CHAPTER 1

Overview of Sedimentation Engineering

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1.1 INTRODUCTION

1.1.1 General

Sedimentation engineering embraces the identification, planning, analysis, and remediation, principally in the context of civil and hydraulic engineering practice, of projects or technical investigations to avoid and/or mitigate problems caused by sedimentation processes. These processes include erosion, entrainment, transport, deposition, and compaction of sediment. External agents and forces driving these processes may include water, wind, gravity, and ice. Human activities also affect sedimentation processes. This volume of *Sedimentation Engineering*, referred to herein as Manual 110, focuses primarily on physical processes, measurements, modeling, and the practice of sedimentation engineering, mainly in the context of rivers and inland water bodies. (Chapter 4, however, addresses fine sediments topics, including those found in coastal and estuarine environments.)

The original ASCE Manual 54 *Sedimentation Engineering,* edited by Vito A. Vanoni (1975), represents a 10-year effort by the Task Committee for the Preparation of a Manual on Sedimentation under the coordination of the Sedimentation Committee of the Hydraulics Division of ASCE. Professor Vanoni and the Task Committee assembled and organized state-of-the-art information on sediment mechanics and sedimentation engineering available at the time. Since then, awareness of the importance, scope, and potential consequences of sedimentation processes in relation to civil engineering works, human activities, and the environment has greatly increased. Also greatly expanded are the scientific and engineering understanding and knowledge of underlying processes related to sedimentation engineering. Manual 110 is designed to update selected topics in the original manual and to present recent advances and new topics in sedimentation engineering as a complement to the original Manual 54. Manual 110 is intended to supplement rather than replace the original manual, which contains a wealth of fundamental information that has not lost its validity. Together, both manuals document the evolution of the specialized field of sedimentation engineering over a 50-year period.

1.1.2 Global Aspects and Changing Roles

As awareness of sedimentation processes and the consequences of poor sediment-management practices has increased among civil engineers and other water resources professionals, it has increasingly been realized that a multidisciplinary approach to problem identification, quantification, and management is often required to deal with the interrelated effects of geomorphologic, environmental, and engineering issues. This type of comprehensive systems approach is also demanded by more stringent legal and regulatory requirements regarding sediment and hydraulic processes in water bodies.

Factors that have resulted in increased public awareness and greater potential impacts to water resources and the environment include the following:

- Growing global populations place increasing pressures on land and water resources. As forest and farmlands become subject to increased soil erosion (Fig. 1-1), reservoirs designed for centuries of useful life may fill with sediment in a few decades, and water supply, irrigation systems, and critical aquatic habitat areas may become clogged with sediment deposits, while poorly managed forests and farmlands decline in function and productivity.
- Human settlements have increasingly occupied areas more vulnerable to erosion and sedimentation, thus aggravating runoff, soil erosion, and gullying (Fig. 1-2). Poor land use planning, management, and maintenance

Fig. 1-1. Severe soil erosion resulting from annual burning of underbrush in teak forests on hillsides in Java, Indonesia. *Photograph by B. J. Evans.*

Fig. 1-2. Accelerated land erosion and gullying: active gullying resulting in severe soil loss and high sediment yields on the upper plateau of Rio Calicanto, Bolivia. This fertile cropland was abandoned by local farmers because of their migration to coca producing areas. Because of neglect and lack of annual maintenance, the altered lands are no longer managed or stabilized, resulting in rapid erosion and headcutting of gullies during rainstorms. Irrigation reservoirs downstream are now filled with sediment eroded from this area, resulting in significant impacts to water supply and flood control. *Photograph by V. J. Galay.*

practices often lead to dramatic consequences. Severe natural events such as floods, hurricanes, earthquakes, landslides, and volcanic eruptions can produce more dramatic geomorphic changes and sedimentation effects in highly altered settings that can last for decades.

- One of the most significant factors affecting global management and delivery of sediment has been the construction of dams on rivers. Approximately 80,000 dams have been built in the United States of America during the past century (Graf 2001). Morris and Fan (1997) summarize how construction of dams provides many benefits but may alter a river's natural balance of sediment inflow and outflow. They emphasize the urgent need to improve global planning, operation, maintenance, and management of dams and reservoirs with respect to sediment-related problems. An example is the Davis Dam on the Colorado River near Las Vegas (Fig. 1-3), which, along with the Hoover, the Glen Canyon, the Parker, the Headgate Rock, the Palo Verde, the Imperial, and the Laguna dams, have fragmented the river into a series of pools and sediment sinks that alter the nature and movement of sediment along the Colorado River.
- Scientific experts and governments worldwide acknowledge strong scientific evidence demonstrating that human activities are changing the Earth's climate and that further change is inevitable. Expected results include an increasing likelihood worldwide for more frequent occurrences of extreme storms and flood events (National Research Council 1989; Hasselmann et al. 2003; Watson 2003). Such events are often responsible for a major part of long-term morphologic changes and sedimentation activity, while the occurrence of severe hydrologic events on highly altered, destabilized landscapes may result in more dramatic consequences than previously anticipated. This may become one of the most important engineering and environmental issues facing societies worldwide.

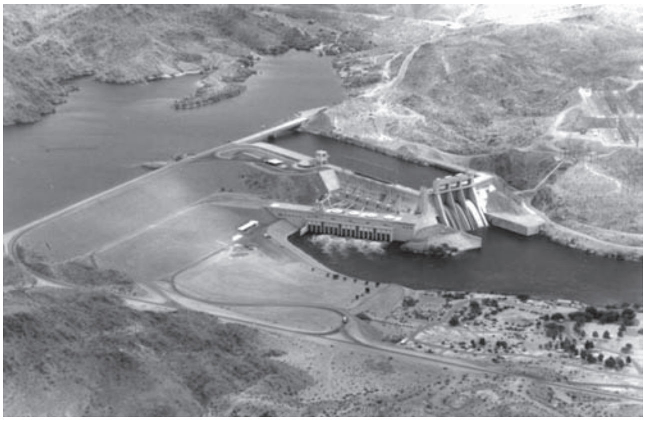

Fig. 1-3. Photo of Davis Dam on the Colorado River. Watershed sediments are trapped behind a series of eight dams and reservoirs resulting in approximately 20 feet of riverbed lowering in places along the Colorado River. *Photograph by V. J. Galay.*

The following excerpts from a volume devoted to reservoir sedimentation by Morris and Fan (1997) raise difficult issues related to water resources and sedimentation engineering:

> In a number of countries population growth seems to be rapidly outstripping the available water resources base. . . . Water resource engineers and development planners have a responsibility to study, understand and communicate the capacity and limits of the earth's resources. . . . Is it a legitimate or ethical function of the engineering profession to destroy entire ecosystems to feed a runaway human population?

With increasing awareness of the importance, scope, and potential consequences of sedimentation processes in relation to civil engineering works, human activities, and the environment, sedimentation engineering studies require consideration of basinwide processes associated with sediment sources, transport routes, and depositional sinks, as well as the potential future effects on the environment and on upstream and downstream interests. Forecasting may be required of incremental and cumulative impacts from a sequence of past and future projects—for example, possible impacts of a series of road and bridge crossings on the hydraulics and morphology of a river floodplain should be assessed prior to project construction. Sedimentation issues often embrace water quality, contaminant transport (e.g., heavy metals, pesticides, and petroleum by-products that attach to sediments), and impacts on natural habitat, health, and amenities, requiring that sedimentation engineers participate in multidisciplinary teams to plan and design effective projects. In the United States and other countries, legislation increasingly calls for detailed quantification of sedimentation processes as well as other impacts from water resources projects.

1.1.3 Additional Comments

Some general observations on the state of sedimentation engineering in the early years of the twenty-first century are as follows:

- Sedimentation processes are not always adverse or undesirable as some writings suggest. To the contrary, sedimentation processes are essential for the maintenance of morphologic balance and are critical components of aquatic ecosystems. For example, fertile agricultural lands and wildlife areas may benefit from periodic flooding and silt deposition, and fish may rely on continual renewal of bed sediment (gravels) in spawning areas. Sedimentation processes are key components of most fluvial systems.
- Project planners and designers are presented with so much information on environmental and biological issues that the importance of hydraulic and sedimentation processes are sometimes overlooked or underestimated. Given the need for reliable field data, however, it is important to address sedimentation issues at an early stage. Where there are clearly significant problems or impacts, sediment data collection should receive as much attention as hydrometeorologic and environmental data. It is as important to develop uninterrupted long-term sedimentation data sets as it is to monitor hydrologic and biologic changes and trends.
- Field studies providing full-scale confirmation of theoretical and laboratory results are relatively scarce, compared to the large number of theoretical and small-scale experimental studies proposing methods for the computation of sediment transport rates, scour depths at bridge foundations, and so on. This is not surprising given their difficulty and cost, but the limitations of theoretical formulations and scaled-up laboratory results are sometimes overlooked.
- Sediment management issues and morphological changes may arise from reduction of sediment inputs as well as from increases in sediment production. Poor project planning, poor land use management, or the occurrence of significant natural hazards (fires, earthquakes, and floods) may result in short- or long-term sediment imbalances. For example, construction of storage reservoirs that trap fluvial sediment or excessive mining (extraction) of fluvial sediments may have adverse effects on channel morphology and the biological habitat in downstream river reaches and cause undermining of structure foundations and alter coastal morphology and stability.
- Addressing real-world problems in water resources and sedimentation engineering is often challenging because of the extreme complexities related to large spatiotemporal heterogeneities, sparsity of reliable data, and knowledge gaps that limit our ability to predict morphologic changes during individual storm events or during longer, decadal periods of time. Perhaps even more challenging to hydraulic and sediment engineering scientists is understanding and quantifying the interaction between flow and sediment dynamics, and the short- and long-term effects of these processes on aquatic ecosystems (modified from Lyn, 2006). Solutions to this class of challenging issues will require a multidisciplinary approach from engineers and scientists. This need is "driving the development of a predictive science of Earth surface dynamics that integrates many disciplines and approaches, including hydrology, geomorphology, ocean and atmospheric science, sedimentary and structural geology, geochemistry, and ecology" (Paola et al. 2006).

1.1.4 Scope of Subsequent Chapters and Appendices

Chapters 2 through 23 and Appendices A through D address a wide range of sedimentation topics. To a considerable extent, the topics covered reflect the expertise and interests of individual authors and are intended to present recent advances and new topics in sedimentation engineering. Primary topics include:

- Sediment sources, erosion, and hazards: Chapters 6, 17–19.
- Sediment transport mechanics and measurement: Chapters 2–5.
- Computational modeling of sediment transport: Chapters 14, 15, 19, and 23.
- Lateral stability of river channels: Chapters 7 and 8.
- Assessment and remediation of selected sedimentation problems: Chapters 9–12 and 23.
- Environmental issues: Chapters 9, 21, and 22.
- Ice effects on sediment transport: Chapter 13.
- Turbulence modeling: Chapter 16.
- Sedimentation law: Chapter 20.

Appendices A through D provide summaries on additional topics including rock erosion, riprap design, the use of physical models for assessing sediment engineering problems, and methods for estimating sediment discharge. Appendices E and F provide a glossary of terms and unit conversions.

1.2 OVERVIEW OF EROSION

1.2.1 General

ASCE's original Manual 54 (Vanoni 1975) distinguished between geological (or natural) erosion and accelerated (or human-induced) erosion, viewing the latter as a mainly local phenomenon. In the twenty-first century, such a view is outdated. Hooke (1994) estimated annual global volumes of erosion due to various agents and concluded that "humans are arguably the most important geomorphic agent currently shaping the surface of the Earth." However, others (Valdiya 1998) have shown that geological erosion through mountain ranges, such as the Himalayas, continues to produce immense volumes of sediment.

It is often difficult to determine whether an observed erosional process is natural or whether it results wholly or partly from human influences. For example, gullying and landslides that appear natural may have been triggered or aggravated by overgrazing, significant land use modifications such as urbanization, infiltration of irrigation water, or deforestation. Overviews of erosion, sediment transport, and deposition are presented in Sections 1.2, 1.3, and 1.4, respectively.

1.2.2 Geologic or Natural Erosion

Geological erosion results from tectonic uplift, earthquakes, weathering, and chemical decomposition and the long-term action of water, wind, gravity, and ice (see Chapters 6, 17, and 18). Over long periods, such processes have produced some enormous erosional scars—for example, the Grand Canyon in Arizona (Fig. 1-4). In some regions, the bulk of natural erosion may result from severe episodic events like earthquakes, landslides, volcanic eruptions, and extreme floods.

Fig. 1-4. Grand Canyon, Arizona: spectacular example of geologic erosion by flowing water through layers of sedimentary deposits. Note sites where active erosion provides sediment directly into the river from small, steep drainages. *Photograph by V. J. Galay.*

Rates of geologic erosion vary widely both among and within regions. Summerfield and Hutton (1994) list average rates of natural erosion estimated for major world drainage basins. Rates tend to be slow in terms of a human lifetime but may be significant enough to require consideration in some projects. Control is often difficult or impractical because the erosion is distributed over large areas divided among multiple owners and resource management jurisdictions. Poorly designed and implemented land or water use projects can dramatically accelerate prior erosion rates.

Geologic erosion rates have varied widely over time, primarily as a result of climatic variations. Rapid climate change in the form of global warming has led to unprecedented erosion in sensitive areas like the Arctic coast of North America (McCarthy et al. 2001).

1.2.3 Accelerated or Human-Induced Erosion

Accelerated erosion may be wholly or partly caused by human activities. The impacts of individual or cumulative human activities may be subtle and may commence slowly but can result in dramatic rapid changes in morphology, sediment production, and deposition with time once critical geomorphic stability thresholds are exceeded. Hatheway (2005) explains that prior to the nineteenth century, humans possessed a relatively limited ability to alter the geologic landscape. However, anthropogenic effects on global landscapes and the environment dramatically accelerated during the nineteenth and twentieth centuries. Besides causing sedimentation problems and impacting constructed facilities, poorly planned human activities often lead to environmental degradation and damage to habitat. Simply to address accelerated erosion as a local engineering problem without regard to basinwide sources and responses is generally inadvisable. The potential for erosion should be considered in the context of a multidisciplinary and participatory approach to a range of associated problems. In the face of growing populations and associated pressures placed on land and natural resources, the basic problems associated with sedimentation processes may not be fully solvable, but at least they should be recognized and faced by authorities and the public.

1.2.4 Sources of Accelerated Erosion

Extensive discussions on a number of sources of accelerated erosion are contained in the original Manual 54. Some important sources are discussed briefly below and in Chapters 6 and 17 through 19.

1.2.4.1 Agricultural Activities Manual 54 cited an estimated annual soil loss from croplands in the United States of 4×10^9 tons/year, of which about 25% was estimated to reach the oceans. In the United States, severe soil erosion in the 1930s was followed by intensive conservation efforts, which substantially reduced rates of soil loss by about 40% in vulnerable regions, between 1982 and 1997 (Uri and Lewis 1998).

Global population increases, on the order of 80 million people per year between 1975 and 2000, have placed severe pressures on agricultural and water resources on several continents. It has been estimated that toward the end of the twentieth century, from 5 to 7 million hectares of arable land worldwide were lost annually because of soil degradation and erosion (Hauck 1985; Jalees 1985; Brown 1991). Although improvements have occurred and continue to take place in the United States, Canada, and some other parts of the world, soil loss has substantially increased in other regions, leading to a net increase in worldwide annual soil loss (Barrow 1991; Food and Agricultural Organization of the United Nations [FAO] 2001).

1.2.4.2 Forest Activities World timber demand, extended agriculture, and use of wood for fuel in many regions have caused extensive destruction of forest land by cutting or burning, especially in parts of Africa, Asia, and South America (Bryant et al. 1997). In a single decade between 1990 and 1999, the global forest area declined by nearly 20% (FAO 2001). It has been claimed that conversion of forestland to agriculture generally increases soil erosion by a factor ranging from several times to as much as 25 times (Golubev 1982).

Where forests are managed for sustainable timber yield, extraction activities are not necessarily erosional, but accelerated erosion often results from cutting on steep slopes or close to streambanks and from construction of access roads and skid trails. In steep terrain, alteration of streams and drainage patterns can trigger destructive debris flows containing boulders, gravel, fine sediment, and woody debris (Costa 1988; Slaymaker 1988). Poorly planned, irresponsible conversion of forestlands has led to dramatic long-term environmental impacts and loss of stable forest areas in Asia, Africa, and in the Amazon River basin in South America. Stabilization and rehabilitation of such channels and river systems may require large-scale and expensive engineering measures (Wieczorek and Naeser 2000).

1.2.4.3 Urbanization Rapid growth of cities and suburban areas in the later twentieth century, especially in less developed countries, contributed to increases in erosion due to accelerated runoff from developed areas, especially where steep hillsides are used for unregulated low-cost shelter (Ismail 1997). In some cases, disastrous landslides and mud flows following severe rainfall have caused large-scale property destruction and loss of life (Quinones and Johnson 1987).

In well-planned urban developments, on the other hand, local erosion tends to be important only during construction. Accelerated runoff from developed areas has customarily been directed into storm drains or hard-lined flood-control channels, but this may cause adverse changes in downstream rivers and water bodies. In some jurisdictions, there is pressure to replace hard-lined channels with restored natural stream systems (see Chapter 9). Restoring natural streams to a semistable condition where they receive substantial urban runoff requires multidisciplinary planning and careful engineering design, generally involving storage facilities or the maintenance of large undeveloped floodplain areas to reduce flow peaks and trap sediment. Once confined, realigned, and affected by increased urban runoff, former natural channel processes are forever altered. This often results in regular, long-term management and maintenance requirements (including annual monitoring, permitting, and funding to support these activities) that may have been unanticipated by project proponents.

1.2.4.4 Roads, Railways, Bridges, and Levees The main sedimentation impacts of these facilities, apart from temporary construction effects, are (1) alteration of natural drainage patterns by redirecting and concentrating dispersed cross-flows into bridge and culvert openings (which may have serious effects in steep terrain) and (2) interference with natural river migration and overbank flow patterns by construction of permanent bridge crossings, approach embankments, and levees running alongside rivers (Figs. 1-5 and 1-6). Chapters 8, 10, and 11 present materials relevant to these topics.

1.2.4.5 Mining Activities Attention is given in technically advanced countries to controlling erosion from open-pit mining operations, but operations in less developed countries have often proceeded with insufficient planning and oversight. Uncontrolled excessive in-channel and floodplain mining can result in geomorphic alteration of river form and processes (Collins and Dunne 1990; Kondolf 1994, 1998a, 1998b; Brown et al. 1998; Church 2001). Poorly managed mining can lower water surface elevations and disrupt the balance between sediment supply and a stream's transporting capacity, which can result in channel incision, bed degradation, diversion of flow through disturbed sediment removal sites, increase of channel instability, and changes in overall channel morphology and sediment transport processes (Fig. 1-7).

1.2.4.6 Dams and River Regulation The primary sedimentation effect of a dam is usually to trap riverborne sediment in the reservoir and thereby reduce the availability of sediment load for downstream sediment transport, often leading to local "sediment starvation" and channel incision downstream of the reservoir. Sediment deposition

Fig. 1-5. Jacalitos Creek, California: the creek is attempting to outflank a highway bridge because the narrow bridge constriction and approach embankment prevent natural down-valley migration of meanders. Flow is from right to left. *Photograph by V. J. Galay.*

Fig. 1-6. Lower Guadalupe River below the City of San Jose, California: an example of a channelized urban river. The formerly meandering river was significantly straightened and leveed, restricting floodwaters to the main river channel. Formerly an agricultural area, the floodplain is now mainly occupied by urban and industrial development. View downstream. *Photograph by R. C. MacArthur.*

Fig. 1-7. Natural (top photo) and mined (bottom photo) reaches of Cache Creek, California, in 1986. Historically, excessive aggregate mining significantly altered the channel's morphology, causing channel degradation and thalweg lowering (incision). Implementation of comprehensive mining regulations in 1996 has improved conditions. *Photographs by R. C. MacArthur.*

in reservoirs is addressed in Chapters 2 and 12. Chapters 6 and 18 discuss other beneficial aspects of reservoirs as well as their potential impacts on river systems.

Erosional effects associated with dams and reservoirs may include the following:

- Slope flattening and headcutting of the downstream river and consequent destabilization of tributary streams due to sediment starvation, increased flow duration, and/or magnitude of flows (Fig. 1-8).
- Wave erosion around the shorelines.
- In circumpolar regions, collapse of shorelines by thawing of permafrost.

Engineering works such as flood protection levees, which do not generally produce increased sediment inputs, may nevertheless have significant erosional effects because they increase in-channel flows and as well as average channel velocities. The downstream channel gradient may flatten by channel incision and headcutting, resulting in undercutting of channel banks and undermining of engineering works such as bridge and pipeline crossings (U.S. Army Corps of Engineers [USACE] 1994).

River channel alterations designed to augment hydraulic capacity for drainage purposes can cause serious erosion, particularly when meandering channels are straightened and cleared of vegetation without introducing resistant linings or grade control structures (Schumm et al. 1984; USACE 1994). Chapters 6 through 9 present relevant information regarding these topics.

Fig. 1-8. Severe erosion and headcutting in former natural channel below Grapevine Dam Spillway, Texas, resulting mainly from greatly increased maximum outflows from collected urban flood runoff. *Photograph by C. R. Neill.*

1.2.4.7 Warfare and Population Migrations The main potential erosional effect of these activities results from construction of defense works and the neglect or abandonment of traditional agricultural methods, water conveyance systems, or engineering works that previously protected land and streams against erosion. Heavy armored transport, shelling, bombing, and fires can also cause significant destruction of forests and erosion protection and land conservation systems. Rose (2005) discusses how historical military activities have impacted local and regional geological conditions by changing the nature and rate of erosion and deposition processes.

1.2.4.8 Multiple Causes Accelerated erosion in many world regions may arise from a combination of causes. For example, a publication edited by Walling et al. (1992) presents a regional approach for evaluating basin-wide changes and deals with interrelated problems of erosion, debris flows, and the environment in mountain regions, with particular attention to the Pacific Rim.

1.2.5 Estimation of Erosion Rates and Quantities

Estimation of erosion rates and sediment yield from river basins can involve large uncertainties due to the sparsity of reliable data. The problem can be approached indirectly by considering source quantities of erosion or soil loss, or more directly by considering sediment yield—that is, the quantity delivered to the river system—which is usually much less than the source erosion. The first approach tends to be favored by geographers, soil scientists, and agriculturists and the second by urban planners and water resource engineers. Extensive literature exists for both approaches (see, e.g., Barfield et al. 1981; Simons and Senturk 1992; Haan et al. 1994; Reid and Dunne 1996; de Boer et al. 2003). In many basins, a significant proportion of the material eroded from the land surface does not reach the river system because of intermediate topographic features that act as sediment sinks (traps or temporary storage areas).

Erosion from land surfaces can be considered on a large scale in the context of typical rates per unit area from specific regions or specific types of terrain, or at small scale in the context of experimental plots that measure erosion from different types of soil under different vegetation covers and land uses. Experimental plots often tend to overpredict effective sediment production and delivery rates from larger areas. On the other hand, estimates based only on land surface erosion may overlook erosion from valley slopes, gullies, and stream channels. In the case of migrating stream channels, reliable determination of net erosion quantities is difficult because erosion at one location is often compensated by deposition at another.

Sediment yield can be considered globally in the form of typical rates per unit area from various regions or terrain types, or more locally from measured deposition quantities in lakes and reservoirs or measured rates of sediment transport in rivers. Uninterrupted, long-term sediment delivery data from monitored basins produce the most reliable sediment yield estimates. Unfortunately, very few basins have such data, so sediment yield estimates must usually be developed from empirical relationships. For specific regions, empirical correlations are available relating sediment "delivery ratio" (the ratio of net sediment yield to gross erosion) to drainage area or other physiographic parameters. There are also methods (Barfield et al. 1981; Haan et al. 1994; Reid and Dunne 1996) for estimating sediment yield in unmonitored basins from regional soil erosion and yield maps, empirical yield estimation relationships, or simplified soil loss and delivery models, as well as methods for translating measured sediment yield values from a monitored basin to an unmonitored basin of similar character. Sediment yield is addressed in Chapter 17.

1.2.6 Local Erosion and Scour Associated with Engineering Works

Many types of engineering works in water bodies with erodible beds cause local erosion, usually referred to as scour when it proceeds downward into a channel bed (Fig. 1-9). This problem is an important consideration in the design of bridge foundations, dams, culverts, weirs, riverbank protection, and other works. Scour associated with bridges is treated in Chapters 10 and 11; references include Melville and Coleman (2000), Richardson and Davis (2001), and Transportation Association of Canada (2001). Rock scour is addressed in Appendix A. Other publications covering a broader range of local scour and erosion problems include USACE (1994), Julien (2002), and May et al. (2002). Thompson (2005) discusses the history of the use and effectiveness of in-stream structures on river processes in the United States. Appendix B discusses erosion countermeasures.

Fig. 1-9. 1995 photo of bed scour and bank erosion under Highway 162 Bridge on Sacramento River, California. Long lengths of formerly buried piles are exposed by bank recession associated with toe scour. *Photograph by R. C. MacArthur.*

1.3 OVERVIEW OF SEDIMENT TRANSPORT

1.3.1 General

Sediment transport is treated extensively in several chapters of Manual 54 (Vanoni 1975). That earlier treatment includes transport by wind and transport in pipes, neither of which is addressed in the present volume. Substantial parts of the material in the original Manual 54 are of a fundamental nature and retain their validity. Chapters 2 through 5 of Manual 110 mainly update selected aspects of the topic. Chapters 14 through 16 and 23 cover numerical modeling, a topic that has developed rapidly since 1975 and was not covered in the original Manual 54. Appendix D discusses methods for estimating sediment discharge.

1.3.2 Modes of Sediment Transport

The term *sediment* covers a wide range of grain sizes transported by flowing water, ranging from fine clay particles to large boulders. These are often viewed in specific size classes, such as fine sand, coarse gravel, and so on, using one of several alternative classification systems (ASCE 1962). Depending on grain sizes and sediment material density, fluid density and viscosity, and the strength and turbulence of the flow, sediment transport may occur in a variety of modes involving different size classes at the same time or the same classes at different times.

In rivers and channels with moderate gradients, there are two overlapping systems of classifying transport modes: (1) as *bed load* plus *suspended load* or (2) as *bed-material load* plus *wash load* (see Chapter 2). Under the first system, *suspended load* consists of the finer sediment maintained in suspension by turbulence, whereas *bed load* consists of the coarser particles transported along the bed intermittently by rolling, sliding, or saltating. Under the second system, *bed-material load* comprises all sizes normally found in the bed, whether transported as bed load or in suspension, whereas *wash load* consists of fine sizes that always travel in suspension and are not found in significant quantities in the bed.

Bed-load transport may take place similarly to a "conveyor belt" (or "moving layers") or by evolution and migration of various bed and channel forms (dunes, bars, bends, and so on). In some environments, unusual and rare forms of bed-load transport may occur, such as the development and movement of "armored mud balls" (Fig. 1-10).

Suspended load is generally transported within and at the same velocity as the water, whereas *bed-load* transport may occur only occasionally during high-flow events. The boundary between suspended sediment and bed-load transport is not precise and may vary with the flow strength. The higher the flow, the coarser the sediment that can be suspended by turbulence. Suspended load plus bed load, or wash load plus bed-material load, together compose the *total sediment load* (see Table 2-4 in Chapter 2).

Fig. 1-10. Mud ball train in ephemeral Arroyo Hondo, western San Joaquin Valley, California. These rare bed-load features, up to 1 meter in diameter, formed and were transported during an intense flood in March 1997. Flow direction is from right to left. Such ball-like sediment agglomerations are found in some ephemeral streams in California with high loads of clay, silt, and sand. *Photograph by R. Leclerc.*

Particles that can move either as suspended load or as bed load and that periodically exchange with the nonmoving bed constitute the bed-material load. At least in theory, this part of the total sediment load can be calculated from hydraulic parameters and the composition of the bed material. On the other hand, wash load consists of the finer particles (usually silt and clay) in the suspended load that are continuously maintained in suspension by the flow turbulence and that are not found in significant quantities in the bed. This part of the total load is usually related to watershed supply and cannot be determined theoretically in most cases.

Another form of transport that occurs only in limited settings and steep channels is referred to as *hyperconcentrated flow,* where water and very high concentrations of sediment move as an integrated mass having properties somewhere between those of a Newtonian and a non-Newtonian fluid. Flows of this type, which include mud flows, debris flows, lahars, and rock and boulder torrents, form a special group of sediment hazards with unique fluid properties, high energy, and very destructive capabilities. Snow avalanches and ocean density currents represent somewhat analogous phenomena in other environments. Chapter 19 addresses this class of fluids and associated sediment hazards.

1.3.3 Sediment Transport Mechanics

Sediment transport mechanics as used herein (Chapters 2 through 5) refers to theories and experiments concerning physical factors that determine sediment displacement and transport and methods of estimating quantities transported. Although the fundamentals were fairly well established before 1975, the output of publications treating the subject has continued. Significant references since 1975 include Raudkivi (1976), Garde and Ranga Raju (1977), Yalin (1977), Parker (1978), Graf (1984), Thorne et al. (1987), Chang (1988), Ikeda and Parker (1989), Parker (1990), Simons and Senturk (1992), van Rijn (1993), Yang (1996), Chien and Wan (1999), and Julien (2002).

When estimating sediment transport rates for given hydraulic conditions, the engineer may select from a wide range of transport formulas, algorithms, or procedures, many of which are offered as options in computer programs for sediment transport modeling. Most of those have a partially theoretical background but depend importantly on laboratory experimental data for their quantitative aspects. A considerable degree of experience and judgment may be required to select those most appropriate for the particular circumstances. It is usually advisable to compare results from several methods because results may vary over a wide range. Wherever practicable, some degree of calibration against field measurements is highly desirable. Comparisons of sediment transport calculation procedures were summarized by Vanoni (1975) and more recently by Chang (1988), Gomez and Church (1989), Simons and Senturk (1992), Yang (1996), Chien and Wan (1999), and Julien (2002), among others. This topic is covered further in Chapters 2 through 5.

Published procedures may deal with one or more components of total sediment transport. In general, hydraulic-based relationships cannot predict wash load, which is usually supply limited and may constitute a significant portion of the total load. The wash load portion of the total load is generally determined from field measurements. Some hydraulic relationships predict bed load only and are limited mainly to gravel and coarser sediment. Others predict total bed-material load and are more appropriate where sand is an important size class. Although theoretical relationships cannot predict wash load in quantitative terms, they can predict the competence of the flow to transport given sizes in suspension and their distribution with depth. This can greatly assist interpretation and extrapolation of suspended sediment data obtained from field measurements.

Basic issues in sediment transport mechanics are the definition of hydraulic conditions required to (1) initiate movement of a given sediment grain size on the bed of a channel and (2) lift it into suspension. These issues which are closely linked to sediment transport calculations and in the first case to the determination of stable sizes for erosion protection, have been addressed both theoretically and experimentally since the early days of hydraulic engineering and form the subject of numerous studies and publications. Chapters 2 through 5 address these topics in considerable detail.

1.3.4 Sediment Transport Measurements

Sediment measurement techniques are discussed in detail in Chapter 5 and Appendix D. Edwards and Glysson (1999) also provide a thorough summary of sediment measurement methods according to USGS-approved protocols. Field data are often needed to develop reliable sediment budgets and are essential for proper calibration and validation of numerical models used to predict sediment dynamics in rivers and reservoirs. Borgen et al. (2003) report advances in these techniques.

Suspended load concentrations are often reported routinely along with stream-flow data at certain river gauging stations. Limited data on grain size distributions in suspended loads and in the bed may also be reported. Suspended load data reports are usually based on sampling the water column down to a short distance above the bed. Measured suspended-load data include virtually all the wash load and, especially in the case of sand transport, part of the bed-material load. Where routine data are not available, special measurements may be undertaken over a limited time period.

For estimation of sedimentation in reservoirs and related problems, measured suspended-load data over a period of years are generally correlated with flow data to develop a sediment rating curve. Total sediment delivery over a period is then determined by applying the sediment rating curve to a flow-duration relationship. An allowance on the order of 10% is often added to account for bed load or other unmeasured load. However, the percentage of bed load can be substantially greater than 10% in steep rivers and streams with large supplies of gravel and coarse materials.

Sediment rating curves usually show wide scatter because the transport-flow relationship may vary widely with season, basin cover conditions, and other factors. Where the available data do not include much information on high flows, extrapolation of the curve to flood flows—which may account for a large proportion of the transport—may introduce a high degree of uncertainty. Testing and validation of extrapolated values is always recommended.

Bed load is difficult to measure and is not normally measured on a routine basis. For project purposes, special field measurements may be undertaken using techniques described in Chapter 5 and Appendix D.

1.3.5 Sediment Modeling

After the publication of Manual 54 in 1975, the use of integrated computer programs for numerical modeling of sediment erosion, transport, and deposition in time and space became increasingly common (see Chapters 14 and 15). Some are one-dimensional, typically applied for evaluation of sedimentation processes along rivers and channels. Others are two- or three-dimensional, typically applied for evaluation of sedimentation processes in broad floodplains, estuaries, coastal regions, and stratified water bodies. Numerical models are particularly valuable for examining the effects of historical or proposed changes and of alternative project proposals. Chapter 23 presents methods for modeling the effects of sediment transport associated with dam removal, while Chapter 16 discusses turbulence modeling associated with sedimentation processes.

Modeling programs generally contain default values of various parameters that are meant to be adjusted by calibration against real data, typically consisting of observed morphological changes (erosion or deposition) or observed sediment transport rates. In the absence of model calibration, results may differ widely from reality. There is also a danger of redefining the actual problem to suit the limitations of the model being used. In modeling future conditions, past data may not provide reliable guidance because of shifts in trends or changes in controlling factors. Experience and insight are often needed to select a reasonable range for key variables and hydrologic conditions. It may also be necessary to consider the potential for catastrophic events that are not represented in the historical record (see Chapter 19).

Physical modeling of sediment displacement and transport for proposed civil engineering projects or facilities can provide an alternative means for assessing project performance and testing project alternatives. This is accomplished in a hydraulic laboratory with a mobile-boundary modeling facility. The reproduction on a small scale of both bed-load and suspended-load behavior may present severe difficulties, and modeling compromises are often necessary with concentration on key aspects for the problem in hand. Where the prototype setting involves sand beds, it is usually advisable to use low-density granular material in the model in order to achieve sufficient mobility and transport. Sediment transport scaling for physical models is addressed in Appendix C.

Numerical sedimentation models are sometimes referred to as morphological models because the processes being simulated involve the interaction and feedback between the flow structure and the movable channel boundaries. Typically, sediment erosion, transport, and deposition are simulated along the long profile (i.e., down-channel) through a one-dimensional formulation. The St. Venant equations for open channel flow (or some simplification of these equations) are typically coupled to a solution of the conservation of sediment mass—often referred to as the Exner equation (USACE 1993a). The simulation progresses forward in time, with user-specified boundary conditions defining the hydrologic events of interest. Numerical model results typically consist of the time history of river stage, discharge, channel bed elevation, bed material gradation, and quantity and gradation of sediment transport, all at specified locations along the long profile axis. Additional details on the formulation, assumptions, and typical applications of one-dimensional numerical models can be found in Chapter 14.

As of 2006, application of multidimensional (two- and three-dimensional) numerical models is becoming more common, given the relative economy of powerful computers, the continued development and testing of efficient numerical approximation schemes, and the ongoing training and experience gained by practitioners as the tools become more widely available and affordable (Gessler et al. 1999). Chapter 15 provides extensive information on issues associated with the theoretical formulation and application of these computational tools. Graphical user interfaces (GUIs) are usually applied for the setup, execution, and evaluation of the extensive databases typically generated by the time-variant solution of multidimensional equations of hydrodynamics and conservation of sediment mass. On the other hand, the convenience of GUIs enables inexperienced users to unknowingly set up poorly formulated or erroneous simulations. (This dilemma is not unique to multidimensional sedimentation modeling.) It is, therefore, highly recommended that modelers seek thorough independent review of their problem formulations and results.

Additional subsets of computational numerical models presented in Chapter 8 were developed specifically to depict and quantify the response of channel cross-sectional geometry and planform to changes in water and sediment inputs. Although not as extensively applied in engineering practice as the one-dimensional and multidimensional models described in Chapters 14 and 15, these models utilize advances in understanding of complex morphological processes and provide a means of assessing erosion risk for infrastructure located in the vicinity of active fluvial systems. (Chapter 7 summarizes the extensive research and analysis on stream-bank erosion and channel width adjustment conducted since publication of Manual 54.) Recent models address the effects of human-induced influences such as flow regulation by reservoirs, land use changes and associated changes in runoff and sediment yield, and alteration of floodplain boundaries due to levee construction (Parker 1978; Paola et al. 2006). Chapter 8 discusses the physical processes and numerical modeling of river meandering and channel planform adjustment. Planform response models are based on linkages between channel curvature, velocity redistribution, and bank erodibility (Ikeda and Parker 1989). Chapter 19 addresses the computational modeling of sediment hazards such as mud and debris flows and flooding in alluvial fans.

1.4 OVERVIEW OF SEDIMENT DEPOSITION

1.4.1 General

As in the case of erosion, sediment deposition can be categorized into geological (or natural) and accelerated (or human-induced) deposition. Geologic deposition occurs because of natural processes of tectonic uplift, volcanic eruptions, earthquakes, climate warming, glacial movements, and so on. This category of processes usually occurs over long periods but may also result from severe episodic events. On the other hand, human-induced deposition resulting from various human activities usually results in relatively rapid changes in river morphology and sedimentation.

Products of erosion may be transported and deposited over a wide range of distances from their source. Where there are long distances to the ultimate sink of the oceans, only a minor fraction of the source load may arrive there. It has been estimated that in the United States, only about 10% of the material eroded from upland basins reaches the oceans, the remainder being stored in lakes, reservoirs, channels, and land surfaces (Curtis et al. 1973; Holeman 1981).

Deposited sediment may be harmful or beneficial according to circumstances and viewpoints. Although sediment may fill reservoirs and eliminate their storage capacity or aggrade riverbeds and lead to increased flooding, silt deposits on floodplains may eventually form valuable agricultural soils, and gravel deposits in rivers may provide valuable fish habitat and a source for building materials. Where deposition in downstream reaches of rivers poses problems, settlement basins are sometimes provided to store deposited sediment at upstream locations. These may offer only temporary relief unless the deposits can be removed at regular intervals. Construction of dams and other flow control structures that encourage sediment deposition can reduce sediment delivery downstream to coastal areas and may lead to long-term beach erosion and shoreline retreat.

Problems and studies involving sediment deposition have greatly expanded beyond concerns over engineering works (structures) into environmental concerns such as effects on fish habitat and benthic communities and the role of sediment in storing and releasing toxic contaminants. Chapters 21 through 23 address these topics further. Acute problems of sediment deposition may follow catastrophic events such as earthquakes, volcanic eruptions, dam failures, massive landslides, and debris flows (see MacArthur et al. 1985, 1990; Costa and Wieczorek 1987; Committee on Alluvial Fan Flooding (CAFF) 1996; Chen 1997; Wieczorek and Naeser 2000). Chapter 19 discusses these topics further.

1.4.2 Causes of Sediment Deposition

1.4.2.1 Upland River Deposits Deposits at the base of eroding slopes are discussed in Manual 54. Some other forms of near-source deposits are described briefly below.

Debris flows in steep streams produce run-out deposits containing large woody debris mixed with finer organic material and sediment of a wide range of sizes up to large boulders (Fig. 1-11). Such deposits may block roads and

Fig. 1-11. Debris flow deposit from small tributary of Tinau River in Nepal. *Photograph by V. J. Galay.*

railroads, redirect the course of streams, or destroy buildings and properties. Debris flows may have natural causes but may also be initiated or aggravated by logging and road construction on steep forest slopes.

Alluvial fans (or inland deltas) generally form where a stream emerges from a mountain zone, becomes laterally unconfined, and undergoes an abrupt reduction in gradient. Fans, which may be of any size, may contain sand, gravel, and boulders and are characterized by multiple shifting stream channels with sudden "avulsions" during floods. Fans may exist in an aggrading, degrading, or stable state. The morphology and hydraulics of fans are discussed by French (1987), Rachocki and Church (1990), and CAFF (1996).

Braided river deposits (or outwash valley trains) somewhat resemble narrow elongated fans, with multiple shifting channels (Fig. 1-12). They may be found downstream of eroding mountain ranges or glaciers. Gravel deposits are most common in braided river systems; however, braided sand or boulder rivers also occur (Ikeda and Parker 1989; Best and Bristow 1993).

1.4.2.2 Intermediate and Lowland River Deposits Channel and floodplain deposits are discussed in Manual 54. Other forms are discussed briefly below.

Deposits of riverborne sediment often cause problems in engineered conduits such as canals, tunnels, culverts, and pipelines that divert river water for irrigation, hydropower, and so on (Fig. 1-13). The sediment may deposit at shallow depths over a long length and may not be noticed until hydraulic capacities are severely reduced by loss of area, increased roughness, and weed growth.

Meandering rivers with their adjacent floodplains generally represent large volumes of stored sediment that gradually work downstream through a process of meander migration, eroding sediment from one place and depositing it farther downstream (Fig. 1-14). A section through the floodplain generally exhibits coarser riverbed sediments up to a certain level and fine overbank deposits above. Installation of dikes, levees, and bank protection may disrupt natural processes and cause unforeseen problems, such as channel aggradation or degradation or accelerated erosion of unprotected banks.

1.4.2.3 Sedimentation Due to Mining Activities Mining activities in river basins and failures of mine tailings dams can produce disastrous sedimentation and contamination of downstream rivers/water bodies (Figs. 1-15 and 1-16). The design, construction, and maintenance of such facilities have often been inadequate (see, e.g., United Nations Environment Program and International Commission on Large Dams [UNEP/ICOLD] 2001). Once constructed, mines and tailings dams often result in long-term hazards that may culminate in costly mitigation having to be performed by future generations of landowners and governments. When mines and tailing ponds are eventually abandoned, extensive engineering measures may be needed to prevent future erosion or release of contaminated sediments.

1.4.2.4 Deposits in Lakes and Reservoirs Deposits in larger lakes and reservoirs that receive riverborne sediment generally consist of coarser sediment (sand and gravel) forming a delta at the inlet end and finer sediment (silt and clay)

Fig. 1-12. Braided river system located on the Rio Maule, Chile, comprised primarily of cobble and boulder materials. *Photograph by C. R. Neill.*

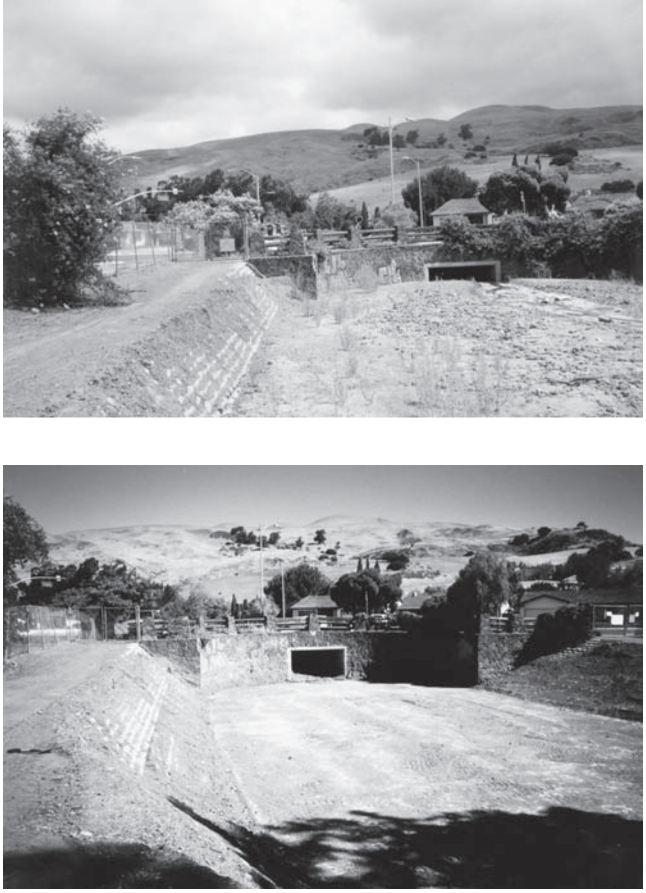

Fig. 1-13. Box culvert and sediment detention basin on urbanized reach of Upper Berryessa Creek in Milpitas, California. Basin filled with gravel is shown in top photo and after cleaning in bottom photo. View is upstream. *Photographs by R. C. MacArthur.*

Fig. 1-14. Meandering reach of Walker River, California. *Photograph by E. Wallace.*

Fig. 1-15. Copper and gold mine on Mount Fubilan in Papua New Guinea. Since the mid-1980s, the mine has discharged 70 million tons per year of contaminated rock and tailings into the Ok Tedi and Fly rivers. *Photograph by B. Hall.*

Fig. 1-16. Fly River in Papua New Guinea: an example of man-induced ecological disaster. Sediment deposition from the Ok Tedi mine continues to aggrade riverbeds and amplifies flooding and sedimentation of forest areas, killing fish, forcing animals to migrate, and destroying vegetation over vast areas. *Photograph by B. Hall.*

spread out over all or a substantial part of the bottom area (Figs. 1-17 and 1-18). In smaller water bodies, the delta may eventually extend to occupy most of the volume. Lake-bottom sediments in some regions exhibit annual layers ("varves") that reflect different conditions of deposition between seasons. These can sometimes be used to determine the variation of deposition rates over long periods of time. Deposition patterns of finer sediment may be affected by weak currents, wind, and density currents arising from the different densities of sediment-bearing inflows and clear lake water.

During the middle part of the twentieth century, when large numbers of dams and reservoirs were constructed worldwide in regions of unstable physiography for purposes such as hydropower, irrigation, and water supply, the problem of reservoir sedimentation tended to receive insufficient attention in many preproject planning studies. Sediment deposition severely affects operations and

Fig. 1-17. High sediment concentration turbidity currents from Frosst Creek, British Columbia, Canada, plunging through delta into Cultus Lake. *Photograph by V. J. Galay.*

Fig. 1-18. Lake Solano, California: example of significant reservoir siltation. *Photograph by R. C. MacArthur.*

the useful life of the facility. A related problem is how to manage reservoir sediment deposits to avoid adverse downstream consequences when a dam is removed or decommissioned because of disuse, structural deterioration, and so on. Chapter 23 discusses how numerical models can be used to assess potential changes in sediment transport associated with dam removal.

Morris and Fan (1997) provide extensive information regarding deposition in reservoirs and lakes, including dam removal, and cite numerous case studies. They provide an overview that emphasizes sustainable development and the need for long-term viewpoints in planning and design. White (2001) presents information devoted to removal of sediment from reservoirs. The morphodynamics of reservoir sedimentation is addressed in Chapter 2. Chapter 12 provides an additional overview of reservoir sedimentation issues.

1.4.3 Environmental and Habitat Effects of Sediment Deposition

Sediment deposition may have major effects on zoological habitat, particularly for salmonid and other non-warmwater fish species in streams. Problems tend to occur whenever the natural hydrologic and sediment regime is disrupted in such a way that changes occur in quantities and gradation of delivered sediment or in the physical characteristics of the riverbed. In many jurisdictions, regulations regarding both short- and long-term disturbances have become increasingly stringent.

Where sediment is trapped in new reservoirs, downstream fishery effects may be beneficial or harmful. If the stream formerly carried high suspended loads of fine sediment, trapping may be beneficial to aquatic species. On the other hand, if sand and gravel is trapped from a relatively clear stream, downstream reaches may downcut to a flatter gradient and become paved with large stones that offer poor habitat and biological environment for a variety of benthic and pelagic species. Reduction of flood peaks by reservoir regulation may adversely affect annual flushing of fine sediment from spawning areas. Chapter 3 contains material useful to addressing these topics.

Where land use changes increase inputs of fine sediment to a river, its deposition downstream may clog spawning beds (Huang and Garcia 2000). Construction operations for bridge and pipeline crossings may temporarily increase fine sediment inputs, with similar results.

Many toxic substances and contaminants in water become preferentially attached to sediment (particularly to fine sediments) and accumulate within deposition zones. Contaminated sediments may become buried if the source is discontinued but may be exposed later by erosion and channel shifting. Concentration by bioaccumulation, especially of heavy metals and pesticides, is often a major concern. Deposits behind mine tailings dams are often highly contaminated, requiring massive cleanup operations in cases of failures of such structures (UNEP/ICOLD 2001). These topics are discussed further in Chapters 21 and 22.

1.4.4 Estimation of Deposition Rates and Quantities

Estimation of past rates and quantities of deposition in static water bodies is usually based on periodic bathymetric surveys aided by core sampling and dating. Reservoirs subject to significant sediment deposition should be surveyed and sampled at regular intervals. Statistics on reservoir deposition are often available from owners, operators, and regulating agencies.

Estimation of future deposition rates for new reservoirs, flood control facilities, and sediment basins may be based empirically on data from other water bodies in similar environments with regard to dimensions and trap efficiency or semiempirically on studies of sediment yield and delivery with regard to grain size distributions and settlement rates or based on comprehensive numerical modeling that accounts for currents, wind, and turbulence. Depending on the dimensions of the water body, one- or two-dimensional modeling may be appropriate and beneficial during project evaluations.

1.5 MANAGEMENT AND TREATMENT OF SEDIMENTATION PROBLEMS

1.5.1 General

In general, management and treatment of sedimentation engineering problems can be addressed upstream at the sources of the sediment production, downstream at the site of the problem, or at intermediate locations. However, the efficacy of sediment management can be enhanced by addressing and managing sediment problems at a whole-watershed level rather through a series of disconnected locally independent projects. Obviously, the best solution is to avoid problems through good planning and design. More important, restoration of process is more likely to address the causes of river degradation, whereas restoration toward a fixed endpoint addresses only the symptoms (Wohl et al. 2005). Some problems, such as scour at bridge foundations, are clearly local and require only local treatment. Others, such as deposition in reservoirs, often derive from an extensive drainage basin and might be addressed either on a local or on a basinwide basis. In many sedimentation problems, a complete “solution” is not possible, and the best that can be achieved is a reliable system for management and monitoring. Attention should generally be given to the feasibility of nonengineering as well as engineering approaches.

Treatment of erosion at the source would often be the most satisfactory solution in the long term, but in many cases it may not be physically, economically, or socially feasible because the sources are too widely distributed and are associated with natural geological processes or human activities regarded as inviolable. The engineer must then design works and develop methods for handling sediment at or nearer to the site of interest to ensure that the performance and life of the works are not unreasonably affected. In the case of a storage reservoir liable to fill too rapidly with sediment, consideration could be given to land reclamation in the basin, to the provision of intermediate sediment detention basins upstream of the site, or to methods of bypassing sediment past the reservoir or flushing it out at intervals to minimize downstream impacts. The relative advantages of alternative approaches may depend on the planned life of the facility and on environmental concerns upstream or downstream.

Sediment control methods are treated extensively in Manual 54. As of 2005, much of the material contained therein is still valid. In the present volume, coverage and updating are limited. Chapter 9 addresses the restoration of streams adversely affected by human activities or extreme natural events, Chapter 11 addresses prevention of scour around bridge foundations, Chapter 12 addresses reservoir sedimentation, Chapter 19 discusses "sediment hazards," Chapter 23 discusses the use of modeling to determine changes in sediment transport associated with dam removal, and Appendix B addresses the design of riprap erosion protection.

1.5.2 Problem Identification and Definition

During planning and design of new projects and before attempting to devise alternative solutions to existing sedimentation engineering problems, it is important to develop a clear definition of existing and potential problems, which may be complex and may ultimately involve other interdisciplinary concerns. To do this, each important component of a problem (or potential problems) must be identified and quantified to some level of certainty. Thorough project planning and evaluation of future project performance can greatly increase project reliability while reducing maintenance and possible future sediment-related problems. Chapter 3 in the Corps of Engineer's EM 1110-2-1416, *River Hydraulics* (USACE 1993b), outlines procedures for conducting hydraulic engineering studies so as to avoid unforeseen sediment or project performance problems. Questions to consider during plan formulation and problem identification and definition phases may include the following:

- Where are the sources of erosion and sediment, and what are their relative significances?
- Is the problem ascribable mainly to fine wash-load sediment such as silt and clay; to coarser bed-material sediment such as sand, gravel, and boulders; or to both? In what modes will the material be transported under various stream-flow conditions?
- Is the problem associated mainly with river flood conditions or with a wide range of stream flows?
- Is the problem new or has it been developing for a long period of time? Is the problem periodic or chronic? What is the history of the sources of erosion?
- Is the problem localized or more regional in nature? Is its scale small or large?
- Is the problem associated with scour, deposition of materials, or both?
- What information is available on rates and quantities and grain sizes of sediment in transport?
- Have rates and quantities been increasing, and, if so, why? Have there been significant changes in land use or river works and management, or have extreme events occurred recently?
- If sediment will be stored in reservoirs or detentionbasins, how fast will this occur, and what will happen when these are filled? What are the downstream engineering and environmental implications of periodic storage and release of materials from the reservoir in the future?
- What are the degrees of uncertainty in quantitative estimates, and what are the project implications of under- or overestimating future quantities? What allowances should be made for land use change and climate change?
- What essential data are needed to better define potential problems and solutions?
- What alternative solutions are there, and how sustainable are alternative solutions in both engineering and environmental terms?

Many of these important questions are addressed in the following chapters and appendices of this manual. The key to successful problem avoidance and solution is to achieve objective, credible problem identification early in project planning. This will facilitate more effective field and office investigations and the development of feasible alternatives. Careful attention to this step can produce economies in investigations and avoid the formulation of inappropriate solutions. Chapter 20, "American Sedimentation Law and Physical Processes," discusses changes in legal requirements and liabilities associated with standards of care, responsible project planning, and design.

Since the printing of Manual 54 in 1975, the focus of sedimentation engineering has greatly expanded from the identification and solution of individual problems (however complex they may be) to much broader involvement in multidisciplinary planning, analysis, and design of multipurpose projects. This role often requires careful balancing of engineering science, environmental concerns, public interests, and affordability.

1.5.3 Engineering Treatment

Engineering (or engineered) treatment embraces the planning and design of civil engineering works and operational systems to deal with and manage sedimentation processes so as to avoid serious problems. The chapter on sediment control methods in Manual 54 is devoted mainly to this type of treatment. Engineering treatments and erosion countermeasures are usually associated with more traditional structural "hardscape" solutions (see Chapters 11 and 19 and Appendices A and B).

Examples of works and projects most amenable to engineering treatment include (1) intakes from rivers into pipelines and canals for purposes of hydropower, irrigation, or water supply, where the aim is to reduce or eliminate the inflow of specific size classes of sediment that would clog or deposit in diversion conduits and facilities; (2) bank protection and channel maintenance in large or fast-flowing rivers and streams (Fig. 1-19); (3) protection of river-crossing facilities against bank erosion and bed scour; (4) dams and reservoirs, where it is infeasible to deal with upstream basin conditions and sediment inflows must be accepted as delivered to the site; and (5) flood control facilities to provide public safety during severe flood events.

The design of intakes to reduce the entry of sediment is addressed, among others, by Bouvard (1992), Raudkivi (1993), and ASCE (1995). Riverbank protection is addressed by Appendix B and USACE (1991, 1994), CUR (1995), Thorne et al. (1995), and Escarameia (1998). Scour at bridges is addressed in Chapters 10 and 11 herein, and reservoir sedimentation is addressed in Chapter 12.

In formulating and presenting engineering solutions, it is important to identify limitations in knowledge and uncertainties as to future outcomes and to provide flexibility for future changes if quantitative estimates and performance of works prove to be less favorable than expected. The limitations and uncertainties inherent in quantitative sediment estimates and sediment modeling are not always fully understood by project planners, environmentalists, and structure designers. Legal aspects and responsibilities of sediment engineers are discussed in Chapter 20.

1.5.4 Nonengineering (Nonstructural) Treatment

In the latter part of the twentieth century, a trend developed to replace engineering treatment of sedimentation problems by nonengineering, or nonstructural, treatment with apparently greater environmental benefits; fewer hardscape-type structures; more bioengineering features; and more environmental acceptability. Project planning and design specifications began to seek opportunities and requirements for enhancing and restoring natural aspects of water resource systems and to discourage engineered "hardscaping." Examples of nonengineering treatments include the following: (1) for reservoirs, upstream improvements in soil conservation and land use, such as reforestation, reduction of grazing pressure, or restriction of urban development; (2) for shifting streams, bank stabilization and restoration using vegetation and bioengineering techniques instead of rock or concrete erosion protection (Figs. 1-20 and 1-21); and (3) for flood control projects, restoring wetlands and natural water and sediment storages instead of constructing artificial sediment detention basins or excavating larger

Fig. 1-20. Planting vegetation to reduce flow velocities, capture debris, and encourage sediment deposition to provide protection along an eroding bank of the Russian River, California. *Photograph by D. Ripple.*

Fig. 1-19. Bank protection works in urban setting consisting of riprap toe armor and bank revetment materials with horizontal rows of willow pole plantings, as installed on Soquel Creek, California. *Photograph by S. Seville.*

Fig. 1-21. Bioengineered logjams being installed to protect eroding river banks, to increase habitat complexity, and to provide deep pools for fish on the Mahatta River, British Columbia, Canada. *Photograph by B. Walsh.*

flood conveyance channels. Chapter 9 presents detailed discussions of the benefits and methods for restoring river systems using a variety of bioengineering techniques.

Some publications and guidelines prepared by nonengineers have tended to recommend the application of nonengineering and bioengineering measures in circumstances where they are unlikely to be successful—for example, vegetation plantings for bank protection in steep streams with high velocities and turbulence. It is therefore an unfortunate misrepresentation associated with recent movement toward nonengineered or bioengineered methods to imply that less engineering analyses and judgment is required in order to achieve better results. To the contrary, significant hydraulic, river, and sedimentation engineering experience and analyses are required with input from other biological and ecological disciplines to ensure successful project planning and design. Also of importance is the movement toward "restoration of function" as opposed to piecemeal treatment of site-specific problems. In general, a holistic view should be taken of sedimentation management to utilize both engineering and nonengineering measures where appropriate and feasible (Petts and Calow 1996; Federal Interagency Stream Restoration Working Group 1998; Copeland et al. 2001). In locations that have been severely damaged by poor land use practices and neglect, the benefits of such an approach may extend far beyond the project under consideration (see Natural Resource Conservation Service 1992, 1996; Gray and Sotir 1996).

1.5.5 Fish Habitat and Environmental Issues

Since publication of Manual 54 in 1975, many jurisdictions in technically advanced countries have enacted strict requirements for the design and construction of works in water bodies to avoid or mitigate erosion and sedimentation effects on fish habitat and aquatic resources. Engineers and planners have sometimes considered certain regulatory controls to be excessive—for example, when placement of small areas of rock riprap around river bridge piers is prohibited or made conditional on the provision of artificially constructed "habitat" elsewhere. In general, however, recognition by engineers of the necessity for tough legal requirements for environmental protection (see Chapter 20) has improved significantly since the mid-1980s (Bass and Herson 1993a, 1993b).

Stream restoration projects are often designed to improve or restore fish habitat (Fig. 1-21) or improve fish passage (Fig. 1-22) (Clay 1995) and to support ecosystems in streams that have been adversely affected by logging or other human activities (Committee on Restoration of Aquatic Ecosystems 1992; Cooke et al. 1993; Wohl et al. 2005). As of 2006, the success of such projects in terms of biological productivity was not universally accepted. Kellerhals and Miles (1996) stated that the scientific basis linking morphological change, habitat, and fish productivity was weak in terms of prediction and that some stream restoration projects had been undertaken without a proper understanding of biological limiting factors or a sound basis for predicting the results of habitat manipulations. In some cases, long periods of many years may be needed to re-establish a viable habitat, and the effort may be largely nullified by overexploitation of the fish resource. This complex topic is discussed further in Chapter 9.

Fig. 1-22. Photos show barrier to fish passage through bridge culvert before (top) and after (bottom) construction of log step weirs and gravel-bottom pool and step approach aprons on Little Salmon Creek, Toledo, Washington. View is upstream. *Photographs by J. Johnson.*

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