

Appendix E

Fundamentals of Fluvial Geomorphic Principles

Content:

- Brief introduction to fluvial geomorphic principles

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1.1 The Science of Fluvial Geomorphology

Fluvial geomorphology is the science studying the processes by which moving water shapes the land. It focuses on changes in the independent variables of **discharge**, sediment load supplied to reach, and valley slope give rise to adjustments in the dependent variables of **sediment load** and particle size, hydraulic characteristics, and morphologies, all of which interact with each other. It is a fundamental discipline of river science allowing for both the quantitative description of stream behavior in the present, as well as for the ability to make reasonable predictions of future behavior under specified conditions.

Fluvial geomorphology and the related disciplines of hydrology and hydraulic engineering, geology, landscape and aquatic ecology and soil science together provide the technical underpinnings for sound watershed management. A brief overview of basic principles of fluvial geomorphology, with an emphasis on their application to stream and watershed management is presented below.

1.1.1 Major Models

Streams exist in a state of dynamic equilibrium in which, the erosive forces of channel formation are counter-balanced by the resisting forces of the geological, ecological and soil strata the channel forms within. The driving force gravity, acts on a stream as the rate at which water and sediment move through the channel. While the resisting force, the channels shape and roughness, is determined by the strength or cohesiveness of the channel boundary materials and the friction they exert on the water moving through the channel.

When the driving forces exceed the resisting forces, the stress applied by water or sediment (applied shear) exceeds channel strength. The stream channel subsequently responds by altering its geometry in plan, profile and cross-section form to accommodate the changes in flow volume and applied shear. Once disturbed, the processes by which streams respond are: 1) incision or degradation, 2) widening, 3) aggradation or deposition and 4) plan form adjustments. Through these processes, streams eventually re-establish equilibrium. Determining which process is dominant and the likely progression of the stream processes is one of the principle challenges of stream management.

While gravity and friction are the primary drivers of channel form, at the most fundamental level, stream manager's grapple with their many manifestations including sediment source, size and abundance, changing hydrologic conditions, shifting ecological influences of vegetative community disturbance and succession and a broad range of geological influences. In disturbed systems, the chosen approach evaluates each channel process separately then develops an integrated assessment using energy relationships derived from the following mathematical model. Given the large number of independent variables and the complex relationships between the many dependent variables that drive the patterns we see in natural systems such as streams, it is necessary to seek mathematical and process based models that organize the variables into easily observed and measured patterns.

Although there are three commonly recognized approaches to stream design, each with advantages and limitations (Skidmore et al. 2001), the two simplest approaches, often called analog and empirical methods, explicitly assume equilibrium conditions regarding hydrology and sediment transport. Because Little Salt Creek is not in an equilibrium condition, as discussed in more detail in Section 8.3.1 Existing Channel Process, the analytical approach is used.

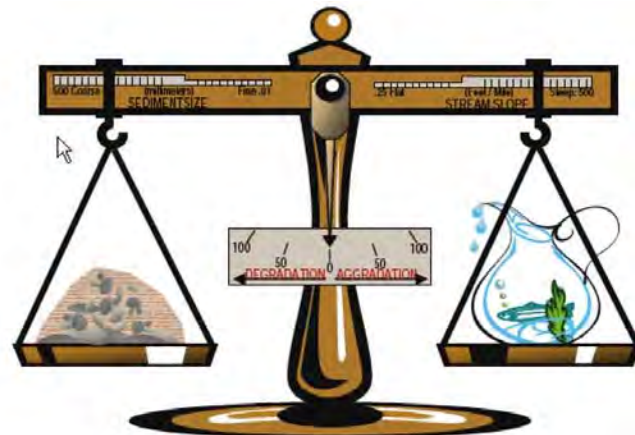
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1.1.1.1 Lane's Relationship

In 1955, E.W. Lane expressed the relationships between the driving and resisting forces for channel change in the following simple proportionality.

$$Q_s D_{50} \propto S Q_w$$

Where Q_s ≡ Rate of sediment flow
 D_{50} ≡ Median size of mobile particles
 S ≡ Slope of the channel bed
 Q_w ≡ Rate of water flow



(Sediment LOAD) x (Sediment SIZE) \propto (Stream SLOPE) x (Stream DISCHARGE)
(Adapted from Lane, E. W., *The Importance of Fluvial Geomorphology in Hydraulic Engineering*, 1955)

Here the D_{50} stands as proxy for boundary strength and S for channel shape. From this relationship, it is clear that a change in any of these parameters will, once a threshold is exceeded, induce a change in one or more of the others. The familiar increase in Q_w associated with urban development illustrates this point well. The response to this increase is some combination of the following: a decrease in channel bed slope (incision), an increase in sediment load (increased erosion) and an increase in the median size of mobile particles.

When considering all four parameters, these responses often occur in sequence. The following examples illustrate:

- Initial change: $Q_w \uparrow$; response: $Q_s \uparrow$. Often the bed slope remains relatively unchanged at first, so to maintain the proportionality, Q_s increases. The increase in sediment load is generated by down cutting of the channel bed (incision), scour of the stream banks or both. The incision locally steepens the channel slope, compounding the driving force for more erosion. This local steepening of bed slope is called a knick point. Knick points migrate upstream liberating sediment as they progress. When the stream banks exceed their critical height, mass failure ensues. This reconfiguring of the channel geometry continues until the equilibrium described by Lane is re-established.
- Initial change: $Q_w \uparrow$; response: $D_{50} \uparrow$. This condition occurs when there is little sediment initially available in the bed or banks. So, to maintain Lane's proportionality, the size of the median mobile particles increases. Under this condition, rock armor that previously protected a structure becomes mobile as the D_{50} increases. Subsequently, the service life of the infrastructure declines. Moreover, the natural bed armoring aggregate, previously mobile only during less frequent floods, becomes mobile during more frequent events and the underlying, more erosion-prone bed and bank materials are exposed to greater and more frequent erosive force.
- Initial change: $Q_w \uparrow$; response: $S \downarrow$. If the channel bed is relatively resistant to incision, the stream may respond to increased flows by decreasing its slope. The stream accomplishes this decrease in slope by meandering or increasing the channel length over the same change in elevation. The downstream progression of point bars (crescent-shaped sediment deposited on the inside bank of stream bends) opposite the downstream progression of eroding and failing cut banks (steeper outside banks of stream bends) are classic signs of meandering.

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- Initial change: $S \uparrow$; response: $Q_s \uparrow$. Increasing channel slope is often accomplished through channel straightening to achieve greater flood conveyance or to optimize land development. This increase in slope causes an increase in sediment load, in mobile D_{50} size or both. Bed and banks erode to generate the sediment that deposits downstream where channel slopes are flatter. The effective change in water surface slope may extend upstream well beyond the actual channel straightening, extending the accelerated erosion. The sediment eroded from upstream of the channelization and deposited downstream counteracts the effect of the channelization and improvements in flood conveyance are often less than anticipated.

Lane's Relationship is useful for broad conceptual understanding of stream behavior. It is also valuable for testing hypotheses concerning stream behavior in various scenarios. The following models more specifically address stream processes.

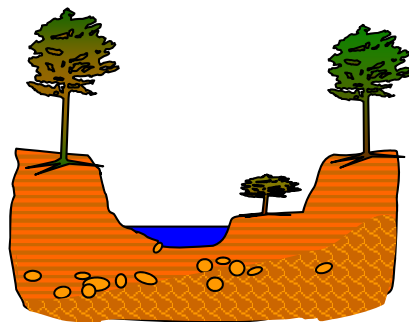
1.1.1.2 Channel Evolution Model – Evaluating Channel Changes in Cross-Section

When considering streams from a management perspective, it is especially helpful to note that streams trend toward the equilibrium condition. Schumm (1984) and most recently Simon (2001) have described process by which streams reacquire equilibrium after a disturbance in the watershed. Simon separates changes in channel morphology into six stages: I) Pre-disturbance, II) Disturbance, III) Incision, IV) Widening, V) Deposition, and VI) Recovery and Reconstruction. Determining the phase of channel evolution in the various project reaches was an important part of the analysis.

At Stage I, the channel is stable and transports the water and sediment delivered to it without significant adjustment. Although not a universal feature, internal floodplains are common in stable streams including those in the Central Midwest. Bankfull floodplains occur at the elevation corresponding to the dominant discharge. The dominant discharge is the flow that, over time, accomplishes the most work on the stream channel. In undisturbed streams, the dominant discharge typically occurs every 1.5 to 2 years. The bankfull floodplain performs a valuable function by lowering the bank shear during higher flows and effectively managing the stream energy.

Stage I Pre-disturbance

- Bed and bank materials balanced with erosive forces
- Permanent woody vegetation near the water line
- Two-stage channel shape evident at about 1.8 year return interval

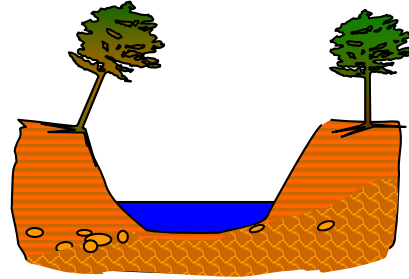


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During Stage II, natural or manmade events disturb the channel. In disturbed systems, the dominant discharge often occurs far more frequently and may not support the development of internal floodplains . Common forms of manipulation include increases in the rate, volume or timing of flow or direct alteration of channel dimensions or alignment.

Stage II Disturbance

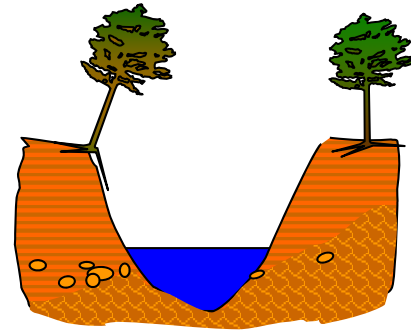
- Channel altered, hydrology or sediment inputs modified
- Removal of permanent woody vegetation near the water line
- Two-stage channel shape eliminated or no longer supported by flow conditions



In Stage III, the stream cuts downward, lowering its channel slope to redistribute energy. This incision process migrates upstream. The migrating face of an incision front is referred to as a knickpoint or knickzone. The typical shape of these channels is V- shaped or narrow U-shaped. In soils such as loess, incision may proceed rapidly; migration rates exceeding 1000 feet/year occur in the Central Midwest. Incision proceeds until the channel has reached a stable slope, the incision reaches a more resistant layer or the stream banks begin failing because of mass wasting.

Stage III Incision

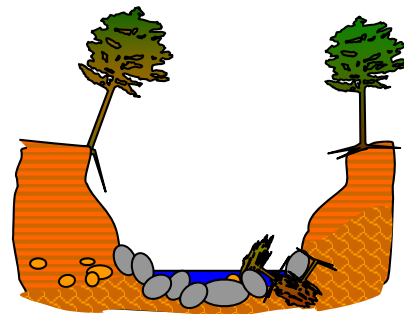
- Downcutting liberates sediment
- Lost or perched bankfull floodplains
- “U” shaped channel
- Woody vegetation high on bank with many “surfer” trees



Channel widening through mass wasting of the stream banks, Stage IV, follows incision. There are two common mechanisms of bank failure. Fluvial action erodes soil away from the toe of the slope resulting in a cantilevered bank, which eventually fails through toppling. Alternatively, the incision cuts deeply enough into the bed that the stream banks exceed their critical height and fail. Both mechanisms are operational in a stream.

Stage IV Channel Widening

- Widespread bank failures as banks exceed critical height or were undercut by toe scour
- Channel adjusts to new flow regime
- Significant sediment loads generated; most significant erosion hazard in this phase
- Bank armoring generally ineffective

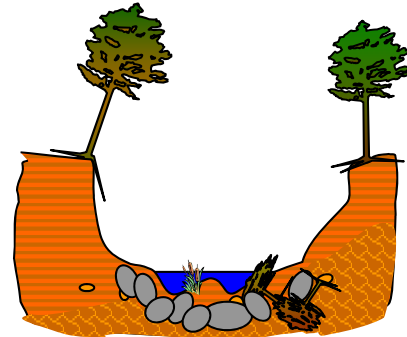


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The next phase of channel evolution is Stage V when the channel has sufficiently widened and begun depositing sediment eroded from upstream reaches in the bed. The deposits occur as channel bars and occasionally as internal floodplains.

Stage V Deposition

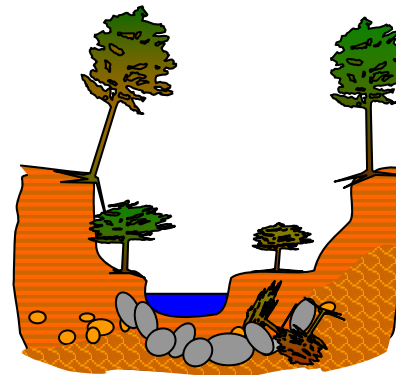
- Deposition begins from liberated sediment
- Vegetation establishes near water line



In Stage VI, the channel regains the equilibrium condition and efficiently transports both water and sediment. If a substantial increase in Q_w precipitated the adjustment, final dimensions of the channel (in cross section) will probably be larger than the pre-disturbance condition.

Stage VI Recovery and Reconstruction

- Bankfull floodplains may be reconstructed from liberated sediments
- Woody vegetation establishes near water line
- Stability re-established

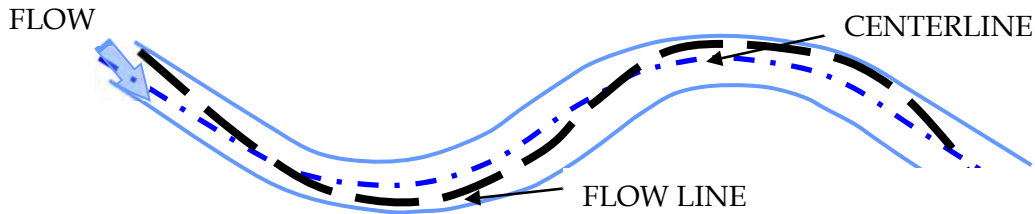


1.1.1.3 Meander Formation and Migration – Evaluating Channel Changes in Plan Form

Adjustments in plan form are common and have an important influence on the sustainability of a storm water system as well as on the safety and service life of near-stream infrastructure. Some plan form adjustments can liberate significant sediment and present major erosion hazards. The management requirements of plan form adjustment differ from those of an incising or widening stream. Consequently, distinguishing between these processes is an important part of any investigation and analysis into the stability of a watershed. Straight stream channels are rare, requiring a narrow set of circumstances to maintain dynamic equilibrium in a natural setting. Like all other open systems, streams adjust their form to minimize the expenditure of energy. The formation of pool-riffle patterns and meanders are consistent with this trend towards maintaining an equilibrium condition. Meanders are complex in both formation and behavior. Meander formation graphically demonstrates the principle of cause and effect in stream mechanics. The cause in this instance is the force applied by moving water and sediment while the effect is the shape of the stream channel.

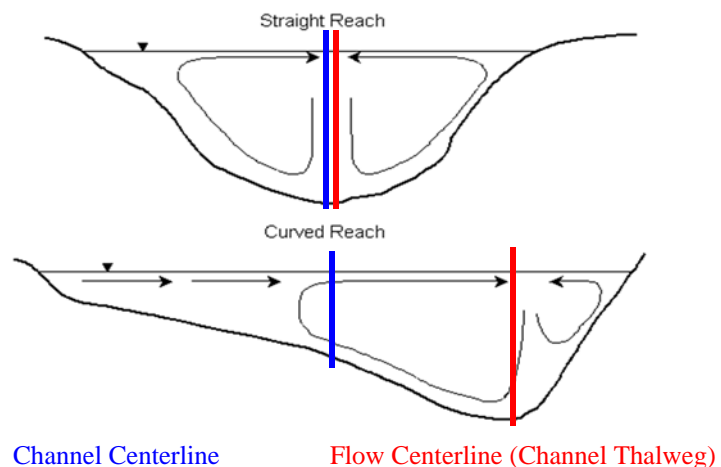
To describe the basic process of meander formation, the distinction between the meander flow or discharge centerline and the channel centerline is important. As illustrated in Figure 8.6, the channel centerline (effect) lags the discharge flowline or the channel thalweg (cause). This is a result of the resistive forces

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of friction being unevenly applied to the water moving through the channel, recall that these resistive forces are expressed as the shape of the channel (in cross-section and Planform) and the channel paving materials. Consequently the flow in a stream channel is slower at the margins or boundaries of the channel. This is due to the higher levels of friction in these zones, which causes the flow in a stream to not progress in straight lines parallel to the stream channel. Therefore faster moving water from the interior of the channel is always spilling out into the space not occupied by the slower moving water at the margins of the channel.

Therefore, flow in a stream is comprised of a primary flow oriented downstream with secondary transverse flows oriented perpendicular to the primary flow. As illustrated in Figure 8.7, along the channel thalweg, these inward and outward transverse flows are balanced in terms of the quantity of water which is being discharged. However, along the channel centerline, there is considerable asymmetry. Because of the variable turbulence and secondary flow patterns, the flow velocity, sediment transport and boundary shear stress are resultantly non-uniform across the channel. These areas of turbulence produce alternating pulses of sediment scour and deposition.

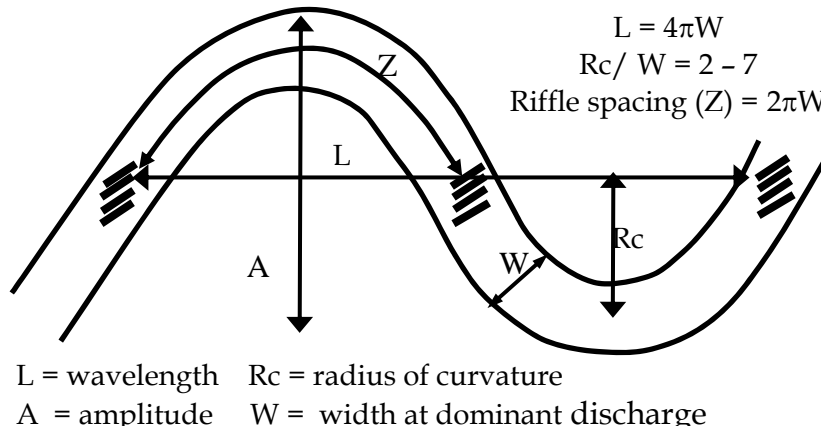


The resulting areas of scour and deposition alternate along the axis of discharge flow producing a pool along the outer bend and a corresponding point bar on the inner bend. As the pattern of scour and deposition alternates from one side of the channel to the other, the thalweg (deepest portion of the channel cross section) and maximum flow velocity cross over the center of the channel. These cross over points become the riffles. This alternating pattern of bar building and bank scour causes straight streams to evolve into meandering ones with a sinuous pattern. Specifically, this is how channelized reaches eventually reacquire a sinuous shape.

Although the process of creating riffles and pools encompasses highly variable processes, the riffles and pools occur at generally predictable intervals. The spacing of these riffles or pools along the thalweg relates closely to the width of the stream at the elevation of dominant discharge. The figure below illustrates riffle geometry in plan form. Further, the spacing of the pools, which are near the outside bend and slightly

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downstream of the maximum curvature of the meander, have essentially the same relationship to channel width as the riffles.



In alluvial streams of homogeneous material, meanders take the form of sine-generated curves. Leopold and Langbein⁽¹⁹⁶⁹⁾ demonstrated that this shape is the most hydraulically efficient form for turning water. Further, Chang (1998) presents a more analytical assessment of this meander plan geometry. These relationships between stream width, riffle spacing, meander wavelength and radius of curvature are remarkably consistent for streams and rivers throughout the world.

Most stable relationships in channel geometry include the channel width at the elevation corresponding to the dominant discharge. Riffle spacing (Z) generally occurs every 6.3 bank widths (W) where W is the width at the dominant discharge., this spacing is essentially $2\pi W$. Meander wavelength is approximately 12 bank widths, which approaches $4\pi W$.

The radius of curvature is also related to the channel width at dominant discharge elevation. The ratio of meander radius of curvature (R_c) to channel width (W) generally ranges between 2 and 7. Bagnold's (from Thorne et al, 1997) investigation of energy losses at bends confirmed the empirical observations by determining that flow energy losses are minimized through this shape. A tighter radius causes a flow separation and severe energy losses, a hydraulic inefficiency that is not persistent. In natural rivers, channel bends erode to a R_c/W ratio of 2-5 and then maintain that form, which indicates that the hydraulic efficiency is optimized by this form.

In streams containing heterogeneous media and in confined channels, the meander pattern is interrupted by variations in bank structure, infrastructure, confluences, geologic features and channel manipulation. Streams out of equilibrium also display distortions in meander pattern and growth. Nevertheless, the fundamental relationships describing these patterns remain broadly applicable.

Consistent with the location of peak stress downstream of each bend apex, meander waveforms migrate downstream. In stable streams, the meander migration generally occurs at a rate that does not affect infrastructure. However, accelerated migration may pose a substantial risk. A rapid increase in sediment load delivered from an incising or widening reach upstream is the most likely trigger for accelerated migration in Xxxx.

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1.1.1.4 Profile Analysis

The measurement of the effect of gravity on a channel is often understood through an analysis of the channels longitudinal profile or gradient. In this manner, the dominant bed-slope of the channel is quantified. Channels with steeper bed-slopes, as determined by the difference in elevation between the crest of one riffle and the crest of an upstream or downstream riffle, have a higher level of hydraulic energy which must be dissipated by the channels shape and roughness. Abrupt changes in the overall pattern of channel profile indicate areas where incision is occurring now or where the degradation is arrested by manmade or natural structures. The advancing front of incision is known as a knick point or where slope changes are slightly less abrupt, knick zone. It is especially important to identify and manage incision because it usually precedes processes that are more destructive.

1.1.1.5 Energy Relationships

Other fundamental relationships used to understand stream mechanics are energy, continuity and loss relationships. Remembering that energy can neither be created nor destroyed, that mass is conserved and that all dynamic systems have losses, we can calculate flood elevations and erosive stresses.

First, the total energy in a system can be expressed as:

$$E = w + v^2/(2g) + z - L$$

Where: E \equiv energy (ft-lb/lb)
 w \equiv work per unit mass
 $v^2/(2g)$ \equiv kinetic energy
 z \equiv potential energy
 L \equiv losses

The total energy at any point is equal to the total energy at any other point and is expressed as:

$$w_1 + v_1^2/(2g) + z_1 = w_2 + v_2^2/(2g) + z_2 - L$$

Additional equations such as continuity¹ and Manning's loss equation² allow the designer to calculate the depth and velocity at any point in the system. Energy, continuity and Manning's equations are the bases for programs such as HEC-RAS.

Bringing these concepts together in the context of stream mechanics, work is the movement of sediment by water, kinetic energy is the movement of water, potential energy is the depth of the water and losses are friction and sound. HEC-RAS does not include a separate calculation of work. The energy exchange of work moving sediment is included by default in losses and kinetic energy.

Some designers consider sediment transport competency for major projects by establishing a sediment budget to analyze sediment movement through the designed intervention. More sophisticated techniques include computer based analyses. For small projects, it is usually difficult to justify a sophisticated model. The designer, however, can achieve a basic understanding of sediment transport competency and erosion hazard from data and analyses used to determine water surface elevations. The designer estimates area of erosion and deposition from the continuity of the stream power or boundary shear stress. Routines in the

¹For modeling purposes, the continuity relationship expresses the concept that the quantity of water in any one point in a system is the same as the quantity of water at another point or changes only gradually. At each confluence, hydraulic models are partitioned into discrete reaches.

² Manning's loss equation is commonly expressed as $Q = 1.49(R^{2/3}S^{1/2})A/n$

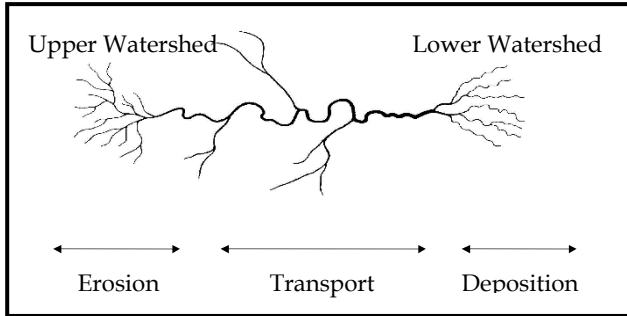
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HEC-RAS model calculate stream power and boundary shear stress. The values of either stream power or boundary shear stress are plotted against the longitudinal profile. The designer compares the zones of highest and lowest values to his field observations of size and distribution of bed material and the location of scour and erosion. The designer then establishes threshold values from these observations. Improved sediment transport competency results from using these threshold values in design. Boundary shear stress is the product of density, depth and slope. The designer predicts areas of scour and erosion by comparing the boundary shear stress to the shear resistance of the bed or bank toe materials. The shear resistance for granular materials is calculated using empirical relationships. The shear resistance for cohesive materials is usually compared to measured or tabulated values.

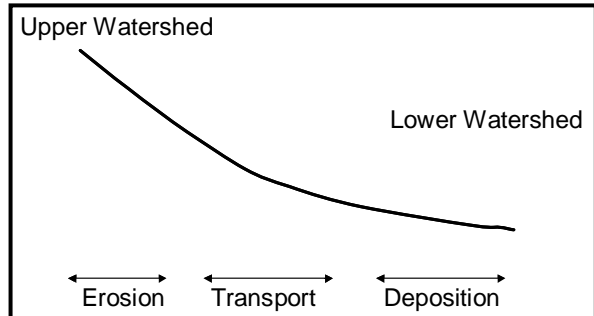
Lane's proportionality allows the designer to understand and predict the effect of forces on a stream. Energy and continuity equations allow the designer to predict the depth and average velocity at any point. The energy and continuity equations are the bases for understanding the exchange of energy modes. Perhaps the simplest useful way to apply these principles is to think of energy as either kinetic or potential. For the purposes of stormwater, flooding occurs when potential energy is higher than we can accept and accelerated erosion occurs when kinetic energy is higher than we accept.

1.1.2 Temporal and Spatial Implications

The dominant process in a stream reach is influenced by its location in the watershed. As shown on the following figures, the profile of the channel slope becomes flatter progressing downstream. In the most general sense, incision dominates the steep, upper watershed and plan form adjustments dominate the relatively flat lower watershed.



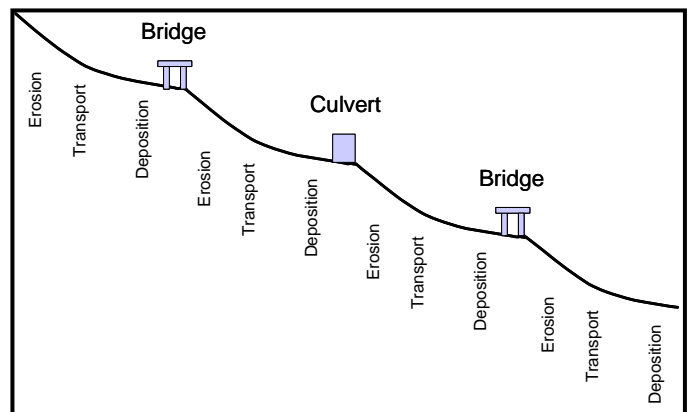
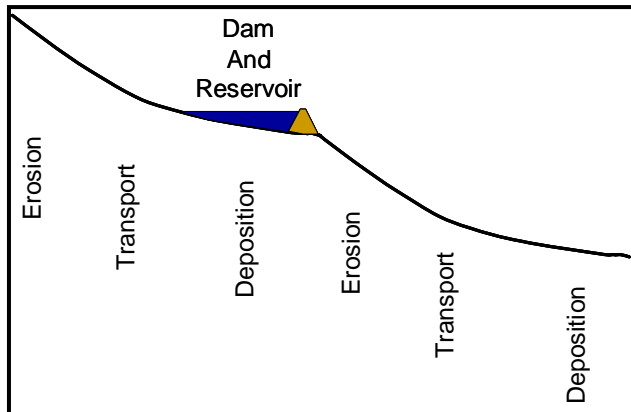
Stages of a river system (adapted from Rienick and Singh, 1980).



General channel profile of a watershed.

In disturbed watersheds, this pattern may be reset by infrastructure. For example, a dammed stream can act as the end of a watershed, where sediment and water is deposited in the receiving lake.

Here the outfall behaves like a spring beginning the next watershed. Stream crossings such as bridges and culverts can also reset river formation, as shown on Figure 8.4. In developing areas, the characteristic profile shape of natural watersheds may be repeated after each hard crossing that materially effects transport of water and sediment. These obstructions may geomorphically isolate the reach.



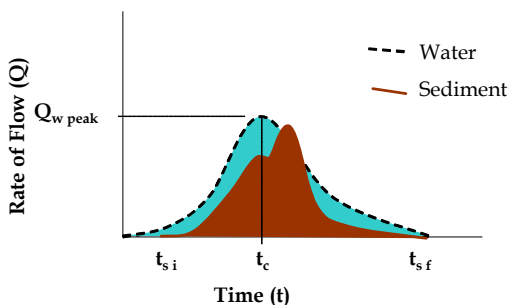
1.1.3 Sediment Transport

Natural channels transport both water and sediment through the watershed. Sediment and water movement play parallel roles in flood and erosion control and in the performance of bridges and culverts. For this discussion, sediment includes large woody debris, man-introduced materials and other debris that comes to rest on the streambed. A stream in dynamic equilibrium maintains the movement of water and sediment without sudden and wholesale areas of erosion and deposition. Flow rate governs both the initiation of sediment movement and its deposition, moving material when the system has sufficient kinetic energy and depositing it when the kinetic energy is depleted. As described earlier, gravity, expressed here as hydraulic slope, is the driving force acting on the system. The movement of water transfers that force to dislodge and keep particles moving. Figure 8- is a generic hydrograph and sedigraph relating the rate of flow to time . Note that there is a lag between the flow of water and the movement of sediment ($t_{s,i}$). The lag represents the flow necessary to exceed the critical shear stress as described in Section 6. At the peak water flow there is often a decrease in the transport of sediment as the hydraulic slope decreases. The falling leg of the hydrograph may coincide with the peak of the sedigraph with the particles already mobile and an increase in hydraulic slope.

As the flow recedes and kinetic energy declines, the stream deposits particles of decreasing particle size. This process forms the riffles between pools. In XXXX, this is most apparent where the woody debris jams morphologically behave as riffles.

Issues of sediment transport are particularly relevant to stream managers at infrastructure crossings. Bridge, culvert and pipeline crossings may interrupt the hydraulic slope with predictable, adverse consequences. A crossing backwatered under high flow conditions decreases the hydraulic slope and may induce deposition that reduces flow capacity. Over-widened or excessively smooth crossings increase hydraulic slope and induce scour. The scour may occur immediately downstream and undermine the structure or may, as the result of an upstream drawdown curve, induced incision. This incision migrates upstream until the stream reaches a stable bed slope.

Hydrograph and Sedigraph



Management activities that remove or add material to the stream also interrupt equilibrium sediment transport and may have similarly adverse consequences.. Snagging, straightening and widening a channel all disrupt the sediment balance. These and similar activities induce upstream erosion and eventual deposition at the site of disturbance. Un-designed bank armor such as dumped riprap or waste concrete disrupts sediment transport when it migrates into the bed. These large, rough particles induce deposition where they enter the bed but induce scour downstream. Dumping materials on the bed can also reset the pool and riffle sequence if the dumped material becomes the hardest point in the reach.

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