U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

A Field Guide for the Assessment of Erosion, Sediment Transport, and Deposition in Incised Channels of the Southwestern United States

Water-Resources
Investigations Report 99—4227

Prepared in cooperation with the BUREAU OF INDIAN AFFAIRS

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By John T.C. Parker

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Tucson, Arizona
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Multiply	By	To obtain
inch (in.)	2.54	centimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer

DEFINITION OF TERMS

Alluvial fan—A fan-shaped deposit of sediment formed where a stream substantially decreases velocity such as in the transition from a steep, narrow mountain valley to a broad, flat plain. Most common in semiarid areas.

Alluvium—Sediment that has been transported and deposited by water.

Angle of repose—The angle at which loose, unconsolidated material, such as sand, will fall to rest on a pile of the same material.

Arroyo—An entrenched channel system. A stream channel has downcut into valley alluvium so deeply that floodwaters no longer inundate the former flood plain. The terms 'channel' and 'arroyo' are equivalent only when the channel occupies the entire arroyo bottom and the arroyo walls also are the channel banks. More often, the channel occupies only a portion of the arroyo bottom and the channel banks are inset into the arroyo. See **incised channel**.

Channel—That part of a stream or river that contains the streamflow. A stream may have more than one channel. The stream may have a low-flow channel that carries most of the flows and a high-flow channel that contains most higher flows.

Channel reach—An arbitrary length of stream used for management or study purposes. A channel reach may be tens of feet long for engineering studies or miles long for a regional study.

Channel slope—The amount of elevation loss of channel bottom over a given amount of distance.

Colluvial—Referring to erosional and depositional processes that are initiated primarily by gravity, usually in combination with weathering. Includes all processes, which are not caused by flowing water, that cause movement of sediment down hillslopes.

Colluvium—Sediment that has been transported and deposited by colluvial or gravitational processes.

Conveyance—The capacity of a channel section to conduct streamflow.

Debris aprons—Cones or blankets of colluvium at the base of arroyo walls and stream banks.

Entrainment—The movement and suspension of sediment particles by a transporting force such as wind or running water.

Ephemeral stream—A stream that generally is dry and has flow only in direct response to precipitation.

Fluted—Referring to arroyo walls or stream banks that have deep grooves eroded into their faces to form a row of alternating columns of sediment and grooves called flutes. Flutes, or fluted walls, are caused by erosion from lateral runoff.

Fluvial—Referring to erosional and depositional processes initiated by running water. Refers to the entire system of drainage basins, channels, flood plains, and associated deposits that are formed by streams or rivers.

Headcut—The upstream end of an incised channel. A headcut often forms an abrupt scarp extending from the surface of the valley floor to the bottom of the channel or arroyo.

Incised channel—A channel that has cut into the valley floor. A more general term than arroyo, which usually refers to a channel, especially in western North America, that has incised into its historic flood plain. See **arroyo**.

Lateral runoff—Runoff that enters a stream channel as unchannelized flow over the banks or by means of minor channels that branch off the main channel as opposed to streamflow that enters a reach from the channel upstream from it.

Meander—A curve or bend in the course of a stream channel, often occurring as a series of alternating loops as a result of a river's movement from one side of a valley floor to the other.

Piedmont—A plain at the base of a mountain range.

Pipes—A tunnel caused by underground erosion, often running from the surface of the valley floor to the side of an arroyo wall or streambank.

Point bar—A deposit of sediment on the inside of a curve or meander of a stream channel.

Roughness—In stream channels, the term refers to the unevenness of the channel bed and banks resulting from vegetation, bed material, bedforms, and any other obstruction to flow. Increasing roughness causes a decrease in flow velocity.

Runoff—All water from precipitation that enters streams, including that which flows overland and that which flows underground to stream channels.

Sediment—Particles of rock yielded by the weathering of larger bodies of rock that are then available for transport by wind, water, ice, or gravity.

Sinuosity—A measurement of the circuity of a stream or river as it twists and turns along its course. Sinuosity is stated as the ratio of the distance between two points along the middle of a channel to the distance of a straight line between the same two points.

Soil—The layer of material, including sediment particles and organic matter, at the surface of the Earth in which biological activity, especially plant growth, takes place.

Soil creep—The slow movement of soil or unconsolidated sediment downslope under the force of gravity. Soil creep typically occurs at rates of several inches or less per year.

Stream piracy—The capture of the drainage area of one stream by the headward migration of another stream that then intercepts the flow that formerly went into the first stream's channel.

Stream power—The amount of power available for transporting sediment in a stream, which is calculated as the discharge of the flow times the slope of the channel.

Surface erosion—Erosion of sediment on ground surfaces caused by water, wind, or ice that is not channelized as opposed, for example, to bank erosion or channel degradation by streamflow. Rill and gully erosion generally are considered surface erosion even though the flows that cause them are channelized because the channels are transient and not considered part of the stream network.

Terrace—A land surface, such as a flood plain or channel bottom, formed by streamflow that is no longer subject to inundation by the river that formed it because it has been isolated by downcutting or migration of the channel.

Valley fill—The sediment that fills a valley as it is shed from the erosion of adjacent highlands or deposited on the flood plain of the river or stream that flows through the valley.

Weathering—The physical breakdown of rock into smaller particles by ice, plant roots, abrasion, and formation of cracks and joints, and the chemical alteration of minerals in the rocks by reactions with chemicals in rain, soil, and the atmosphere.

A Field Guide for the Assessment of Erosion, Sediment Transport, and Deposition in Incised Channels of the Southwestern United States

By John T.C. Parker

Abstract

Deeply incised channels, commonly called arroyos, are a typical feature of the dry alluvium-filled valleys of the southwestern United States. Unlike many geological processes that operate over millions of years, the formation of many miles of arroyos is one that took place in a little more than a century. Most arroyos in the region began to form in the late 19th century. Because dry landscapes change so quickly, they present society with special problems. Rapid expansion of channels by headcut migration, deepening, and widening causes loss of productive agricultural and commercial lands and threatens infrastructure such as roads, bridges, and buildings. High rates of sedimentation shorten the life of reservoirs, clog culverts, and fill stream channels to the extent that they can no longer contain streamflow within their banks.

This report presents an explanation of erosional and depositional processes in desert landscapes, especially those characterized by incised channels, for the use of those who use, manage, and live on such lands. The basic principles of erosion, sediment transport, and deposition are presented including the formation of sediment, the forces that erode and transport it, the forces that resist its erosion and transport, and the conditions that cause it to be deposited. The peculiarities of sedimentation processes in the Southwest include the infrequent and variable precipitation, the geological setting, and the sparseness of vegetation.

A classification system for incised channels that is intended for users who do not necessarily have a background in fluvial hydrology has been developed and is presented in this report. The classification system is intended to enable a user to classify a reach of channel quickly on the basis of field observations. The system is based on the shape and condition of channels and on the sedimentation processes that are predominantly responsible for those conditions. Because those processes are controlled by environmental factors operating on the entire drainage basin, classification of channels can provide land managers and users with an understanding of what areas are likely to be most susceptible to erosion or the effects of high sedimentation rates and under what conditions they are most likely to occur.

INTRODUCTION

Throughout the semiarid southwestern United States and, in fact, over much of the world's dry regions, the land is gouged and scarred by erosion. Hillslopes and plains are etched with networks of rills—tiny **channels** no more than a few inches wide and deep. Some of these channels enlarge to waist-deep gullies narrow enough to jump over. And with time and enough streamflow, these gullies can become gorges—called **arroyos** in the southwestern United States—cut more than 50 ft into crumbly layers of fine sand and silt called **alluvium**. And finally, such arroyos can widen to form canyons and valleys thousands of feet wide between vertical cliffs of **sediments** so weakly cemented that they can be excavated with a spoon. Ordinarily, we think of the formation of geological features, such as landscapes, to be the result of processes, such as the erosion of hills and the formation of river valleys, that take place over vast expanses of time—hundreds of thousands to millions of years. Yet most of the arroyos that we see today in the Southwest have formed in little more than 100 years. Indeed, landscapes in dry regions are extremely susceptible to change and may undergo substantial geologic change within the course of a human lifetime and sometimes within the course of a single flood.

Because dry landscapes can change so much and so quickly, they create special problems for society. The rapid expansion of channels by **headcut** migration, deepening, and widening causes loss of productive agricultural and commercial lands and threatens infrastructure such as roads, bridges, and buildings. The large volumes of sediment that are transported in the course of such erosion present additional problems when sediment is deposited into reservoirs, clogs culverts, and fills stream channels to the extent that they can no longer contain streamflow within their banks. People who use, manage, and live on such lands must understand the nature of erosional and depositional processes in the often fragile landscapes. In particular, they need to know what areas have potential for high sediment yields, what areas are susceptible to erosion, what the nature of such erosion is likely to be, and at what speed the erosion is likely to occur. This information is necessary to minimize those activities that could initiate or accelerate processes that reduce the productivity of such lands and to minimize the effects of those processes on human facilities and activities by the proper location of infrastructure.

The purpose of this report is to explain in nontechnical language how field observations can be used to recognize the potential for change by erosion, sediment transport, and deposition in dry regions and particularly those regions characterized by incision of channels into the landscape. Because technical terms cannot be eliminated altogether, definitions of selected terms are provided at the beginning of this publication. Words that are included in the list of definitions are printed in bold face the first time they are used in the text. This guide is based on work done in the East Dinnebito Wash drainage basin on Black Mesa in the Navajo Partitioned Lands (NPL) in northeastern Arizona and earlier studies done in central and southeastern Arizona. The general principles that are used to assess the potential geomorphic instability of landscapes, however, can be applied throughout most of the dry temperate regions of western North America.

PRINCIPLES OF EROSION, SEDIMENT TRANSPORT, AND DEPOSITION

What causes erosion? Why are so many of the world's dry regions so susceptible to erosion? What can be done about it? Why do streams in some areas run as clear as glass but in other areas flow is so laden with sediment that boulders can float on the surface? Where does the sediment go?

Weathering and Decomposition of Bedrock

Sediment is composed of the **weathering** products of rocks (fig. 1). Sediment particles are detached from larger bodies of rock by physical and chemical weathering. Physical weathering is the disintegration of rock into smaller pieces by mechanical stresses such as expansion of freezing water in rock joints and pores. Chemical weathering is the decomposition of rock from chemical reactions between rock minerals and chemicals in the atmosphere and soil. The rate of rock weathering and sediment production depends on climatic factors, such as amount of rainfall and average humidity, and the type of rock. As the physical and chemical breakdown of rocks proceeds, a mantle of debris accumulates on the land surface and becomes the source of a drainage basin's solid sediment load.

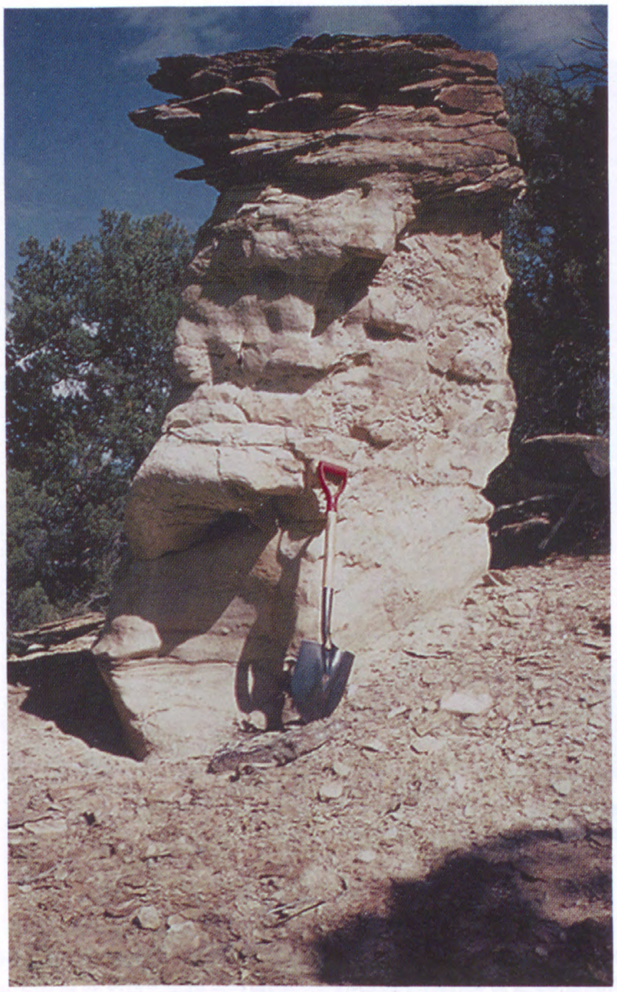


Figure 1. Weathering of a sandstone pillar. A pillar of sandstone crumbles, dissolves into gravel, and then into smaller particles as a result of effects of sun, rain, ice, and the atmosphere.

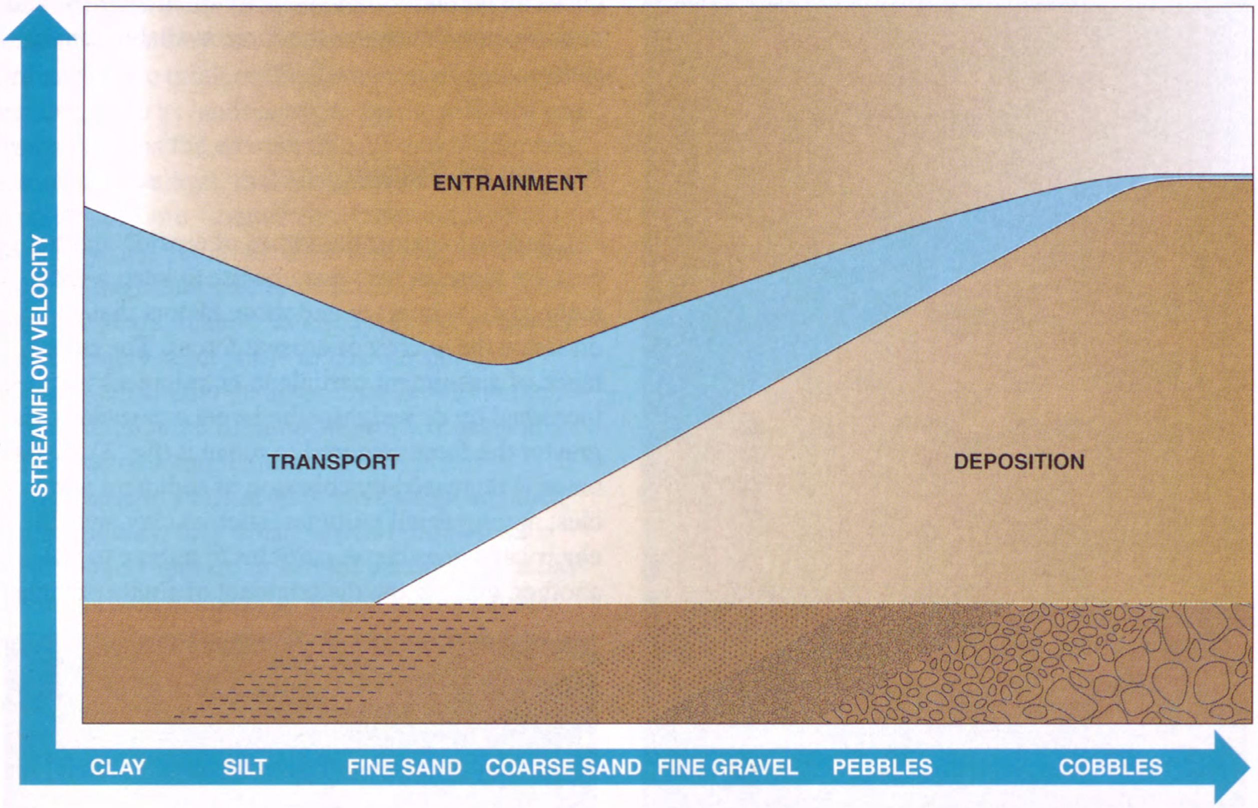
Forces of Erosion

Entrainment of sediment—the initiation of erosion—occurs when sufficient force is applied to a particle to overcome all the forces that keep the particle lodged in place. The forces that initiate sediment transport include the impact of falling raindrops, the flow of water or wind, the thrusting of ice crystals, the burrowing of a badger, or the pull of gravity. Anything that works to intensify these forces increases the likelihood of erosion and increases the rate and amount of erosion (fig. 2). For example, a change in climate that causes an increase in the intensity of storms can produce an increase in the force with which raindrops strike and dislodge sediment particles. An increase in the frequency and duration of storms can increase the amount of **runoff** available to erode and transport sediment. An increase in stream **channel slope** produces an increase in the velocity of streamflow and consequently increases the force available for erosion.

Forces of Stability

Arrayed against the forces of erosion and transport are those factors that operate to keep a sediment particle in place and those factors that dissipate the energy of erosive forces. The resistance of a sediment particle to entrainment is increased by its weight—the larger a particle is, the greater the force required to move it (fig. 3). Resistance is increased by cohesion of sediment particles; among small particles, such as clay and silt, electrical forces cause particles to adhere to one another, making the dislodgment of single particles

Figure 2. A pillar of soil remains standing after erosion has removed the surrounding soil during an intense rainstorm.



Modified from Hjulstrom Curve in Knighton (1984), p. 59

Figure 3. The relations among sediment-particle size and thresholds of entrainment, transport, and deposition show that the smallest particles are nearly as hard to move as the largest ones. Coarse silt and sand are the most mobile particles.

more difficult. Chemical cohesion cements particles together with minerals, such as calcite, that come out of solution when interpore waters evaporate. Resistance also is caused by the interlocking of sediment particles with one another. The largest particles, such as cobbles, can be removed only by the most powerful streamflow.

Factors that dissipate the energy of erosive forces include anything that slows the velocity of runoff or other transport mechanism. Vegetation accomplishes this in a number of ways (fig. 4). The energy of falling raindrops is dissipated before striking the ground when rain is intercepted by tree canopies, shrubs, and ground cover such as grass. Vegetation also increases the permeability of **soils**, which enables stormwater to infiltrate and become slow-moving, low-energy subsurface flow rather than faster moving, more erosive surface flow.

Vegetation in channels increases the hydraulic **roughness** of stream channels—as does the accumulation of debris or sediment deposits, which slows stream velocities and reduces erosive power. Channel widening also increases roughness and dissipates **stream power**.

Sediment Transport and Deposition

Once sediment is dislodged and is in transport, it will remain in transport until the energy of the transport mechanism, such as streamflow, declines below some level and deposition starts to occur (fig. 5). Many of the same factors that provide resistance to erosion also contribute to sediment deposition. Large particles fall out of suspension faster than small particles and therefore are deposited at higher streamflow than are small particles.

Figure 4. Vegetation provides significant resistance to erosion of the channel banks and scour of the flood-plain surface in an arroyo that is tributary to Oraibi Wash, northeastern Arizona.

Deposition can be expected to occur where steep slopes—on hillslopes or stream channels—give way to gentle slopes; where narrow channels give way to wide channels; where flow paths are blocked by obstructions such as logs or dams.

SEDIMENTATION PROCESSES IN THE SOUTHWESTERN UNITED STATES

For decades, scientists have debated the causes of the abrupt change in the streams of the southwestern United States from shallow channels that meandered over a broad flood plain to the deep trenches that have cut into the valleys of so many drainage basins of the region. Overgrazing, adjustments of channel slope, drought and floods have all been blamed. Most scientists now think that a combination of factors were involved. At any rate, the presence of arroyos is one of the major flood-plain management issues in the Southwest. The ability to interpret the conditions of **incised channels** permits flood-plain and resource managers and land users to assess the recent history of channels that have little or no streamflow record and to estimate the probable response of channels to future events.

Most streams in the region are dry or nearly so most of the time (fig. 6). In such streams, flow occurs only in direct response to precipitation or, at higher elevations, to snowmelt. Prolonged winter storms may produce high flows on the larger alluvial channels of the lowlands (fig. 7). Most often, however, precipitation is delivered to the drainage basins of the Southwest by scattered summer thunderstorms that strike with sudden violence and are gone just as quickly; therefore, flood conditions typically last only for hours rather than days.

The infrequency and briefness of storms in dry regions limit opportunities for directly observing the processes of erosion, sediment transport, and deposition especially in remote areas such as Black Mesa. Careful observation of the landscape, of changes in channel shape, of fresh scars upon the hillslopes and valleys, of movements of sand, and patterns of vegetation growth, however, can tell much about how those processes have been working at a particular location. A field guide at the end of this report will enable observation of the landscape in terms of recognizing the potential of a site for erosion or deposition, for reading its history, and for relating those observations to their environmental significance. The guide is presented from the top of the drainage basin to the bottom, from the ridge tops to the valley mouth. Most of the examples are from Black Mesa in northeastern Arizona and from the Santa Cruz River Basin in southeastern Arizona. With attention to the general principles involved and local variation in lithology and climate, the guide should be useful for those readers working in other similar environments.

Sources of Sediment

Almost all of the sediment that is available for transport through a drainage basin is initially supplied by the decomposition of exposed bedrock

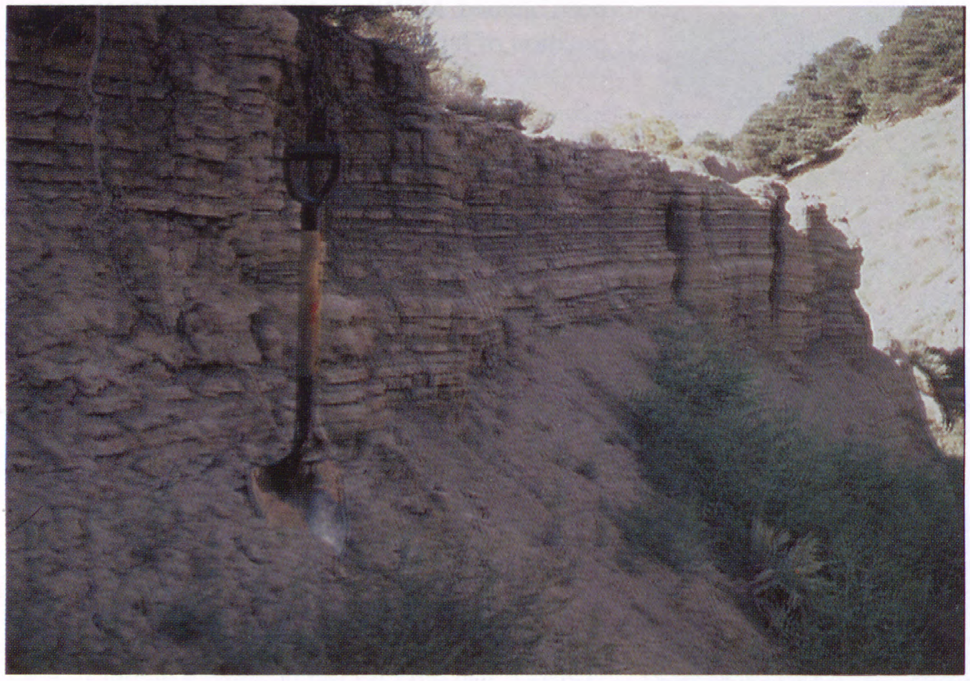


Figure 5. Layered sediments, exposed in the walls of an arroyo on East Dinnebito Wash, northeastern Arizona, record the history of deposition into the quiet waters of a reservoir.

Figure 6. Water in the arroyo of Oraibi Wash on Black Mesa, northeastern Arizona.

within that basin. Depending on the rock type, topography, and climate, fresh sediment may travel rapidly and directly into the channel system, or it may be stored as **colluvium** on hillslopes or in **valley fill,** including **alluvial fans** or **piedmonts,** for periods of time ranging from decades to hundreds of thousands of years and even millions of years.

In areas of poorly consolidated bedrock, such as much of Black Mesa (fig. 8), the weathering of exposed rock produces a large supply of sediment particles for transport and deposition. Because of the weakness of the underlying sedimentary rock, exposed bedrock disintegrates rapidly. Bedrock outcrops are sparse because of the rapid weathering and soils generally are deep on the crests of ridges and on shallow slopes and hollows (fig. 9). Many of the rocks in Black Mesa weather almost entirely to silt and very fine sand, which are the most easily transported particle sizes. Because the fine-grained sediment is so mobile, it is moved readily downslope by rainfall and runoff or by gravity when the soil layer on slopes becomes overly deep. Sediment-storage times on the ridges are short because of the mobility of the sediment. Sediment that moves off the ridges may be transported immediately into the channel system but more likely will be stored on the valley floor for some period of time. Most fill in the valleys of Black Mesa has been in storage for less than 5,000 years.

Where upland areas are composed of hard, resistant bedrock, such as the mountains flanking the valley of the Santa Cruz River, the breakdown of rock into sediment particles for transport takes place more slowly than on the ridges of Black Mesa and produces much less sediment per unit of area (fig. 10). Valley fill, which was deposited in such alluvial fans and stored for hundreds of thousands to millions of years, supplies most of the sediment now delivered

Figure 7. Floodwaters nearly reach the top of the arroyo of the Santa Cruz River south of Tucson during the winter of 1993.

Figure 8. Gently sloping ridges barely rise above the surrounding valleys of this drainage basin on Black Mesa, northeastern Arizona. The easily weathered and highly erodible bedrock of sandstone, siltstone, and mudstone, creates a subdued landscape of low ridges and sediment-filled valleys

into the channel of the Santa Cruz River.

Sedimentation Processes

Recognition of the mechanisms of sedimentation is important because the rates and magnitudes of erosion, transport, and deposition that are possible vary for different mechanisms. The mechanisms described here are associated with entrenched channel systems. The main sedimentation mechanisms are either **fluvial**, those caused by flowing water, or **colluvial**, those caused by the effects of weathering and gravity.

Headcut Migration

Once channel entrenchment begins, the incision of valley fill generally migrates upstream by the retreat of headcuts (fig. 11). A headcut is the upstream end of an entrenched channel and forms a steep scarp, which is sometimes tens of feet high, in the alluvium into which the channel is

Figure 9. A thick soil mantle on the slope of a ridge on Black Mesa, northeastern Arizona, is composed of highly mobile particles of silt and find sand. The soil is readily eroded, which results in rapid transport of sediment to the channel system or the valley floor.

Figure 10. Santa Rita Mountains rise above the Santa Cruz River Valley, southeastern Arizona, and provide little sediment directly to the modern channel system. The piedmont slopes gently away from the base of the mountains and is the remnant of an alluvial fan formed more than 1 million years ago as sediment was eroded off the mountains and stored as valley fill. The piedmont is the landform between the mountains and the flood plain that has roads (from an aborted subdivision) along the ridge crests toward the base of the mountains.

Figure 11. A headcut incises the valley fill in a drainage basin on Black Mesa, northeastern Arizona.

entrenched. Because of the steep slope, water pouring over the edge of the headcut into the channel has a high degree of stream power and may readily erode the alluvium causing the headcut to move further upstream. During the initial periods of valley entrenchment, headcuts can migrate quickly upstream. As entrenchment of valleys approaches its maximum possible extent, migration slows. Headcut migration continues in many areas of the Southwest; however, the rate and frequency of such migration generally is much lower than it was from the late 19th to middle 20th century.

Even minor amounts of headcut migration can be a major problem for land managers and users because of the threats migration poses for roads and other infrastructure (fig. 12). Headcuts leading from the sides of entrenched channels are common in some areas. In most cases, headcuts seem to result from runoff that has become channelized and directed toward the edge of the entrenched channel. Several factors seem capable of causing such channelization of runoff to occur including poor road construction, occurrence of cattle trails or footpaths, ruts from off-road vehicle traffic, and random distribution of vegetation.

Rill Erosion

When water gathers on land surfaces during rain or snowmelt and begins to flow downhill, it forms small rivulets of water, called rills, that can erode tiny channels into unprotected soil surfaces (fig. 13). On surfaces such as **debris aprons** or arroyo walls, where the runoff is generated from a small area, the rills may remain small and heal over during dry periods. On larger surfaces, however, such as the valley floor or a bare hillslope, rills can enlarge into gullies and even turn eventually into stream channels if sufficient runoff is available.

Erosion in Arroyos

Arroyo walls are susceptible to erosion from **lateral runoff** flowing from the valley floor over the top edge of the arroyo as well as to streamflow within the arroyo channel. Grooves formed by lateral runoff usually cut back only a few feet into the alluvium to form a fluted wall of alternating columns and grooves (fig. 14). Some, however, become spur gullies—short branches off the main arroyo channel that migrate back into the valley fill by headcut migration (fig. 15). Spur gullies may be several tens of feet to several hundreds of feet in length. Their ultimate size probably is determined by the area above the spur gully from which runoff is generated to erode the headcut.

Sediment is almost continually sliding down the face of arroyo walls (fig. 16). In areas where snowpack occurs, such as Black Mesa, meltwater in the spring infiltrates the pore spaces of sediments during the day and then freezes during the night. The formation of ice crystals in the sediment breaks down the cohesion of the sediment particles, so that they are mobile and will move down steep slopes by gravitational forces alone. Where freeze-thaw processes are not important, considerable colluvium can still be produced by

Figure 12. A headcut threatens a road in a valley bottom on Black Mesa, northeastern Arizona.

desiccation of sediments during dry periods. Desiccation weakens the cohesion of sediment particles, and individual particles are detached from arroyo walls and accumulate in debris aprons at the edge of the channel. Many large debris aprons in a channel indicate that streamflow processes have been weak in recent months or years.

Continued erosion of arroyo walls by lateral runoff enlarges the flutes and causes formation of isolated columns of sediment that eventually erode away from **surface erosion** or simply collapse into the channel bottom (fig. 17). **Pipes** are tunnels caused by erosion from subsurface flows (fig. 18). Pipes that open on arroyo walls may cause weakening and collapse of the walls as they enlarge.

Lateral runoff erodes arroyo walls from the top down. Streamflow erodes sediment storage areas within the arroyo bottom and attacks arroyo walls from the base. Streamflow undercuts precarious, oversteepened arroyo walls and can cause large blocks of material to slide into the channel at one time (fig. 19).

In large, well-developed arroyos, streamflow is the dominant agent of erosion (fig. 20). Most of the time, erosion on the outside of the meander bend occurs at a moderate rate although tens of feet of erosion have occurred in some places from only moderate streamflow. **Point bars** are deposited on the inside of the meanders. During extremely large floods, some arroyos have undergone hundreds of feet of erosion on the outside of meander bends and point bars, and other channel deposits have been extensively eroded. Arroyo walls that have been recently eroded by streamflow tend to be smooth and lacking in flutes or other signs of erosion caused by lateral runoff or colluvial processes.

Sediment Storage

Once sediment is released from the weathering of bedrock, it goes into storage. The sediment particles may travel only a few feet from the parent rock and form a soil mantle at the site of formation or they may be transported thousands of feet to the next site of deposition to remain for days or centuries (fig. 21). Although sediment may be stored anywhere in a drainage basin from the crest of the ridges to the mouth of the channel, the valleys are the main sediment-storage unit. In the dry Southwest, where rainfall is sporadic and sparse, sediment lurches from one storage site to another, sometimes residing in short-term sites for a few months or years, sometimes residing in long-term sites for thousands of years. In general, the longer sediment is in storage, the more resistant it is to erosion and transport, but there are many exceptions.

Most arroyos that formed in the late 19th and early 20th centuries in western North America cut down into sediments that had been in storage for several centuries to 6,000 years. Geological evidence shows that such episodes of channel downcutting occurred at many locations several times

Figure 13. Rill erosion in poorly cemented sediment on an arroyo wall.

before the present episode. Nonetheless, the rapid evacuation of large volumes of sediment that have been stored several hundred to several thousand years generally is an uncommon event in the history of these valleys. In a well-developed entrenched channel system, valley fill is still being evacuated; however, the rate of removal from long-term storage is slower than during periods of initial entrenchment and headcut migration. Significant volumes of valley fill may enter arroyo channels where the channels impinge directly on arroyo walls, generally at the outside edge of channel meanders, and erode away large sections of the walls. Where the arroyo walls are protected from erosion by streamflow, they are subject to the slower processes of degradation by weathering and lateral runoff.

Once a particle of sediment enters the arroyo, it may be entrained and deposited several times before it is finally removed from a drainage basin. The particle may fall onto a debris apron at the base of the arroyo wall. If the debris apron forms at the edge of the main channel, the particle may only be in storage until the next streamflow. If the debris apron forms along the inside edge of a point bar,

Figure 14. Runoff has formed grooves several feet deep from the top to the bottom of the arroyo walls on East Dinnebito Wash, northeastern Arizona.

Figure 15. Spur gullies cut back from the main arroyo channel into adjacent valley fill on this tributary of the Little Colorado River in northeastern Arizona.

Figure 16. Colluvium collects in debris aprons at the base of arroyo walls from degradation of arroyo walls.

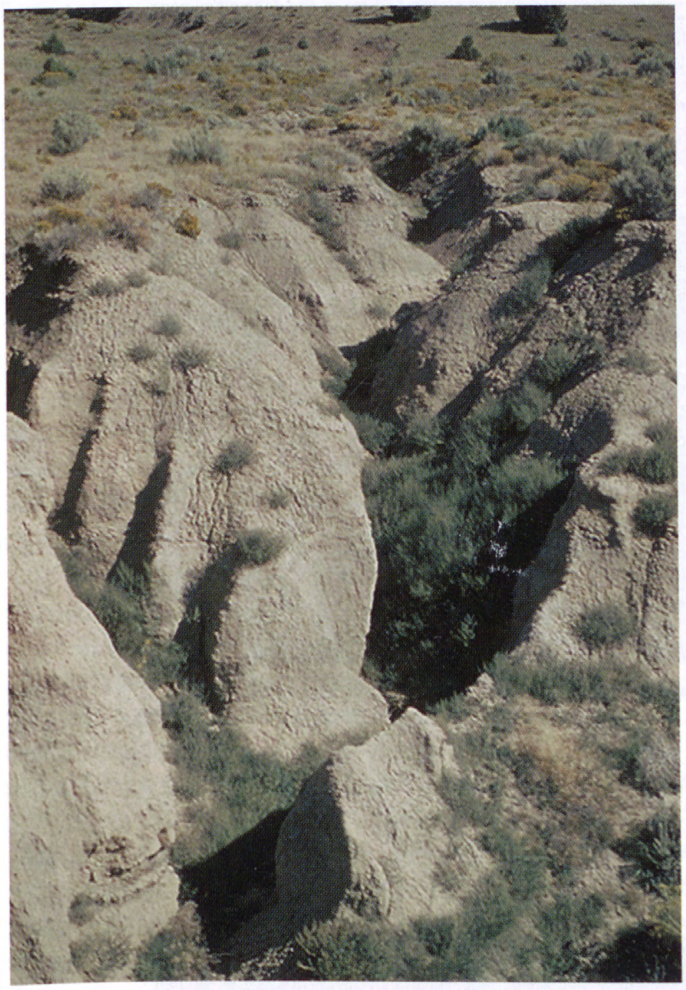


Figure 17. Advanced decay of these arroyo walls from lateral runoff and degradation by colluvial processes, East Dinnebito Wash, northeastern Arizona.

sediment may be stored there for decades. The next time a sediment particle is picked up by streamflow, it might be transported for many miles or the particle might travel only several hundred feet before being deposited on a point bar or along the channel margins or even in the middle of the channel. Again, the particle might sit in storage for as little as a few days if the storage site is within the path of sufficiently strong streamflow. If the storage site remains undisturbed, however, because it sits too high above most streamflow or because the channel has shifted away from the site or because streamflow has been diminished by drought, the particle may remain in storage for decades and even centuries. If a site remains undisturbed long enough, vegetation growth and cementation of sediment particles can make future erosion and removal of sediment more difficult than when the storage site was younger.

Figure 18. Piping erosion has contributed to the decay of these arroyo walls along Greenes Canal in south-central Arizona.

Figure 19. A massive failure of arroyo-wall material blocks the channel, East Dinnebito Wash northeastern Arizona.

Figure 20. A meandering channel erodes the arroyo wall on the outside of a meander bend and deposits a point bar on the inside.

A CLASSIFICATION SYSTEM FOR ENTRENCHED CHANNELS

Much of the activity of streams, especially **ephemeral streams** in rural or wilderness areas, goes unobserved and unrecorded. To know what has happened at a particular site—whether streamflow has been frequent or seldom or recent or long ago, whether floods or drought have dominated a landscape, whether a channel is filling with sediment or being scoured of it—and to estimate what could happen in the future, it is necessary to make observations indirectly. Stream channels are the most dynamic element of semiarid landscapes. More than hillslopes or valley floors, their condition reflects the environmental conditions that have most recently dominated a landscape.

The purpose of this section is to present a classification system for incised stream channels in semiarid lands that can be used by those who work, manage, and live on such lands. The classification system is based on process and morphology. Process is everything that occurs—rainfall, runoff, streamflow, **soil creep**, animal burrowing, plant growth—to cause the channel to have the characteristics it does at the time of observation. An understanding of process leads to an understanding of channel behavior. Morphology is the shape and appearance of the channel. Understanding morphology enables identification and classification of a channel and provides evidence of the processes that shaped the channel. The system presented here is designed to be used in the field to classify a **channel reach** at a glance. All classification systems of natural phenomena, however, come up against the fact that natural variability is almost always continuous, which complicates attempts to put nature into neatly labeled categories. The user will find channel reaches that are transitional between categories, reaches that may appear to fit one category on one side of the channel and another category on the other side, and reaches that just do not quite match up with any category. Although increasing the number of categories and increasing the number of criteria that define a category might reduce the number of ambiguous observations, it also would increase the complexity of the classification system and lessen its value as a means of rapidly describing incised channels for management purposes. The approach here represents a compromise between providing so much detail that the user becomes bogged down in it or so little detail that the categories do not provide enough information about the processes that are affecting a reach of channel.

The value of a classification system based on process is that it provides information about the history and future of a channel system. When a channel reach is put into one category or another, it means that the channel has been subject to erosion or deposition or it has been stable, and that there is at least some general idea of channel behavior. Because channels can change, the category of a reach may change over time. By remapping and reclassifying channel reaches, the classification system then can be a tool for observing trends within a drainage basin.

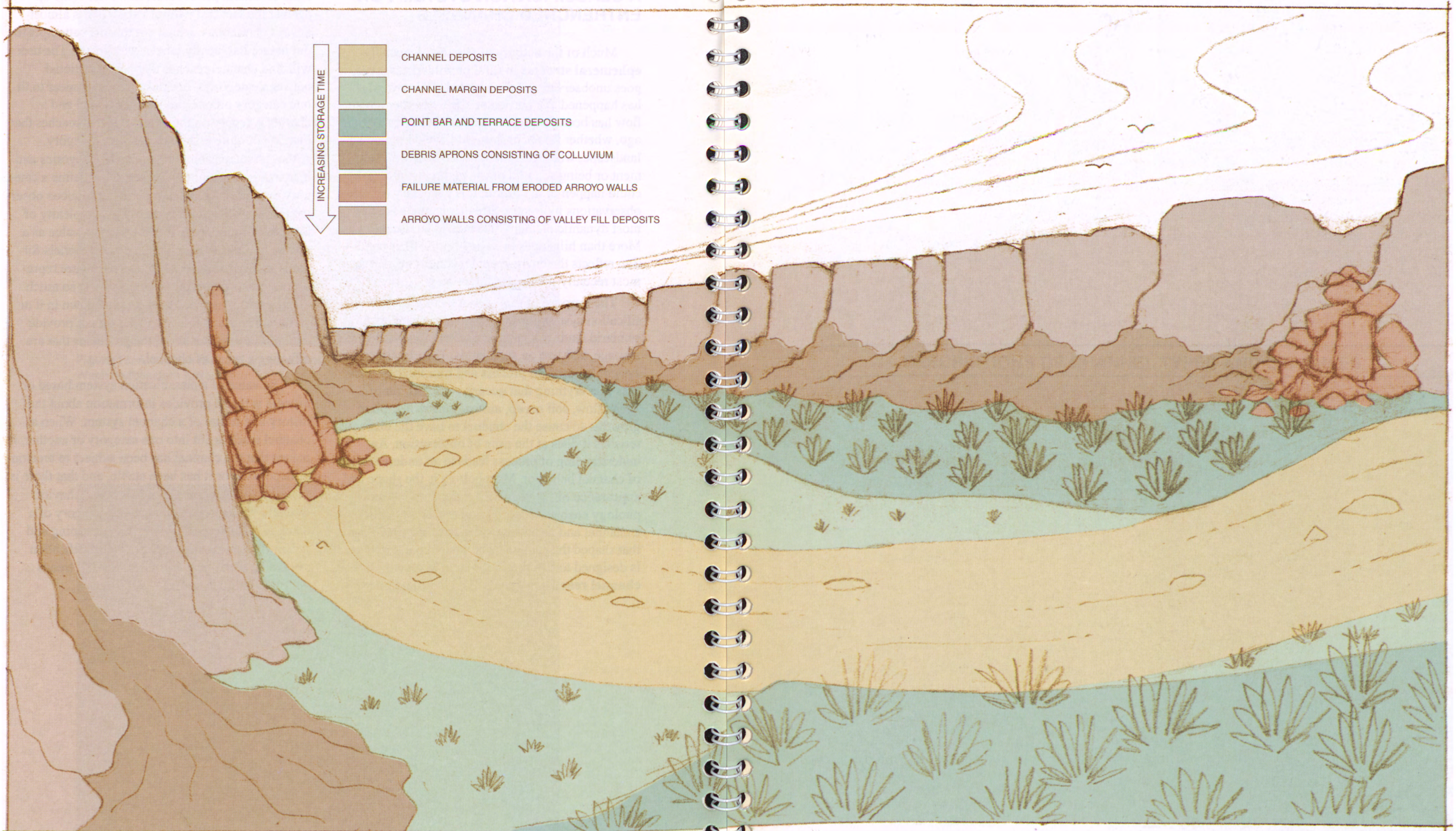


Figure 21. Sediment stored in a typical arroyo. The length of storage time for sediments generally increases from channel deposits to arroyo walls.

DESCRIPTIONS OF CHANNEL TYPES AND EXAMPLES

Type I Channel Dominated by High Rates of Colluvial Transport and Deposition and Intermittent Channel Scour

Characteristics.—Narrow channel with large accumulations of colluvium that may form overlapping debris aprons, often covering the entire channel bottom to a depth of 1 to 2 ft. Where banks are composed of noncohesive material, channel is typically v-shaped. Where banks are cohesive, channel is rectangular or trapezoidal; however, near-vertical banks may be covered almost to their tops by debris aprons. Banks and debris aprons are unvegetated or sparsely vegetated. Little or no vegetation is in the channel bottom. Sediment on slopes is highly mobile so that the slightest disturbance, including wind, small animals, and heavy footsteps, may cause sediment to trickle down the slope (figs. 22 and 23).

Active processes.—Two main processes contribute to the accumulation of colluvium on the channel bottom. Where the banks or arroyo walls are composed of noncohesive to weakly cohesive fine-grained sediments, the sediment moves slowly and constantly toward the channel bottom by soil creep. Sediment also moves to the channel bottom particle by particle when the cohesion between particles is broken by freezing and thawing or by desiccation at the soil surface. Colluvium continues to collect on the channel bottom until streamflow scours some portion of the accumulated sediment from the channel reach. The sparseness of vegetation and the noncohesiveness and fine particle size of the colluvium stored on the channel bottom and banks makes the colluvium highly susceptible to erosion and transport. Only a fraction of the mobile sediment available for transport in a reach is scoured during a typical summer rainy season.

Location.—In uppermost tributaries and in the upper reaches of larger tributaries where banks or arroyo walls are composed of weakly cemented, fine-grained sediment such as silt and very fine sand.

Significance.—Colluvial processes are more important than fluvial processes in such channel reaches. Accumulation of sediment is high. Consequently, a surplus of sediment generally exists in these reaches and when streamflow occurs, sediment concentrations are extreme. If streamflow is absent or low for more than a few years, vegetation may cover the bottom of the channel, and it may become a Type V channel.

Figure 22. Type I channel reach on a tributary of East Dinnebito Wash, northeastern Arizona. The walls of the arroyo are cohesive enough to maintain a near-vertical face. The walls also are fragile enough that particles are easily detached from the face, and a steady stream of particles collects in debris aprons that cover the bottom two-thirds of the arroyo walls. The debris aprons form a continuous blanket of loose, mobile sediment that buries the channel bottom during periods of little or no streamflow.

Figure 23. Type I channel reach on another tributary of East Dinnebito Wash, northeastern Arizona. The colluvium that collected at the base of the arroyo walls has been scoured from the channel bottom by recent streamflow. The colluvium in the debris apron above the channel is highly mobile and will quickly cover the channel bottom again in the absence of additional streamflow.

Type II Channels Dominated by Low Rates of Colluvial Transport and Deposition, Intermittent Erosion from Lateral Runoff, and Intermittent Channel Scour

Characteristics.—Where channels are incised into cohesive, fine-grained sediments, the arroyo is deep and narrow with vertical walls. Debris aprons cover the base of the arroyo walls continuously or discontinuously but generally do not cover more than the bottom fourth to third of the walls. Little or no vegetation on the walls because of their steepness though vegetation may grow on the debris aprons. Walls may be cut with flutes and spur gullies. Where arroyo walls are non-cohesive, they are below the **angle of repose** for the material that composes the walls. Walls are often cut by rills and show other signs of erosion from lateral runoff including fans of fine-grained arroyo-wall material that overlie the channel bottom. Channel bottom is narrow, of low sinuosity, with few or no channel features such as gravel bars, sandbars, point bars, and **terraces**. (fig. 24).

Active processes.— Colluvial deposition is light because of cohesiveness of sediments that compose arroyo walls or because of shallowness of angle of walls or both. Lateral runoff, however, causes flute erosion and formation of spur gullies. Lateral runoff may result in significant contribution of sediment to channel by erosion of arroyo walls. Streamflow generally is light because of the small drainage area above such reaches. Heavy flows may occur during severe summer thunderstorms in the immediate headwaters of such a reach. Streamflow that does occur scours some portion of the sediment stored in debris aprons at the base of the arroyo walls.

Location.—Upper reaches of larger tributaries where sufficient runoff is generated on adjacent valley floor to erode banks by lateral runoff but where drainage-basin area is too small to produce high streamflow except during unusually large storms.

Significance.—High sediment yields from erosion of debris aprons and channel bottom during summer streamflow but somewhat lower yields than Type I channels. Spur gullies may be a land-management problem because of possible headcut migration. Condition of valley floor, particularly vegetation cover and permeability of soil, affects amount of lateral runoff. Erosion of banks by lateral runoff and decrease of bank angle lowers the hydraulic efficiency of channel reach for larger floods.

Figure 24. Type II channel reach on a tributary of East Dinnebito Wash, northeastern Arizona. Vertical arroyo walls on the left side of the photograph and in the background show weakly developed flutes and indentations caused by erosion from lateral runoff pouring over the rim of the arroyo. The sediments that form the arroyo walls are more cohesive than in Type I channels; therefore, detachment of particles occurs less easily and colluvial processes are weaker. Debris aprons cover only the base of the arroyo walls, and they are discontinuous along the channel margins. During periods of no flow, the channel bottom may still become covered with colluvium that is intermittently scoured by streamflow as in Type I channels. The vegetated surface in the foreground on the right side of the photograph is a remnant of arroyo walls that were eroded from the top by lateral runoff.

Type III Channels have Armored Channel Banks or Arroyo Walls So Colluvial Processes are Weak.

Characteristics.—Channel banks are either bedrock or alluvium that is heavily vegetated or that is composed of greater than about 30-percent gravel. Channel generally is scoured of stored colluvial sediments but may have fluvial deposits such as gravel bars and sandbars (figs. 25 and 26).

Active processes.—Sediment storage is sparse, and sediment that is stored tends to be of large size including pebbles and cobbles. Colluvial processes are weak because of stability of arroyo walls and channel banks. Most sediment apparently is transported through the reach possibly because of higher stream velocities relative to channel reaches with more erodible banks or arroyo walls. Vegetation growth on arroyo walls occurs where colluvial processes or erosion from lateral runoff or both are weak. Vegetation further reduces strength of colluvial processes and erosion from lateral runoff.

Location.—Where bedrock is shallowly buried beneath incised alluvium and near outcrops of bedrock and bedrock ridges. Gravel-rich banks are found in channel reaches that incise gravel-rich alluvium especially near bedrock ridges. Vegetation growth on poorly cohesive arroyo walls occurs where angle of walls has declined below angle of repose for sediments that form the walls.

Significance.—High stream velocities may lead to rapid downcutting even into bedrock where rock has little resistance to erosion; otherwise, such reaches generally seem stable.

Figure 25. Type III channel reach, Toh Neh Zhonnie Wash in the drainage basin of East Dinnebito Wash, northeastern Arizona. Arroyo walls have a gravel content of about 30 percent. Although colluvium can be seen at the base of the arroyo walls on the right side of the photograph, the sediment stored in debris aprons is not as mobile as in Type I channels. Consequently, less colluvium reaches the channel bottom, less is stored on the channel bottom between flows, and a higher percentage of stored colluvium is removed by those flows.

Figure 26. Vegetation retards colluvial processes on this Type III channel reach. Stream discharges generally are low as indicated by the narrow channel. Discharges, however, are sufficient to keep the channel clear because of the weak colluvial processes that deliver little sediment to the channel bottom.

Type IV Channels are Dominated Mainly by Fluvial Processes, Particularly the Deposition of Sediment that has been Transported from Upstream Reaches

Characteristics.—Arroyo widening downstream from narrower, deeper reach. Arroyo walls generally less than 6 ft high. Narrow low-flow channel incised up to 3 ft between terraces that are inset into the arroyo. Terraces are underlain mainly by fluvial deposits but also by colluvium from adjacent arroyo walls. Terraces generally are well vegetated (fig. 27).

Active processes.—Sediment-laden streamflow from Type I, II, III, and V channels upstream loses velocity in wider, vegetated channel. Deposition of sediment from streamflow on terraces flanking channel margins; also aggradation of channel bottom. Some colluvial deposition at base of arroyo walls. Continued degradation of arroyo walls by colluvial processes and erosion from lateral runoff. Limited scour of sediment stored beneath vegetated surfaces on terrace.

Location.—Downstream end of small- to medium-sized tributaries especially below sediment-rich reaches.

Significance.—Accumulation of sediment in storage presents a possibility of a pulse of sediment transport if a large flood occurs. Dense mature vegetation on terraces and heavily degraded arroyo walls suggest that deposition and aggradation have been dominant for years to decades. The longer the process continues, the more resistant the channel will be to re-incision of the reach.

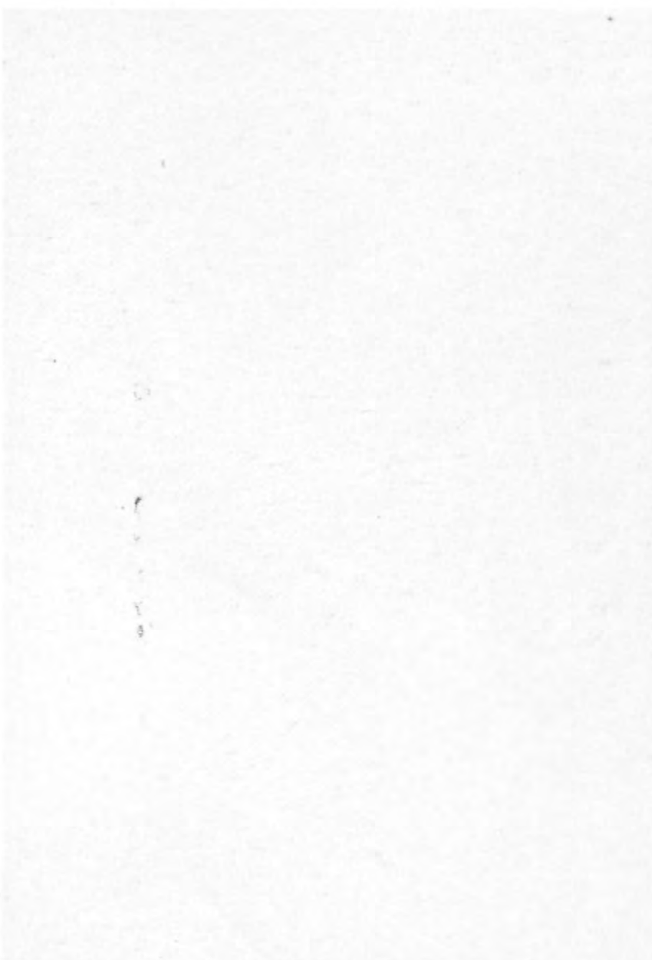


Figure 27. Type IV channel reach is several hundred feet downstream from the Type I channel reach shown in figure 21*A*. The brush-covered areas on each side of the channel are composed of sediment that was scoured from the channel bottom of the upstream reach by brief low-discharge flows. As the flows entered the wider arroyo downstream, their ability to transport sediment decreased and led to deposition of sediment along the channel margins.

Type V Channels Have Not Been Scoured by Streamflow, and Channel Bottom is Covered by Vegetation

Characteristics.—Perennial vegetation covering almost entire channel bottom except perhaps for a narrow low-flow channel that may be obscured by vegetation. Steep, unvegetated or sparsely vegetated channel banks because of steepness or high mobility of sediment that forms channel banks or arroyo walls (figs. 28 and 29).

Active processes.—Degradation of banks by lateral runoff and soil creep similar to Type I channels. Accumulation of colluvium on channel bottom, which causes aggradation of channel and possible formation of low terraces at the base of the banks. Although recently deposited sediment is subject to scour from low to moderate streamflow, sediment stored beneath vegetation, especially within the root zone, is less likely to be scoured during such flows.

Location.—Similar locations as Type I channels.

Significance.—Indicates little or no scour of sediment on channel bottom for sufficiently long period to permit germination and maturation of perennial vegetation, which is at least 1 to 2 years old. As in Type I channels, accumulation of sediment in storage presents possibility of pulse of sediment transport in the event that conditions change to permit scour of the channel bottom.

Figure 28. Type V channel developed from a Type I channel. Sagebrush has covered the channel bottom, which indicates that the channel bottom has not been scoured in several years. Steep arroyo walls remain unvegetated, however, and continue to deliver colluvium to the channel bottom, which causes the channel to aggrade. The growth of vegetation makes future scour of sediment from the channel bottom increasingly difficult.

Figure 29. Type V channel developed from a Type II channel. The absence of channel scour also has permitted the establishment of perennial vegetation on the channel bottom. The arroyo walls, however, are composed of cohesive sediments that produced low rates of colluvial transport and deposition.

Type VI Channels are Channels in Which the Processes of Channel Scour, Erosion from Lateral Runoff, and Colluvial Transport and Deposition are Minimal or Nonexistent

Characteristics.—Heavily vegetated channel bottom; degraded shallow-angle banks less than 6 ft high; banks well vegetated. In heavily decayed channels, only remnants of banks remain, typically appearing as hummocks beneath woody shrubs (figs. 30 and 31).

Active processes.—Continued slow degradation of banks by lateral runoff and soil creep. Slow accumulation of colluvium in channel bottom. Continued maturation of vegetation that increases roughness of channel. Streamflow only in response to heavy precipitation immediately above channel. Sediment transport is limited because of low availability of sediment from vegetated banks and channel bottom and because of high hydraulic roughness that reduces streamflow velocity.

Location.—Uppermost tributaries where drainage basin area is small and streamflow is infrequent. Also anywhere a channel has been cut off from its drainage basin because of damming or because of **stream piracy**.

Significance.—Indicates absence of scour for period of decades. Limited **conveyance**. Because sediment is stored within the nearly filled channels, Type VI channels present the possibility of introducing a pulse of sediment into the channels downstream if conditions change; for example, devegetation of channel bottom, migration of headcut into channel from channel downstream, or occurrence of an exceptional storm.

Figure 30. Type VI channel developed from the decay of an entrenched channel from Type I to Type V and finally Type VI in the uppermost reaches of East Dinnebito Wash, northeastern Arizona. The bottom of this Type VI channel is entirely covered by vegetation, and the slopes of the decayed arroyo walls are nearly covered. Minimum scour of the channel bottom occurs around the bases of woody vegetation. Colluvial processes and lateral erosion are nearly extinguished.

Figure 31. Type VI channel developed from decay of a Type IV channel reach. The wider channel bottom of this Type VI channel reach, as compared to the reach in figure 29, as well as the abrupt termination of the arroyo walls, indicates that this reach developed from the decay of a Type IV channel at the mouth of a discontinuous arroyo.

Type VII Channels are Dominated by Fluvial Processes of Channel Scour and Fill, Deposition, and Lateral Erosion of Channel Banks and Arroyo Walls

Characteristics.—Well-developed fluvial features, including meandering channel, point bars, eroded channel banks, scoured channels, terraces, gravel bars, and sandbars. Arroyo walls smooth where recently eroded by streamflow. Where arroyo walls are protected from stream erosion, they show flutes, spur gullies, and pillars as a result of erosion from lateral runoff. Length of sediment storage time is variable and depends greatly on the occurrence of discharges high enough to scour storage sites (figs. 32 and 33).

Active processes.—Bank erosion, mainly at the outside of meander bends, and deposition at point bars on the inside of meander bends. During low to moderate flows, bank erosion is confined to the most vulnerable areas, usually at the peak of meander bends. During large flows, extensive bank erosion may occur especially on outside of downstream limb of meander bends. Tens of feet of such erosion may occur during large floods, which also scour point bars and terraces. During prolonged periods of low flows, arroyos may store sediment that occupies nearly all of the arroyo floor. Although most sediment in storage in Type VII channel reaches is deposited from streamflow, colluvial deposition also occurs at the base of arroyo walls and accumulates in debris aprons where protected from streamflow by terraces or point bars. Bank failures that occur during low streamflow also may place sediment in channel storage.

Collapse of stream-eroded arroyo walls often occurs during waning flows or during flows so low that the failure material cannot be washed from the reach by subsequent flows, and the material can form a terrace that deflects future flows. As arroyos widen, the channel occupies an ever smaller percentage of arroyo bottom, and arroyo walls are increasingly protected from erosion by terraces and point bars; therefore, expansion of arroyo boundaries ceases or slows greatly at some maximum width, which varies according to the size of the drainage basin and the size of typical floods.

Location.—Within arroyos, meandering channels are found in all but the uppermost tributaries in the steepest valleys. Meander channels are a feature of wide, deeply entrenched arroyos.

Significance.—Where arroyos are incised into well-cemented resistant alluvium or occupy incisions that are greatly oversized for the magnitude of flows that occur in them, rates of bank erosion can be quite low and the location of arroyo boundaries stable. When subject to large or frequent floods, rates of bank erosion can be extremely high, resulting in the removal of many acres of valley bottom land over the course of a single flood. Artificial control of erosion of meandering channels is extremely expensive, and piecemeal reinforcement of channel banks generally is ineffective.

Figure 32. Type VII channel shows a wide clear channel that occupies more than 40 percent of arroyo bottom, Oraibi Wash, northeastern Arizona. Channel conditions indicate that flows have been sufficient to keep the channel cleared of sediment. The smooth, unfluted arroyo walls at the outside of the channel meander demonstrate vigorous lateral stream erosion of arroyo walls.

Figure 33. Narrow Type VII channel occupies less than 25 percent of the arroyo bottom, East Dinnebito Wash, northeastern Arizona. Most of the arroyo bottom is occupied by sediment in storage. The large point bar on the inside of the meander bend is heavily vegetated, which indicates that it has not been scoured for several years. The arroyo walls along the outside of the meander bend are nearly buried in colluvium, which protects them from lateral stream erosion even as they continue to degrade from colluvial processes and lateral runoff. The large point bar and meandering channel indicate that this reach is predominantly fluvial; however, the high volumes of sediment in storage and the fluted arroyo walls indicate that flows have been low in recent years.

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