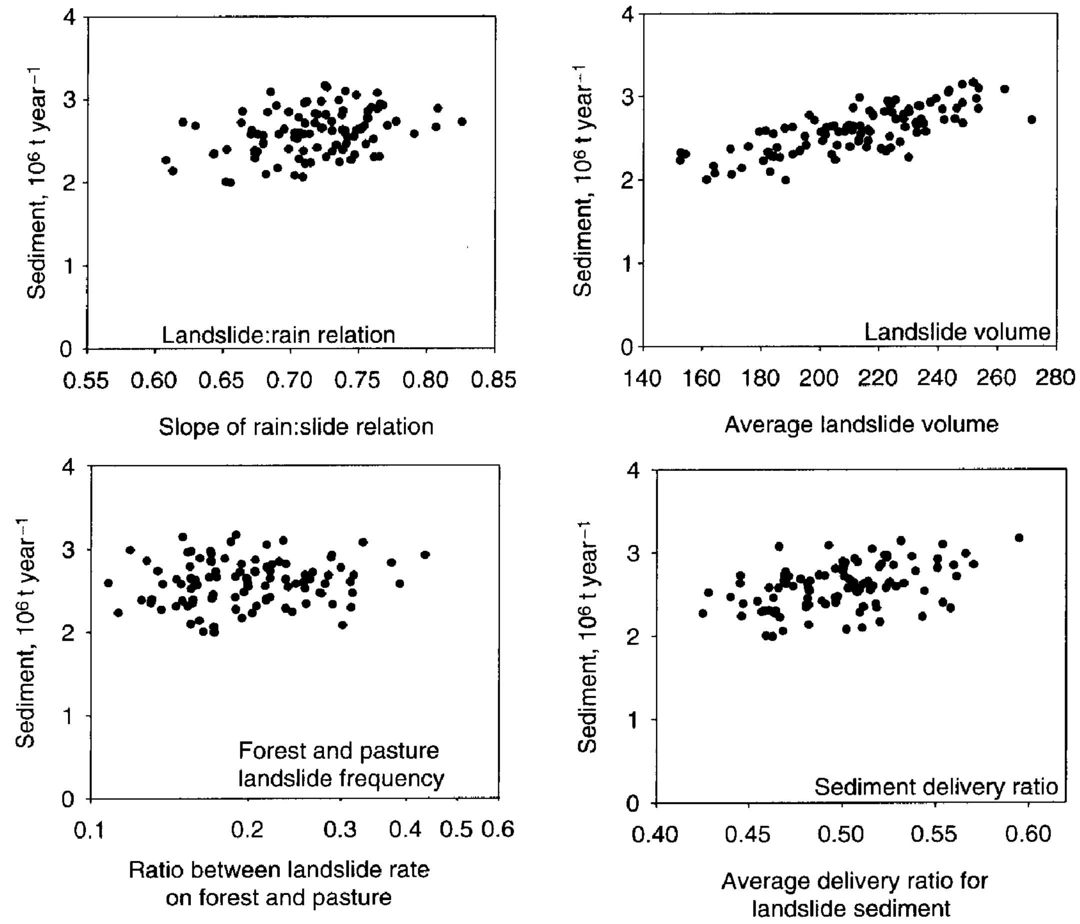

Figure 16.6 Distribution of estimates of sediment yield from shallow landslides in the Waipaoa catchment, North Island, New Zealand, using Monte Carlo simulation to incorporate uncertainty in 32 variables. Errors are selected randomly according to their assumed distributions. Results are displayed as functions of four variables from the Te Arai land system. Scatter in the y-dimension represents the combined influence of errors in the 32 variables; the randomly generated values for each of four variables among the 32 are plotted along the x-axes. The analysis indicates that results are most sensitive to errors in landslide volume, and allows estimation of the confidence interval for the calculated result. Modified after Reid and Page (2002)

soil profile, and their average depth was estimated from average soil depths. The hurricane was relatively dry, so excess sheetwash erosion could have occurred only in areas bared by the hurricane, which were restricted to landslide scars. Trees blown down into streams carried sediment with their roots, and these were mapped from a helicopter in streams wider than 5 m. The average frequency of blown-down trees was then extrapolated to smaller drainages. The volume of sediment carried by each rootwad was estimated from field observations. Sheetwash erosion rates, depths of soil removed by landslides, and rootwad volumes were represented by likely maximum values so that results would represent the maximum potential input.

The orders-of-magnitude of the estimated storm inputs were then compared to expected average annual inputs (Table 16.7). Sediment inputs from Iniki were found to be potentially significant only in the two watersheds that contained large debris flows, but even there the storm-related sediment input was of the same order as an average year's input and so not likely to cause a problem. On this basis, it was recommended that channel cross sections be monitored periodically at potentially vulnerable locations, but that major mitigation efforts for sediment were not necessary. In all, approximately 10 h of helicopter time, one day of fieldwork, and a week of office work were used to construct the budget.

Table 16.6 Examples of strategies selected for two sediment budgeting applications. See Table 16.4 for other options

	Sediment budget attribute	Hurricane Iniki budget (Reid and Smith 1992)	Clearwater road budget (Reid *et al.* 1981)
1	Purpose of budget	Prioritize, plan remediation	Prioritize, plan remediation
2	Focal issue	Particular event and impact	Particular land-use activity and impact
3	Form of results	Relative amounts	Absolute amounts
4	Spatial organization	Distributed by catchments	Hypothetical
5	Temporal context	Describe present	Describe present
6	Duration considered	Event-specific	Synthetic average
7	Precision	Order-of-magnitude	Precise
8	Part of regime	Erosion	Delivery to channels
9	Landscape element	Catchment	Land-use activity sites
10	Material	Non-dissolved	Non-dissolved
11	Method	Modeling, Air photos, Existing evidence	Monitoring, Air photos, Existing evidence

Table 16.7 An order-of-magnitude sediment budget for sediment contributed by Hurricane Iniki to catchments and hydrologic zones on the island of Kauai, Hawaii (adapted from Reid and Smith 1992). Expected annual sediment inputs are on the order of 1000 t km^{-2} year^{-1}. Symbols: — indicates <1 t km^{-2}; +, 1–10 t km^{-2}; ++, 10–100 t km^{-2}; + + +, 100–1000 t km^{-2}

	Watershed or zone	Increased sediment input from hurricane			
		Sheet erosion	Landslides	Uprooting	**Total**
1	Wainiha	++	+ + +	+	+ + +
2	Lumahai	++	+ + +	+	+ + +
3	Waioli	—	—	+	+
4	Hanalei	—	—	+	+
5	Kalihiwai	—	—	+	+
6	Kilauea	—	—	+	+
7	Anahola	—	+	+	++
8	Kapaa	—	+	+	+
9	Wailua	—	+	+	++
10	Hanamaulu	—	—	+	+
11	Huleia	—	—	+	+
12	Waikomo	—	—	+	+
13	Lawai	—	—	+	+
14	Wahiawa	—	—	+	+
15	Hanapepe	++	++	+	++
16	Canyon zone	—	—	+	+
17	Waimea	+	++	+	++
18	Na Pali zone	++	++	+	++

Prioritizing Erosion Control on Roads in the Olympic Mountains, Washington, USA

The 375-km^2 Clearwater watershed, located in the Olympic Mountains of Washington State, is intensively managed for timber production by the Washington Department of Natural Resources. The Clearwater River is an important producer of salmon, and earlier work suggested that the presence of roads is associated with impairment of spawning habitat by intrusion of fine-grained sediment (Cederholm *et al.* 1981). Department staff needed to know the most important sources of road-related sediment to select effective erosion-control measures, so a sediment budget was constructed to evaluate the relative importance of various road-related sediment sources in the area (Reid *et al.* 1981). Work on the budget required less than one person-year distributed over a 2-year period.

The only portion of the sediment regime that required analysis was sediment production to streams. The budget focused on fine-grained sediment, which had been identified as the major problem, and sources not related to roads could be excluded. Results could be in the form of long-term average inputs and so did not need to be related to particular sites or time periods. The budget could therefore be spatially generalized. Because relative values were the major concern, only a moderate level of precision was needed.

Road-related landslide, sidecast erosion, gully, and debris flow rates were evaluated for two watersheds using road construction records and three sequential sets of aerial photographs. Delivery ratios for these sources were assessed by measuring the volumes of sediment deposits at a selection of field sites, and secondary erosion on landslide scars was estimated from root exposure and erosion-pin measurements. Road-surface erosion was evaluated by sampling effluent from 10 culverts during 17 storms of various sizes and defining relations between sediment concentration and discharge for different intensities of road use. Similar measurements on a paved road segment allowed isolation of roadcut and ditch erosion rates, and these were also estimated from erosion-pin measurements and by measuring root exposure on roadcut vegetation. Only the erosion pins required a lengthy monitoring period, and they turned out to be redundant because root exposure measurements provided analogous data over a much longer effective sampling period.

Culvert hydrographs were reconstructed for unsampled storms using unit hydrographs. The sediment rating curves then allowed estimation of the sediment yield for each storm over an 11-year period, and an average annual yield was calculated from the storm yields (Reid and Dunne 1984). Delivery ratios for road-surface, ditch, and roadcut sediment were estimated by determining the proportion of culverts that contribute flow directly to streams in the area. Sediment production rates from landslides, sheetwash, and roadcut erosion were then calculated as a rate per kilometer for an average distribution of road types in a hypothetical 20-km^2 watershed, taking into account the distribution of road types and use intensities present in the area. Expected yields for any specific watershed could be calculated using the road distribution actually present. Because relations were quantified between road-surface sediment yields, storm intensities, and traffic levels, average yields can be estimated for particular years, and future yields can be estimated from projected use levels.

Results clearly indicate the sediment sources in most need of control: road-surface erosion and landsliding each produce 10 times as much sediment as other sources (Table 16.8), while roadcut erosion is

Table 16.8 Road-related production of sediment finer than 2 mm in a hypothetical 20 km^2 watershed in the Clearwater Basin (after Reid *et al.* 1981). Road density is 2.5 km km^{-2} and includes an average distribution of road-use intensities: 6% heavily used, 5% moderately used, 39% lightly used, and 50% abandoned. Heavily used roads fall into the "temporary non-use" category at night and on weekends

Source	Fine sediment production (t km^{-2} year^{-1})
Landslides	40
Debris flows[a]	6.6
Gullies	0.4
Sidecast erosion	2.8
Secondary surface erosion on slide scars	12
Rills on landslide scars	3.2
Roadcut erosion[b]	(4.0)[b]
Road surface and roadcut	
Heavy use	36
Temporary non-use	5.2
Moderate use	5.2
Light use	3.7
Abandoned	0.6
Total	116

[a] Only valley-wall erosion is listed here; the triggering landslide is included in the landslide category.

[b] Roadcut erosion is included in the values for "road surface and roadcut" but is listed separately here to allow comparison.

relatively unimportant. Results also demonstrate the importance of road use in generating sediment and suggest that curtailment of use during wet weather could significantly decrease sediment input.

16.5 CONCLUSIONS

Recent studies demonstrate the utility of the sediment budgeting approach in addressing a wide range of theoretical and applied problems in fluvial geomorphology (Table 16.1). The most efficiently constructed and effective budgets have been those designed to incorporate the kind and precision of information necessary and sufficient to address the questions posed. Only with a carefully defined focus can the appropriate options for budget construction be selected from the wide variety available, and only with carefully defined objectives can the reliability of the resulting budget be assessed.

REFERENCES

Abernethy, B. and Rutherfurd, I.D. 1998. Where along a river's length will vegetation most effectively stabilise stream banks? *Geomorphology* 23(1): 55–76.

Allison, M.A., Kuehl, S.A., Martin, T.C. and Hassan, A. 1998. Importance of floodplain sedimentation for river sediment budgets and terrigenous input to the ocean: insights from the Brahmaputra-Jamuna River. *Geology* 26: 175–178.

André, M.-F. 1997. Holocene rockwall retreat in Svalbard: a triple-rate evolution. *Earth Surface Processes and Landforms* 22(5): 423–440.

Archibold, O.W., de Boer, D.H. and Delanoy, L. 1996. A device for measuring gully headwall morphology. *Earth Surface Processes and Landforms* 21(11): 1001–1005.

Asselman, N.E.M. 2000. Fitting and interpretation of sediment rating curves. *Journal of Hydrology* 234(3/4): 228–248.

Asselman, N.E.M. and Middelkoop, H. 1998. Temporal variability of contemporary floodplain sedimentation in the Rhine-Meuse delta, The Netherlands. *Earth Surface Processes and Landforms* 23(7): 595–609.

Auzet, A.-V. and Ambroise, B. 1996. Soil creep dynamics, soil moisture and temperature conditions on a forested slope in the granitic Vosges Mountains, France. *Earth Surface Processes and Landforms* 21(6): 531–542.

Barker, R., Dixon, L. and Hooke, J. 1997. Use of terrestrial photogrammetry for monitoring and measuring bank erosion. *Earth Surface Processes and Landforms* 22(13): 1217–1227.

Benda, L.E. 1990. The influence of debris flows on channels and valley floors in the Oregon Coast Range, USA. *Earth Surface Processes and Landforms* 15(5): 457–466.

Benda, L. and Dunne, T. 1987. Sediment routing by debris flows. In: Beschta, R.L., Blinn, T., Grant, G.E., Ice, G.G. and Swanson, F.J., eds., *Erosion and Sedimentation in the Pacific Rim*, International Association of Hydrological Sciences Publication 165, pp. 213–223.

Benda, L. and Dunne, T. 1997. Stochastic forcing of sediment storage and routing in channel networks. *Water Resources Research* 33: 2865–2880.

Beuselinck, L., Steegen, A., Govers, G., Nachtergaele, J., Takken, I. and Poesen, J. 2000. Characteristics of sediment deposits formed by intense rainfall events in small catchments in the Belgian Loam Belt. *Geomorphology* 32(1/2): 69–82.

Beven, K. and Freer, J. 2001. Equifinality, data assimilation, and uncertainty estimation in mechanistic modelling of complex environmental systems using the GLUE methodology. *Journal of Hydrology* 249(1–4): 11–29.

Booth, D.B. 1990. Stream-channel incision following drainage-basin urbanization. *Water Resources Bulletin* 26: 407–417.

Borówka, M., II. and Rotnicki, K. 2001. Budget of the eolian sand transport on the sandy barrier/beach (a case study of the Łeba Barrier, southern Baltic coast, Poland). *Zeitschrift für Geomorphologie N.F.* 45(1): 55–79.

Bravard, J.-P., Kondolf, G.M. and Piégay, H. 1999. Environmental and societal effects of channel incision and remedial strategies. In: Darby, S.E. and Simon, A., eds., *Incised River Channels*, New York: John Wiley and Sons, pp. 303–341.

Brazier, R.E., Beven, K.J., Freer, J. and Rowan, J.S. 2000. Equifinality and uncertainty in physically based soil erosion models: application of the GLUE methodology to WEPP—the Water Erosion Prediction Project—for sites in the UK and USA. *Earth Surface Processes and Landforms* 25(8): 825–846.

Brizga, S.O. and Finlayson, B.L. 1994. Interactions between upland catchment and lowland rivers: an applied Australian case study. *Geomorphology* 9(3): 189–202.

Brooks, A.P. and Brierley, G.J. 1997. Geomorphic responses of lower Bega River to catchment disturbance, 1851–1926. *Geomorphology* 18(3/4): 291–304.

Brune, G.M. 1953. Trap efficiency of reservoirs. *Transactions of the American Geophysical Union* 34(3): 407–418.

Bull, W.B., King, J., Kong, F., Moutoux, T. and Phillips, W.M. 1994. Lichen dating of coseismic landslide hazards in alpine mountains. *Geomorphology* 10(1–4): 253–264.

Burbank, D.W. 1992. Causes of recent Himalayan uplift deduced from deposited patterns in the Ganges Basin. *Nature* 357(6380): 680–683.

Caine, N. and Swanson, F.J. 1989. Geomorphic coupling of hillslope and channel systems in two small mountain basins. *Zeitschrift für Geomorphologie* 33(2): 189–203.

Caine, N. and Thurman, E.M. 1990. Temporal and spatial variations in the solute content of an alpine stream, Colorado Front Range. *Geomorphology* 4(1): 55–72.

Carrara, P.E. and Carroll, T.R. 1979. The determination of erosion rates from exposed tree roots in the Piceance Basin, Colorado. *Earth Surface Processes* 4: 307–318.

Cederholm, C.J., Reid, L.M. and Salo, E.O. 1981. Cumulative effects of logging road sediment on salmonid populations in the Clearwater River, Jefferson County, Washington. In: *Proceedings of the Conference on Salmon Spawning Gravel: A Renewable Resource in the Pacific Northwest?* State of Washington Water Research Center Report 39, Washington: Pullman, pp. 38–74.

Cenderelli, D.A. and Kite, J.S. 1998. Geomorphic effects of large debris flows on channel morphology at North Fork Mountain, Eastern West Virginia. *Earth Surface Processes and Landforms* 23(1): 1–20.

Chandler, J.H. and Brunsden, D. 1995. Steady state behaviour of the Black Ven Mudslide: the application of archival analytical photogrammetry to studies of landform change. *Earth Surface Processes and Landforms* 20(3): 255–275.

Church, M., Ham, D., Hassan, M.A. and Slaymaker, O. 1999. Fluvial sediment yield in Canada: scale analysis. *Canadian Journal of Earth Sciences* 36: 1267–1280.

Church, M. and Ryder, J.M. 1972. Paraglacial sedimentation: a consideration of fluvial processes conditioned by glaciation. *Geological Society of America Bulletin* 83: 3059–3072.

Church, M. and Slaymaker, O. 1989. Disequilibrium of Holocene sediment yield in glaciated British Columbia. *Nature* 337(6206): 452–453.

Cisternas, M., Araneda, A., Martínez, P. and Pérez, S. 2001. Effects of historical land use on sediment yield from a lacustrine watershed in central Chile. *Earth Surface Processes and Landforms* 26(1): 63–76.

Clapp, E.M., Bierman, P.R., Nichols, K.K., Pavich, M. and Caffee, M. 2001. Rates of sediment supply to arroyos from upland erosion determined using in situ produced cosmogenic ^{10}Be and ^{26}Al. *Quaternary Research* 55: 235–245.

Clapp, E.M., Bierman, P.R., Schick, A.P., Lekach, J., Enzel, Y. and Cafee, M. 2000. Sediment yield exceeds sediment production in arid region drainage basins. *Geology* 28: 995–998.

Clarke, M.F., Williams, M.A.J. and Stokes, T. 1999. Soil creep: problems raised by a 23 year study in Australia. *Earth Surface Processes and Landforms* 24(2): 151–176.

Clayton, J.L. and Megahan, W.F. 1986. Erosional and chemical denudation rates in the southwestern Idaho Batholith. *Earth Surface Processes and Landforms* 11(4): 389–400.

Clayton, K.M. 1997. The rate of denudation of some British lowland landscapes. *Earth Surface Processes and Landforms* 22(8): 721–732.

Cohen, T.J. and Brierley, G.J. 2000. Channel instability in a forested catchment: a case study from Jones Creek, East Gippsland, Australia. *Geomorphology* 32(1/2): 109–128.

Collins, A.L., Walling, D.E. and Leeks, G.J.L. 1998. Use of composite fingerprints to determine the provenance of the contemporary suspended sediment load transported by rivers. *Earth Surface Processes and Landforms* 23(1): 31–52.

Collins, B.D. and Dunne, T. 1986. Erosion of tephra from the 1980 eruption of Mount St. Helens. *Geological Society of America Bulletin* 97: 896–905.

Collins, B.D. and Dunne, T. 1989. Gravel transport, gravel harvesting, and channel-bed degradation in rivers draining the southern Olympic Mountains, Washington, USA. *Environmental Geology and Water Science* 13(3): 213–224.

Collins, B.D. and Dunne, T. 1990. *Fluvial Geomorphology and River-gravel Mining*, Special Publication 98, Division of Mines and Geology, California Department of Conservation, 29 p.

Corominas, J. and Moya, J. 1999. Reconstructing recent landslide activity in relation to rainfall in the Llobregat River Basin, Eastern Pyrenees, Spain. *Geomorphology* 30 (1/2): 79–93.

Couper, P.R. and Maddock, I.P. 2001. Subaerial river bank erosion processes and their interaction with other bank erosion mechanisms on the River Arrow, Warwickshire, UK. *Earth Surface Processes and Landforms* 26(6): 631–646.

Davis, J., Bird, J., Finlayson, B. and Scott, R. 2000. The management of gravel extraction in alluvial rivers: a case study from the Avon River, southeastern Australia. *Physical Geography* 21(2): 133–154.

DeRose, R.C., Gomez, B., Marden, M. and Trustrum, N.A. 1998. Gully erosion in Mangatu Forest, New Zealand, estimated from digital elevation models. *Earth Surface Processes and Landforms* 23(11): 1045–1053.

Dietrich, W.E. and Dunne, T. 1978. Sediment budget for a small catchment in mountainous terrain. *Zeitschrift für Geomorphologie Supplement Band* 29: 191–206.

Dietrich, W.E., Dunne, T., Humphrey, N.F. and Reid, L.M. 1982. Construction of sediment budgets for drainage basins. In: Swanson, F.J., Janda, R.J., Dunne, T. and Swanston, D.N., eds., *Sediment Budgets and Routing in Forested Catchments*, Pacific Northwest Forest and Range Experiment Station General Technical Report PNW-141, US Department of Agriculture, Forest Service, pp. 5–23.

Dunne, T. 1977. Evaluation of erosion conditions and trends. In: Kunkle, S.H., ed., *Guidelines for Watershed Management*, U.N. Food and Agriculture Organization Conservation Guide 1, Rome, Italy, pp. 53–83.

Dunne, T. 1988. Geomorphological contributions to flood-control planning. In: Baker, V.R., Kochel, R.C. and Patton, P.C., eds., *Flood Geomorphology*, New York: Wiley and Sons, pp. 421–438.

Dunne, T. 2000. Critical data requirements for prediction of erosion and sedimentation in mountain drainage basins. *Journal of the American Water Works Association* 34: 795–808.

Dunne, T., Mertes, L.A.K., Meade, R.H., Richey, J.E. and Forsberg, B.R. 1998. Exchanges of sediment between the flood plain and the channel of the Amazon River in Brazil. *Geological Society of America Bulletin* 110: 450–467.

Dunne, T. and Ongweny, G.S.O. 1976. A new estimate of sediment yields in the upper Tana catchment. *The Kenya Geographer* 2: 109–126.

Erskine, W., McFadden, C. and Bishop, P. 1992. Alluvial cutoffs as indicators of former channel conditions. *Earth Surface Processes and Landforms* 17(1): 23–37.

Evans, M. 1997. Temporal and spatial representativeness of alpine sediment yields: Cascade Mountains, British Columbia. *Earth Surface Processes and Landforms* 22(3): 287–295.

Evans, M. and Church, M. 2000. A method for error analysis of sediment yields derived from estimates of lacustrine sediment accumulation. *Earth Surface Processes and Landforms* 25(11): 1257–1274.

Everest, F.H., Beschta, R.L., Scrivener, J.C., Koski, K.V., Sedell, J.R. and Cederholm, C.J. 1987. Fine sediment and salmonid production: a paradox. In: Salo, E.O. and Cundy, T.W., eds., *Streamside Management: Forestry and Fishery Interactions*, University of Washington Institute of Forest Resources Contribution No. 57, Seattle, Washington, pp. 98–142.

Fantucci, R. and Sorriso-Valvo, M. 1999. Dendrogeomorphological analysis of a slope near Lago, Calabria (Italy). *Geomorphology* 30(1/2): 165–174.

Fernández, C.I., del Castillo, T., Hamdouni, R.E. and Montero, J.C. 1999. Verification of landslide susceptibility mapping: a case study. *Earth Surface Processes and Landforms* 24(6): 537–544.

Flanagan, D.C. and Nearing, M.A. 1995. USDA WEPP: Technical documentation, USDA-ARS National Soil Erosion Laboratory Report No. 10, West Lafayette, Illinois.

Flemings, P.B. and Jordan, T.E. 1989. A synthetic stratigraphic model of foreland basin development. *Journal of Geophysical Research* 94: 3851–3866.

Gabet, E.J. 2000. Gopher bioturbation: field evidence for non-linear hillslope diffusion. *Earth Surface Processes and Landforms* 25(13): 1419–1428.

García-Ruiz, J.M., Lasanta, T. and Alberto, F. 1997. Soil erosion by piping in irrigated fields. *Geomorphology* 20(3/4): 269–278.

Garland, G. and Humphrey, B. 1992. Field measurement of discharge and sediment yield from a soil pipe in the Natal Drakensberg, South Africa. *Zeitschrift für Geomorphologie N.F.* 36: 15–23.

Gellis, A.C., Cheama, A. and Lalio, S.M. 2001. Developing a geomorphic approach for ranking watersheds for rehabilitation, Zuni Indian Reservation, New Mexico. *Geomorphology* 37(1/2): 105–134.

Gilbert, G.K. 1917. *Hydraulic-mining Debris in the Sierra Nevada*, USDI Geological Survey Professional Paper 105, 154 p.

Giles, P.T. 1998. Geomorphological signatures: classification of aggregated slope unit objects from digital elevation and remote sensing data. *Earth Surface Processes and Landforms* 23(7): 581–594.

Gomez, B., Eden, D.N., Hicks, D.M., Trustrum, N.A., Peacock, D.H. and Wilmshurst, J. 1999. Contribution of floodplain sequestration to the sediment budget of the Waipaoa River, New Zealand. In: Marriott, S.B. and Alexander, J., eds., *Floodplains: Interdisciplinary Approaches*, Geological Society of London Special Publication 165, pp. 69–88.

Gonzalez, M.A. 2001. Recent formation of arroyos in the Little Missouri Badlands of southwestern North Dakota. *Geomorphology* 38(1/2): 63–84.

Goodbred, S.L. and Kuehl, S.A. 1998. Floodplain processes in the Bengal Basin and the storage of Ganges-Brahmaputra River sediment: an accretionary study using ^{137}Cs and ^{210}Pb geochemistry. *Sedimentary Geology* 121: 239–258.

Goossens, D., Gross, J. and Spaan, W. 2001. Aeolian dust dynamics in agricultural land areas in Lower Saxony, Germany. *Earth Surface Processes and Landforms* 26(7): 701–720.

Graf, W.L. 1994. *Plutonium in the Rio Grande: Environmental Change and Contamination in the Nuclear Age*, New York: Oxford University Press, 329 p.

Grant, G. 1988. The RAPID technique: a new method for evaluating downstream effects of forest practices on riparian zones, USDA Forest Service Pacific Northwest Research Station General Technical Report PNW-220, 36 p.

Haggett, P.E. 1961. Land-use and sediment yield in an old plantation tract of the Serra do Mar, Brazil. *Geographical Journal* 127(1): 50–62.

Ham, D.G. and Church, M. 2000. Bed-material transport estimated from channel morphodynamics: Chilliwack River, British Columbia. *Earth Surface Processes and Landforms* 25(10): 1123–1142.

Harvey, A.M. 1992. Process interactions, temporal scales and the development of hillslope gully systems: Howgill Fells, northwest England. *Geomorphology* 5(3–5): 323–344.

Harvey, B.C. and Lisle, T.E. 1999. Scour of chinook salmon redds on suction dredge tailings. *North American Journal of Fisheries Management* 19(2): 613–617.

Hassan, M.A., Church, M. and Schick, A.P. 1991. Distance of movement of coarse particles in gravel bed streams. *Water Resources Research* 27(4): 503–512.

Heimsath, A.M., Dietrich, W.E., Nishiizumi, K., Finkel, R.C. 1997. The soil production function and landscape equilibrium. *Nature* 388: 358–361.

Heritage, G.L., Fuller, I.C., Charlton, M.E., Brewer, P.A. and Passmore, D.P. 1998. CDW photogrammetry of low relief fluvial features: accuracy and implications for reach-scale sediment budgeting. *Earth Surface Processes and Landforms* 23(13): 1219–1233.

Hill, B.R., DeCarlo, E.H., Fuller, C.C. and Wong, M.F. 1998. Using sediment "fingerprints" to assess sediment-budget errors, North Halawa Valley, Oahu, Hawaii, *1991–1992. Earth Surface Processes and Landforms 23(6):* 493–508.

Hill, B.R., Fuller, C.C. and DeCarlo, E.H. 1997. Hillslope soil erosion estimated from aerosol concentrations, North Halawa Valley, Oahu, Hawaii. *Geomorphology* 20(1/2): 67–79.

Hill, H. 1896. Denudation as a factor of geologic time. *Transactions and Proceedings of the New Zealand Institute* 28(11th of New Series): 666–679.

Hodson, A., Tranter, M. and Vatne, G. 2000. Contemporary rates of chemical denudation and atmospheric CO_2 sequestration in glacier basins: an arctic perspective. *Earth Surface Processes and Landforms* 25(13): 1447–1472.

Hovius, N., Stark, C.P. and Allen, P.A. 1997. Sediment flux from a mountain belt derived by landslide mapping. *Geology* 25(3): 231–234.

Ibsen, M.-L. and Brunsden, D. 1996. The nature, use and problems of historical archives for the temporal occurrence of landslides, with specific reference to the south coast of Britain, Ventnor, Isle of Wight. *Geomorphology* 15(3/4): 241–258.

Jacobson, R.B. and Gran, K.B. 1999. Gravel sediment routing from widespread, low-intensity landscape disturbance, Current River Basin, Missouri. *Earth Surface Processes and Landforms* 24(10): 897–917.

James, L.A. 1997. Channel incision on the lower American River, California, from streamflow gage records. *Water Resources Research* 33(3): 485–490.

James, A. 1999. Time and the persistence of alluvium: river engineering, fluvial geomorphology, and mining sediment in California. *Geomorphology* 31(1–4): 265–290.

Janda, R.J. 1971. An evaluation of procedures used in computing chemical denudation rates. *Geological Society of America Bulletin* 82: 67–80.

Jäckli, H. 1957. Gegenwartsgeologie des bundnerischen Rheingebieters – ein Beitrag zur exogenen Dynamik Alpiner Gebirgslandschaften. Beiträge zur Geologie der Schweiz, Geotechnische Serie, Leiferung 36.

Jones, J.A.A. 1987. The effects of soil piping on contributing areas and erosion patterns. *Earth Surface Processes and Landforms* 12(3): 229–248.

Kelsey, H.M., Coghlan, M., Pitlick, J. and Best, D. 1995. *Geomorphic Analysis of Streamside Landslides in the Redwood Creek Basin, Northwestern California*, USDI Geological Survey Professional Paper 1454-J, 12 p.

Kesel, R.H., Yodis, E.G. and McCraw, D.J. 1992. An approximation of the sediment budget of the lower Mississippi River prior to major human modification. *Earth Surface Processes and Landforms* 17(7): 711–722.

Kirchner, J.W., Finkel, R.C., Riebe, C.S., Granger, D.E., Clayton, J.L., King, J.G. and Megahan, W.F. 2001. Mountain erosion over 10 yr, 10 k.y., and 10 m.y. time scales. *Geology* 29(7): 591–594.

Knighton, A.D. 1991. Channel bed adjustment along mine-affected rivers of northeast Tasmania. *Geomorphology* 4(3/4): 205–219.

Knighton, A.D. 1999. The gravel-sand transition in a disturbed catchment. *Geomorphology* 27(3/4): 325–341.

Kondolf, G.M. and Matthews, W.G.V. 1991. Unmeasured residuals in sediment budgets: a cautionary note. *Water Resources Research* 27: 2483–2486.

Kondolf, G.M. and Swanson, M.L. 1993. Channel adjustments to reservoir construction and gravel extraction along Stony Creek, California. *Environmental Geology* 21: 256–269.

Kuenen, P.H. 1956. Experimental abrasion of pebbles. 2. Rolling by current. *Journal of Geology* 64: 336–368.

Le Pera, E. and Sorriso-Valvo, M. 2000. Weathering, erosion and sediment composition in a high-gradient river, Calabria, Italy. *Earth Surface Processes and Landforms* 25(3): 277–292.

Lecce, S.A. and Pavlowsky, R.T. 2001. Use of mining-contaminated sediment tracers to investigate the timing and rates of historical flood plain sedimentation. *Geomorphology* 38(1/2): 85–108.

Lehre, A.K., Collins, B.D. and Dunne, T. 1983. Post-eruption sediment budget for the North Fork Toutle River drainage. June 1980–June 1981. *Zeitschrift für Geomorphologie Supplement Band* 46: 143–163.

Leopold, L.B., Emmett, W.W. and Myrick, R.M. 1966. *Channel and Hillslope Processes in a Semiarid Area, New Mexico*, USDI Geological Survey Professional Paper 352-G, pp. 193–253.

Lewis, W.M., Jr. and Grant, M.C. 1979. Relationships between stream discharge and yield of dissolved substances from a Colorado mountain watershed. *Soil Science* 128(6): 353–363.

Leys, J.F. and McTainsh, G.H. 1996. Sediment fluxes and particle grain-size characteristics of wind-eroded sediments in southeastern Australia. *Earth Surface Processes and Landforms* 21(7): 661–671.

Liébault, F. and Piégay, H. 2001. Assessment of channel changes due to long-term bedload supply decrease, Roubion River, France. *Geomorphology* 36(3/4): 167–186.

Lisle, T.E., Cui, Y., Parker, G., Pizzuto, J.E. and Dodd, A. M. 2001. The dominance of dispersion in the evolution of bed material waves in gravel-bed rivers. *Earth Surface Processes and Landforms* 26: 1409–1420.

Lisle, T.E. and Hilton, S. 1999. Fine bed material in pools of natural gravel bed channels. *Water Resources Research* 35 (4): 1291–1304.

Lloyd, S.D., Bishop, P. and Reinfelds, I. 1998. Shoreline erosion: a cautionary note on using small farm dams to determine catchment erosion rates. *Earth Surface Processes and Landforms* 23(10): 905–912.

Madej, M.A. and Ozaki, V. 1996. Channel response to sediment wave propagation and movement, Redwood Creek, California, USA. *Earth Surface Processes and Landforms* 21: 911–927.

Malmon, D.V. 2002. Sediment trajectories through a semi arid valley, Ph.D. Dissertation, University of California, Santa Barbara, California.

Malmon, D.V., Dunne, T. and Reneau, S.L. 2002. Predicting the fate of sediment and pollutants in river floodplains. *Environmental Science and Technology* 36(9): 2026–2032.

Maner, S.B. 1958. Factors influencing sediment delivery rates in the Red Hills physiographic area. *EOS American Geophysical Union Transactions* 39: 669–675.

Mantovani, F., Soeters, R. and Van Westen, C.J. 1996. Remote sensing techniques for landslide studies and hazard zonation in Europe. *Geomorphology* 15(3/4): 213–225.

Marron, D.C. 1992. Floodplain storage of mine tailings in the Belle Fourche River system: a sediment budget approach. *Earth Surface Processes and Landforms* 17(7): 675–685.

Marutani, T., Kasai, M., Reid, L.M. and Trustrum, N.A. 1999. Influence of storm-related sediment storage on the sediment delivery from tributary catchments in the Upper Waipaoa River, New Zealand. *Earth Surface Processes and Landforms* 24(10): 881–896.

Matisoff, G., Bonniwell, E.C. and Whiting, P.J. 2002a. Soil erosion and sediment sources in an Ohio watershed using beryllium-7, cesium-137, and lead-210. *Journal of Environmental Quality* 31(1): 54–61.

Matisoff, G., Bonniwell, E.C. and Whiting, P.J. 2002b. Radionuclides as indicators of sediment transport in agricultural watersheds that drain to Lake Erie. *Journal of Environmental Quality* 31(1): 62–72.

Matsuoka, N. and Sakai, H. 1999. Rockfall activity from an alpine cliff during thawing periods. *Geomorphology* 28(3/4): 309–328.

McLean, D.G. and Church, M. 1999. Sediment transport along lower Fraser River. 2. Estimates based on the long-term gravel budget. *Water Resources Research* 35 (8): 2549–2559.

McLean, D.G., Church, M. and Tassone, B. 1999. Sediment transport along lower Fraser River. 1. Measurements and hydraulic computations. *Water Resources Research* 35(8): 2533–2548.

Meade, R.H. 1982. Sources, sinks, and storage of river sediment in the Atlantic drainage of the United States. *Journal of Geology* 90: 235–252.

Meentemeyer, R.K., Vogler, J.B. and Butler, D.R. 1998. The geomorphic influences of burrowing beavers on streambanks, Bolin Creek, North Carolina. *Zeitschrift für Geomorphologie N.F.* 42(4): 453–468.

Megahan, W.F., Seyedbagheri, K.A. and Dodson, P.C. 1983. Long-term erosion on granitic roadcuts based on exposed tree roots. *Earth Surface Processes* 8(1): 19–28.

Megahan, W.F., Seyedbagheri, K.A., Mosko, T.L. and Ketcheson, G.L. 1986. Construction phase sediment budget for forest roads on granitic slopes in Idaho. In: Hadley, R., ed., *Drainage Basin Sediment Delivery*, International Association of Hydrological Sciences Publication 159, pp. 31–39.

Milliman, J.D. and Syvitski, J.P.M. 1992. Geomorphic/tectonic control of sediment discharge to the ocean: the importance of small mountainous rivers. *Journal of Geology* 100: 525–544.

Morgan, R.P.C., Quinton, J.N., Smith, R.E., Govers, G., Poesen, J.W.A., Auerswald, K., Chisci, G., Torri, D. and Styczen, M.E. 1998. The European Soil Erosion Model (EUROSEM): a dynamic approach for predicting sediment transport from fields and small catchments. *Earth Surface Processes and Landforms* 23(6): 527–544.

Mosley, M.P. 1981. The influence of organic debris on channel morphology and bedload transport in New Zealand forest stream. *Earth Surface Processes and Landforms* 6(6): 571–580.

Nachtergaele, J. and Poesen, J. 1999. Assessment of soil losses by ephemeral gully erosion using high-altitude (stereo) aerial photographs. *Earth Surface Processes and Landforms* 24(8): 693–706.

Nakamura, F., Maita, H. and Araya, T. 1995. Sediment routing analyses based on chronological changes in hillslope and riverbed morphologies. *Earth Surface Processes and Landforms* 20: 333–346.

Nakamura, F., Sudo, T., Kameyama, S. and Jitsu, M. 1997. Influences of channelization on discharge of suspended sediment and wetland vegetation in Kushiro Marsh, northern Japan. *Geomorphology* 18(3/4): 279–289.

Newcombe, C.P. and Jensen, J.O.T. 1996. Channel suspended sediment and fisheries: a synthesis for quantitative assessment of risk and impact. *North American Journal of Fisheries Management* 16(4): 693–727.

Nichol, S.L., Augustinus, P.C., Gregory, M.R., Creese, R. and Horrocks, M.H. 2000. Geomorphic and sedimentary evidence of human impact on the New Zealand coastal landscape. *Physical Geography* 21(2): 109–132.

Nolan, K.M. and Janda, R.J. 1995. *Movement and Sediment Yield of Two Earthflows, Northwestern California*, USDI Geological Survey Professional Paper 1454 F, 12 p.

Norman, S.A., Schaetzl, R.J. and Small, T.W. 1995. Effects of slope angle on mass movement by tree uprooting. *Geomorphology* 14(1): 19–27.

Page, M.J., Trustrum, N.A. and Dymond, J.R. 1994. Sediment budget to assess the geomorphic effect of a cyclonic storm, New Zealand. *Geomorphology* 9(3): 169–188.

Page, M.J. and Trustrum, N.A. 1997. A late Holocene lake sediment record of the erosion response to land use change in a steepland catchment, New Zealand. *Zeitschrift für Geomorphologie N.F.* 41(3): 369–392.

Panin A.V., Walling, D.E. and Golosov, V.N.. 2001. The role of soil erosion and fluvial processes in the post-fallout redistribution of Chernobyl-derived caesium-137: a case study of the Lapki catchment, Central Russia. *Geomorphology* 40(3/4): 185–204.

Parker, R.S. 1988. Uncertainties in defining the suspended sediment budget for large drainage basins. In: Bordas, M.P. and Walling, D.E., eds., *Sediment Budgets*, International Association of Hydrological Sciences Publication 174, pp. 523–532.

Pearce, A.J. and Watson, A.J. 1986. Effects of earthquake-induced landslides on sediment budget and transport over a 50-year period. *Geology* **14**: 52–55.

Phillips, J.D. 1986. The utility of the sediment budget concept in sediment pollution control. *Professional Geographer* 38: 246–252.

Phillips, J.D. 1991. Fluvial sediment budgets in the North Carolina Piedmont. *Geomorphology* **4**: 231–241.

Phillips, J.D., Slattery, M.C. and Gares, P.A. 1999. Truncation and accretion of soil profiles on coastal plain croplands: implications for sediment redistribution. *Geomorphology* 28(1/2): 119–140.

Pitlick, J. and Van Steeter, M.M. 1998. Geomorphology and endangered fish habitats of the upper Colorado River. 2.

Linking sediment transport to habitat maintenance. *Water Resources Research* 34(2): 303–316.

Potter, K.N., Zobeck, T.M. and Hagan, L.J. 1990. A microrelief index to estimate soil erodibility by wind. *Transactions of the American Society of Agricultural Engineers* 33 (1): 151–155.

Prosser, I.P., Hughs, A.O. and Rutherfurd, I.D. 2000. Bank erosion of an incised upland channel by subaerial processes: Tasmania, Australia. *Earth Surface Processes and Landforms* 25(10): 1085–1102.

Quine, T.A., Govers, G., Walling, D.E., Zhang, X., Desmet, P.J.J., Zhang, Y. and Vandaele, K. 1997. Erosion processes and landform evolution on agricultural land—new perspectives from Caesium-137 measurements and topographic-based erosion modelling. *Earth Surface Processes and Landforms* 22(9): 799–816.

Rapp, A. 1960. Recent developments of mountain slopes in Kärkevagge and surroundings, northern Scandinavia. *Geografiska Annaler* 42(2/3): 65–200.

Reid, L.M. 1989. Channel incision by surface runoff in grassland catchments, Ph.D. Dissertation, University of Washington, Seattle, Washington.

Reid, L.M. 1998. Calculation of average landslide frequency using climatic records. *Water Resources Research* 34(4): 869–877.

Reid, L.M. and Dunne, T. 1984. Sediment production from forest road surfaces. *Water Resources Research* 20(11): 1753–1761.

Reid, L.M. and Dunne, T. 1996. *Rapid Evaluation of Sediment Budgets*, Reiskirchen, Germany: Catena Verlag GMBH, 164 p.

Reid, L.M., Dunne, T. and Cederholm, C.J. 1981. Application of sediment budget studies to the evaluation of logging road impact. *Journal of Hydrology (New Zealand)* 20 (1): 49–62.

Reid, L.M. and Hilton, S. 1998. Buffering the buffer. In: Ziemer, R.R., ed., *Proceedings of the Conference on Coastal Watersheds: the Caspar Creek Story*, USDA Forest Service Pacific Southwest Research Station General Technical Report PSW-GTR-168, Albany, California, pp. 71–80.

Reid, L.M. and Page, M.J. 2002. Magnitude and frequency of landsliding in a large New Zealand catchment. *Geomorphology* 49 (1/2): 71–88.

Reid, L.M. and Smith, C.W. 1992. The effects of Hurricane Iniki on flood hazard on Kauai, Report to the Hawaii Department of Land and Natural Resources, Honolulu, Hawaii, 26 p.

Renard, K.G., Foster, G.R., Weesies, G.A., McCool, D.K., Yoder, D.C., coordinators. 1997. *Predicting Soil Erosion by Water: A Guide to Conservation Planning with the Revised Universal Soil Loss Equation (RUSLE)*, Agriculture Handbook 703, US Department of Agriculture, 404 p.

Reneau, S.L. and Dietrich, W.E. 1991. Erosion rates in the southern Oregon Coast Range: evidence for an equilibrium between hillslope erosion and sediment yield. *Earth Surface Processes and Landforms* 16(4): 307–322.

Reneau, S.L. 2000. Stream incision and terrace development in Frijoles Canyon, Bandeleier National Monument, New Mexico, and the influence of lithology and climate. *Geomorphology* 32(1/2): 171–194.

Rice, R.M., 1982. Sedimentation in chaparral: how do you handle unusual events? In: Swanson, F.J., Janda, R.J., Dunne, T. and Swanston, D.N., eds., *Sediment Budgets and Routing in Forested Catchments*, US Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station General Technical Report PNW-141, pp. 39–49.

Riley, S.J. 1990. Monitoring the erosion of an expressway during its construction: problems and lessons. *Hydrological Sciences Journal* 35: 365–381.

Roberts, R.G. and Church, M. 1986. The sediment budget in severely disturbed watersheds, Queen Charlotte Ranges, British Columbia. *Canadian Journal of Forest Research* 16: 1092–1106.

Roehl, J.W. 1962. Sediment source areas, delivery ratios, and influencing morphological factors. *International Association of Scientific Hydrology Publication* 59: 202–213.

Rossi, G. 1998. Erosions differ. *Zeitschrift für Geomorphologie N.F.* 42(3): 297–305.

Rumsby, B. 2000. Vertical accretion rates in fluvial systems: a comparison of volumetric and depth-based estimates. *Earth Surface Processes and Landforms* 25(6): 617–632.

Santantonio, D., Hermann, R.K. and Overton, W.S. 1977. Root biomass studies in forest ecosystems. *Pedobiologia* 17 (1): 1–13.

Saunders, I. and Young, A. 1983. Rates of surface progresses on slopes, slope retreat and denudation. *Earth Surface Processes and Landforms* 8: 473–501.

Schaetzl, R.J., Johnson, D.J., Burns, S.F. and Small, T.W. 1989. Tree uprooting: review of terminology, process, and environmental implications. *Canadian Journal of Forest Research* 19(1): 1–11.

Seidl, M.A., Finkel, R.C., Caffee, M.W., Hudson, G.B. and Dietrich, W.E. 1997. Cosmogenic isotope analyses applied to river longitudinal profile evolution: problems and interpretations. *Earth Surface Processes and Landforms* 22(3): 195–209.

Singer, M.B. and Dunne, T. 2001. Identifying eroding and depositional reaches of valley by analysis of suspended sediment transport in the Sacramento River, California. *Water Resources Research* 37(12): 3371–3381.

Skidmore, E.L. and Woodruff, N.P. 1968. *Wind Erosion Forces in the United States and Their Use in Predicting Soil Loss*, USDA Agricultural Research Service Agricultural Handbook 346.

Slattery, M.C., Burt, T.P. and Boardman, J. 1994. Rill erosion along the thalweg of a hillslope hollow: a case study from the Cotswold Hills, Central England. *Earth Surface Processes and Landforms* 19(4): 377–385.

Sloan, J., Miller, J.R. and Lancaster, N. 2001. Response and recovery of the Eel River, California, and its tributaries to floods in 1955, 1964, and 1997. *Geomorphology* 36(3/4): 129–154.

Small, T.W. 1997. The Goodlett-Denny mound: a glimpse at 45 years of Pennsylvania treethrow mound evolution with implications for mass wasting. *Geomorphology* 18(3/4): 305–314.

Small, E.E., Anderson, R.S. and Hancock, G.S. 1999. Estimates of the rate of regolith production using ^{10}Be and ^{26}Al from an alpine hillslope. *Geomorphology* 27(1/2): 131–150.

Smith, R.D. and Swanson, F.J. 1987. Sediment routing in a small drainage basin in the blast zone at Mount St. Helens, Washington, USA. *Geomorphology* 1: 1–13.

Springer, G.S., Dowdy, H.S. and Eaton, L.S. 2001. Sediment budgets for two mountainous basins affected by a catastrophic storm: Blue Ridge Mountains, Virginia. *Geomorphology* 37(1/2): 135–148.

Steiger, J., Gurnell, A.M., Ergenzinger, P. and Snelder, D. 2001. Sedimentation in the riparian zone of an incising river. *Earth Surface Processes and Landforms* 26(1): 91–108.

Stott, T. 1997. A comparison of stream bank erosion processes on forested and moorland streams in the Balquhidder catchments, central Scotland. *Earth Surface Processes and Landforms* 22(4): 383–399.

Swanson, F.J., Fredriksen, R.L. and McCorison, F.M. 1982. Material transfer in a western Oregon forested watershed. In: Edmonds, R.L., ed., *Analysis of Coniferous Forest Ecosystems in the Western United States*, Stroudsburg, Pennsylvania: Hutchinson Press, pp. 233–266.

Swanson, M.L., Kondolf, G.M. and Boison, P.J. 1989. An example of rapid gully initiation and extension by subsurface erosion: coastal San Mateo County, California. *Geomorphology* 2(4): 393–404.

Swanston, D.N., Ziemer, R.R. and Janda, R.J. 1995. *Rate and Mechanics of Progressive Hillslope Failure in the Redwood Creek Basin, Northwestern California*, USDI Geological Survey Professional Paper 1454 E, 16 p.

ten Brinke, W.B.M., Schoor, M.M., Sorber, A.M. and Berendsen, H.J.A. 1998. Overbank sand deposition in relation to transport volumes during large-magnitude floods in the Dutch sand-bed Rhine River system. *Earth Surface Processes and Landforms* 23(9): 809–824.

Terajima, T., Sakamoto, T., Nakai, Y. and Kitamura, K. 1997. Suspended sediment discharge in subsurface flow from the head hollow of a small forested watershed, northern Japan. *Earth Surface Processes and Landforms* 22(11): 987–1000.

Thorn, C.E. 1978. A preliminary assessment of the geomorphic role of pocket gophers in the alpine zone of the Colorado Front Range. *Geografiska Annaler* 60A(3/4): 181–187.

Thorne, C.R. and Tovey, N.K. 1981. Stability of composite river banks. *Earth Surface Processes* 6(5): 469–484.

Trimble, S.W. 1974. *Man-induced Soil Erosion on the Southern Piedmont, 1700–1970*, Ankeny, Iowa: Soil Conservation Society of America, 180 p.

Trimble, S.W. 1977. The fallacy of stream equilibrium in contemporary denudation studies. *American Journal of Science* 277: 876–887.

Trimble, S.W. 1983. A sediment budget for Coon Creek basin in the driftless area, Wisconsin, 1853–1977. *American Journal of Science* 283: 454–474.

Trimble, S.W. 1993. The distributed sediment budget model and watershed management in the Paleozoic plateau of the upper Midwestern United States. *Physical Geography* 14 (3): 285–303.

Trimble, S.W. 1994. Erosional effects of cattle on streambanks in Tennessee. *Earth Surface Processes and Landforms* 19(5): 451–464.

Trimble, S.W. 1997. Contribution of stream channel erosion to sediment yield from an urbanizing watershed. *Science* 278: 1442–1444.

Trimble, S.W. 1999. Decreased rates of alluvial storage in the Coon Creek Basin, Wisconsin, 1975–93. *Science* 285: 1244–1246.

Van Asch, T.J.W. and Van Genuchten, P.M.B. 1990. A comparison between theoretical and measured creep profiles of landslides. *Geomorphology* 3(1): 45–55.

Van Steeter, M.M. and Pitlick, J. 1998. Geomorphology and endangered fish habitats of the upper Colorado River. 1. Historic changes in streamflow, sediment load, and channel morphology. *Water Resources Research* 34(2): 287–302.

van Steijn, H. 1996. Debris-flow magnitude–frequency relationships for mountainous regions of Central and Northwest Europe. *Geomorphology* 15(3/4): 259–273.

Vandaele, K., Vanommeslaeghe, J., Muylaert, R. and Govers, G. 1996. Monitoring soil redistribution patterns using sequential aerial photographs. *Earth Surface Processes and Landforms* 21(4): 353–364.

Vandekerckhove, L., Poesen, J., Oostwoud Wijdenes, D., Gyssels, G., Beuselinck, L. and de Luna, E. 2000. Characteristics and controlling factors of bank gullies in two semi-arid mediterranean environments. *Geomorphology* 33(1/2): 37–58.

Verstraeten, G. and Poesen, J. 2000. Estimating trap efficiency of small reservoirs and ponds: methods and implications. *Progress in Physical Geography* 24(2): 219–251.

Walling, D.E. and He, Q. 1997. Use of fallout Cs-137 in investigations of overbank sediment deposition on river floodplains. *Catena* 29(3/4): 263–282.

Walling, D.E. and He, Q. 1998. The spatial variability of overbank sedimentation on river floodplains. *Geomorphology* 24(2/3): 209–224.

Walling, D.E., Owens, P.N. and Leeks, G.J.L. 1998. The role of channel and floodplain storage in the suspended sediment budget of the River Ouse, Yorkshire, UK. *Geomorphology* 22(3/4): 225–242.

Walling, D.E. and Webb, B.W. 1982. Sediment availability and the prediction of storm-period sediment yields. *International Association of Hydrological Sciences Publication* 137: 327–337.

Ward, P.A., III. and Carter, B.J. 1999. Rates of stream incision in the middle part of the Arkansas River Basin based on late Tertiary to mid-Pleistocene volcanic ash. *Geomorphology* 27(3/4): 205–228.

Wasson, R.J., Mazari, R.K., Starr, B. and Clifton, G. 1998. The recent history of erosion and sedimentation on the Southern Tablelands of southeastern Australia: sediment flux dominated by channel incision. *Geomorphology* 24(4): 291–308.

Wathen, S.J. and Hoey, T.B. 1998. Morphological controls on the downstream passage of a sediment wave in a gravel-bed stream. *Earth Surface Processes and Landforms* 23(8): 715–730.

Wieczorek, G.F. and Jäger, S. 1996. Triggering mechanisms and depositional rates of postglacial slope-movement processes in the Yosemite Valley, California. *Geomorphology* 15(1): 17–31.

Wiele, S.M., Graf, J.B. and Smith, J.D. 1996. Sand deposition in the Colorado River in the Grand Canyon from flooding of the Little Colorado River. *Water Resources Research* 32(12): 3579–3596.

Wilby, R.L., Dalgleish, H.Y. and Foster, I.D.L. 1997. The impact of weather patterns on historic and contemporary catchment sediment yields. *Earth Surface Processes and Landforms* 22(4): 353–364.

Wilcock, P.R., Kondolf, G.M., Matthews, W.V.G. and Barta, A.F. 1996. Specification of sediment maintenance flows for a large gravel-bed river. *Water Resources Research* 32(9): 2911–2921.

Wiles, G.C., Calkin, P.E. and Jacoby, G.C. 1996. Tree-ring analysis and Quaternary geology: principles and recent applications. *Geomorphology* 16(3): 259–272.

Wischmeier, W.H. and Smith, D.D. 1978. *Predicting Rainfall Erosion Losses—A Guide to Conservation Planning*, USDA Agriculture Handbook No. 537, 58 p.

Wohl, E.E. and Cenderelli, D.A. 2000. Sediment deposition and transport patterns following a reservoir sediment release. *Water Resources Research* 36(1): 319–333.

Womack, W.R. and Schumm, S.A. 1977. Terraces of Douglas Creek, northwestern Colorado: an example of episodic erosion. *Geology* 5: 72–76.

Yanda, P.Z. 2000. Use of soil horizons for assessing soil degradation and reconstructing chronology of degradation processes: the case of Mwisanga Catchment, Kondoa, central Tanzania. *Geomorphology* 34(3/4): 209–226.

Yoshida, K., Kikuchi, S., Nakamura, F. and Noda, M. 1997. Dendrochronological analysis of debris flow disturbance on Rishiri Island. *Geomorphology* 20(1/2): 135–145.

Zhang, X., Phillips, C. and Pearce, A. 1991a. Surface movement in an earthflow complex, Raukumara Peninsula, New Zealand. *Geomorphology* 4: 261–272.

Zhang, X., Phillips, C. and Marden, M. 1991b. Internal deformation of a fast-moving earthflow, Raukumara Peninsula, New Zealand. *Geomorphology* 4: 145–154.

Zhang, X., Phillips, C. and Marden, M. 1993. A comparison of earthflow movement mechanisms on forested and grassed slopes, Raukumara Peninsula, North Island, New Zealand. *Geomorphology* 6: 175–187.

Ziemer, R.R. 1992. Effect of logging on subsurface pipeflow and erosion: coastal northern California, USA. In: Walling, D.E., Davies, T.R. and Hasholt, B., eds., *Erosion, Debris Flows and Environment in Mountain Regions*, International Association of Hydrological Sciences Publication 209, pp. 187–197.

Zonge, K.L., Swanson, S. and Myers, T. 1996. Drought year changes in streambank profiles on incised streams in the Sierra Nevada Mountains. *Geomorphology* 15(1): 47–56.