3.2 Introduction to Stream Processes

"You cannot step twice into the same river; for fresh waters are ever flowing in upon you." -Heraclitus, 2500 B.P

Ask anyone who lives streamside, and they'll tell you that living around streams carries both benefits and risks; to enjoy the benefits, we accept the risks. Both the pleasures as well as the dangers of living near streams stem in part from their ever-changing nature. Icy spring flood-flows are exciting and beautiful as long as they don't creep up over their banks and run across your yard into the basement window, or suddenly tear out a stream bank and begin flowing down the only access road to your house. For many reasons, the relatively flat land in the floodplain of a stream may be an inviting place to build a home or road –in fact it may be the only place– but as long-time residents of floodplains know only too well, it's not a matter of *if* they will see floodwaters, but of *when*.

As changeable as streams are, though, there is also something consistent about the way they change through the seasons, or even through an individual storm. As unpredictable as streams can be, they are also predictable in many ways. If we take the time to observe them carefully, we can begin to understand the patterns in the way streams behave and, more importantly, what we might do in our individual roles as stream stewards and managers to increase their benefits to us, and to reduce the risks they pose.

This section of the management plan is provided to offer the reader a basic explanation of what stream scientists know about how streams "make themselves": why they take different forms in different settings, what makes them evolve, and how we can manage them effectively to increase the benefits and reduce the risks they offer.

It's obvious that streams drain water off the landscape, but they also have to carry *bedload* –gravel, cobble, and even boulders– eroded from streambeds and banks upstream.

If you stand near the bank of a mountain stream during a large flood event, you can feel the ground beneath your feet vibrate as gravel, cobble and boulders tumble against each other as they are pushed along by the force of the floodwaters down the streambed. As the water begins to rise in the channel during a major storm, at some point the force of the water begins to move the material on the bottom of the channel. As the stormwaters recede, the force falls and the gravel and cobble stop moving. The amount of water moving through the channel determines the amount of *bedload* moving through it as well.

To effectively manage the stream, then, managers first need to understand how much water is delivered from the landscape to the stream, at any particular point in the system. The amount of water any stream will carry off the landscape is primarily determined by four characteristics of the region:

- the climate, specifically the amount of rainfall and the temperatures the region typically sees throughout the course of a year;
- the topography of the region;
- the soils and bedrock geology; and
- the type of vegetation (or other land cover like roads and buildings) and its distribution across the landscape.

These characteristics also play key roles in determining the type and frequency of flood hazards in the region, the quality of the water, and the health of the stream and floodplain ecosystems.

The shape and size of a stream channel adapts itself to the amount of water and bedload it needs to carry. Within certain limits, the form, or *morphology*, of a stream is self-adjusting, self-stabilizing, self-sustaining. If stream managers exceed those limits, however, the stream may remain unstable for a long time.

Over the period since the last glaciers retreated some 12,000 years ago, the Catskills streams have adapted their shape to these regional conditions. Because the climate, topography, geology and vegetation of a region usually change only very slowly over time, the amount of water moving through a stream from year to year, or *streamflow regime*, is fairly consistent at any given location.[1] This stream flow regime, in turn, defines when and how much bedload will be moving through the stream channel from year to year. Together, the movement of water and bedload carve the form of the stream channel into the landscape. Because the streamflow regime is fairly consistent year after year, then, the form of the stream channel also changes relatively slowly, at least in the absence of human influence. Over the 120 centuries since glaciers covered the region, the stream and the landscape conditions evolved a dynamic balance.

However, as we made our mark on the landscape –clearing forest for pastures, or straightening a stream channel to avoid having to build yet another bridge– we unintentionally changed that balance between the stream and its landscape. We may notice that some parts of the stream seem to be changing very quickly, while others remain much the same year after year, even after great floods. Why is this? Streams that are in dynamic balance with their landscape adapt a form that can pass the water and bedload associated with both small and large floods, regaining their previous form after the flood passes. This is the definition of stability. In many situations, however, stream reaches become unstable when some management activity has upset that balance, and altered the stream's ability to move its water and bedload effectively.

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[1] One exception is when the vegetation changes quickly, such as can happen during forest fires, volcanic eruptions or even rapid commercial or residential development.

The amount of potential force the water has to move its rock is determined by its **slope** –the steeper the slope, the more force– and its **depth** –the deeper the stream, the more force. So, for example, if changes made to a stable reach of stream reduce its slope and/or depth, the stream may not be able to move effectively the bedload supplied to it from upstream. The likely result will be that the material will deposit out in that section, and the streambed will start building up, or *aggrading*.

On the other hand, when we straighten a stream, we shorten it; this means that its slope is increased, and likewise its potential force to move its bedload. Road encroachment has narrowed and deepened many streams, with the same result: too much force, causing the bed of the stream to *degrade* and, ultimately, to become *incised*, like a gully in its valley. Both situations, aggrading and degrading, mean that the stream reach has become unstable, and both can lead to rapid bank erosion, as well as impairment of water quality and stream health. Worse yet, these local changes can spread upstream and downstream, causing great lengths of stream to become unstable.

The lay of the land determines the pattern and grade of the stream, but the stream also shapes the lay of the land. The stable form for a particular stream depends on the larger form of the valley it flows through.

The stream pattern we now see throughout the Catskills is the result of millions of years of landscape evolution: fractured bedrock, chiseled repeatedly by rivers, and then glaciers, and then rivers again, as glacial ages came and went, as valleys were eroded out of the mountains and washed out to sea. In the broader valleys like the Esopus or the Delaware, floodplains formed as they filled with cobble and gravel, sand and silt carved away from the steeper mountainsides by roaring meltwater. The material often settled out as the streams entered into local lakes, created where notches at the lower end of the valley were dammed by glacial ice. When the ice dams melted, the lakebed remained a fairly flat valley floor, poorly vegetated initially, through which the stream could meander from one side of the valley to the other.

As the streams, century by century, shaped these flatter valleys they flowed through, the resulting shape of the valleys in turn changed the streams. As valleys developed floodplains, the streams flowing through them became less steep, and their pattern and shape progressively adjusted to assume new stable forms, in balance with the new landscape.

In many settings, the story is even more complicated. The main valleys were widened out by glacial scouring, while in many small pockets, soil materials melting out of glaciers created complex local deposits of clay, sand, gravel, cobble and boulders, and leaving diverse terrace forms throughout the valley. As the steeper streams coming off the mountainsides joined into a more gently sloped main channel running through the main valley, the stream became wider, and less deep.

The stable form that a stream takes in balance with the steep, mountain notches will be different from the one it takes in medium-gradient valleys, and this will be different still from the stable form in a relatively gently-sloping, broad floodplain like the West Branch of the Delaware.

As our climate warmed, grasses and then trees recolonized the evolving valley floor. As vegetation returned to the floodplains, the conditions that determine the balance between stream shape and the landscape changed once again. Stream banks that have a dense network of tree and shrub roots adding strength to the soil can better resist the erosive power of flood flows, and consequently a new stable stream form emerges; a new balance is struck between resistive and erosive forces. A dense mat of woody roots is essential if we want to maintain a stable stream bank. If streamside trees and shrubs are removed, we can expect the bank to soon begin eroding.

In the Catskills, a naturally stable stream will have trees and shrubs all along the stream bank to help hold the soil together. If you remove the trees and shrubs, and mow right down to the edge of the stream, you may be risking big-time erosion problems.

If we want to maintain healthy, stable streams, then, we need to maintain a stable stream *morphology* and vigorous streamside, or *riparian*, vegetation. Stable streams are less likely to experience bank erosion, water quality and habitat problems. The management plans being developed by the Stream Management Program and their partners generally describe the current condition of the stream form and streamside vegetation throughout the watersheds they address, and then make recommendations for protecting healthy sections of stream and for restoring the stability of those sections that are at risk.

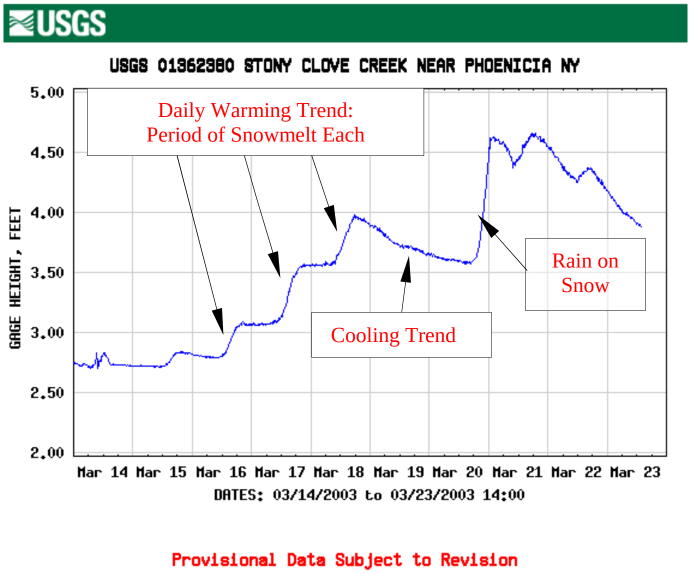
Stream Morphology and Classification

This section provides more technical information for the curious about the relationship between stream ***form*** (or ***morphology***) and physical stream ***function*** (i.e., flood behavior, sediment transport).

The last section described how a stream's form --slope and depth-- determine its function --how much potential force the stream has to move the silt, sand, gravel, cobble and boulders that make up its *bedload*. We focused on slope and depth because they are often changed --intentionally or unintentionally-- by stream managers. There are, however, many characteristics that come together to influence how a stream "makes itself", and whether it is stable or unstable in a given valley. These characteristics[2] include:

Stream flow (Q)

Usually represented as cubic feet or cubic meters per second, streamflow is also called stream ***discharge***. Stream flow changes from hour to hour, from day to day, from season to season, and from year to year.



The typical pattern of streamflow over the course of a year is called the streamflow regime. Some streamflows play a more significant role than others in determining the shape of the stream. In alluvial streams, the "*bankfull flow*" is considered most responsible for defining the stream form, and for this reason, bankfull flow is also sometimes called the *channel-forming flow*. This flow typically recurs every 1-2 years. It may seem surprising that very large floods aren't more important in forming the channel, but while they may induce catastrophic changes in a stream—severely eroding banks and

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[2] Each characteristic is followed, in parentheses, by the variable used to represent it in formulae.

washing countless trees into the channel—these major floods are more rare, occurring on the average every decade or so. The flows that have the most effect on channel shape are those that come more frequently, but which are still powerful enough to mobilize the gravel and cobble on the streambed: the smaller, bankfull flows.

The height of the water in the channel is called the ***stage***. When a stream overtops its banks, it's in ***floodstage***. ***Bankfull stage*** –when the stream is just about to top its banks-- is used as a benchmark for measuring stream dimensions for classifying different stream types (see ***Rosgen Classification System***, below).

Slope (S)

We already mentioned slope as one of the two main determinants of a stream's potential force for erosion of the streambed and banks. The slope of a stream usually refers to the average slope of the water surface when the stream is running at bankfull flow.

Channel average depth (d)

Depth is the other primary determinant of potential force, and is measured from the streambed to the water's surface. Again, this will depend on the level of the streamflow. When used to compare one stream reach to another in ***stream classification systems*** (see below), the average depth of the stream during a bankfull flow is used.

Channel width (w)

Together with average depth, the ***width*** of the channel determines the ***cross-sectional area*** (Area = width x depth). If a roadway encroaches on a stream, its width is reduced. To pass the same sized flood, the stream is going to have to be deeper, that is, floodstage is increased, or move the water faster through it.

Channel roughness (n)

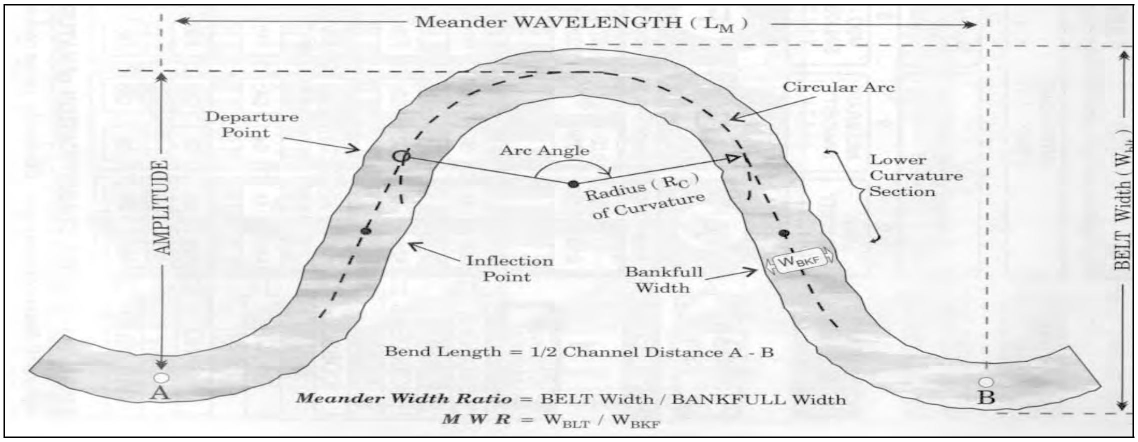
So far we've only talked about what gives the water its potential force to erode the streambed and banks. There are also characteristics of the stream that slow the water down, or resist the flow. One of these is the channel ***roughness***: it's harder for the stream to flow through a section of stream filled with boulders than through a stream with a silt-bottomed bed, and no obstructions. Water flows more slowly across a floodplain filled with trees and dense brush than it does across a smooth, newly mown lawn or parking lot, and so is less likely to cause erosion. Within streams, this is also sometimes referred to as ***bed roughness***.

Sinuosity (k)

A different kind of roughness that slows water down has to do with whether the channel runs straight, or curves. When the flow of a stream is slowed as it moves around a bend in the stream, we say that the flow is encountering ***form roughness***. The curviness of a stream is called its ***sinuosity***, and is measured as the stream length divided by the valley length. That is, if a stream runs completely straight down a mile long valley, both the valley and the stream are the same length, or 1 mile / 1 mile = a sinuosity of 1. If the stream snakes, or ***meanders***, down the same valley, it might be two miles long, or 2 miles / 1 mile = a sinuosity of 2. As a rule of thumb, we find that, in natural channels, the lower the slope, the more sinuous the stream.

Radius of curvature (Rc)

Radius of curvature is another measure the "curviness" of the stream, but at a single curve, and is measured as in this illustration:



Adapted from The Reference Reach Field Book, D. Rosgen.

Belt width

Meander Beltwidth describes the width of a stream's meander through its valley (see figure above). It is measured from the outside of one meander to the outside of the next, perpendicular to valley fall. This is also sometimes referred to as the floodway, and during large floods, the entire meander beltwidth is often inudated, as the stream takes a "shortcut" on its way downvalley. Homes and roads in this region are at greater risk for flooding and damage from erosion.

Sediment size (D50)

It takes more force for a stream to move the material on the bed of the stream if it is made up of large cobble than if it is sand or silt; the smaller the particles, the more easily they will be moved. To characterize a reach of stream, 100-300 particles are randomly selected and measured, and the median size particle gives the ***D50*** of the reach: meaning that 50% of the particles in the stream are smaller, and 50% are larger.

Name	Size
Silts	< 0.062mm
Sands	0.064mm - 2mm
Gravels	2mm - 64mm
Cobbles	64mm – 256 mm
Boulders	256mm – 512mm

Bed and Bank Cohesiveness

Due to the glacial history of the region, soils in the Catskills are extremely variable from place to place, and some soil types hold together better than others, or are more ***cohesive***. Some streambeds have their gravel and cobble locked together in a form that resists movement by streamflow, and others "unzip" easily. The roots of trees and shrubs can reach deep into the soil of a stream bank, and the web of fine root fibers can add a tremendous amount of cohesiveness to the soil.

The "balance" that streams develop over time when they aren't disturbed is the balance between the erosive forces of floodwaters, and the strength of the bed and banks to resist that erosive power. This balance develops because streams will erode away their banks until, eventually, the lengthening of their meanders reduces the slope, or the stream is widened and depth is decreased sufficiently, such that the cohesiveness of the soil and vegetation together just equal the erosive potential of the floodwaters. If the vegetation on the stream bank is changed, the soil cohesiveness will change, and that balance point will change. Likewise, if a stream bank gradually migrates into a less cohesive soil type, it can suddenly begin eroding very quickly.

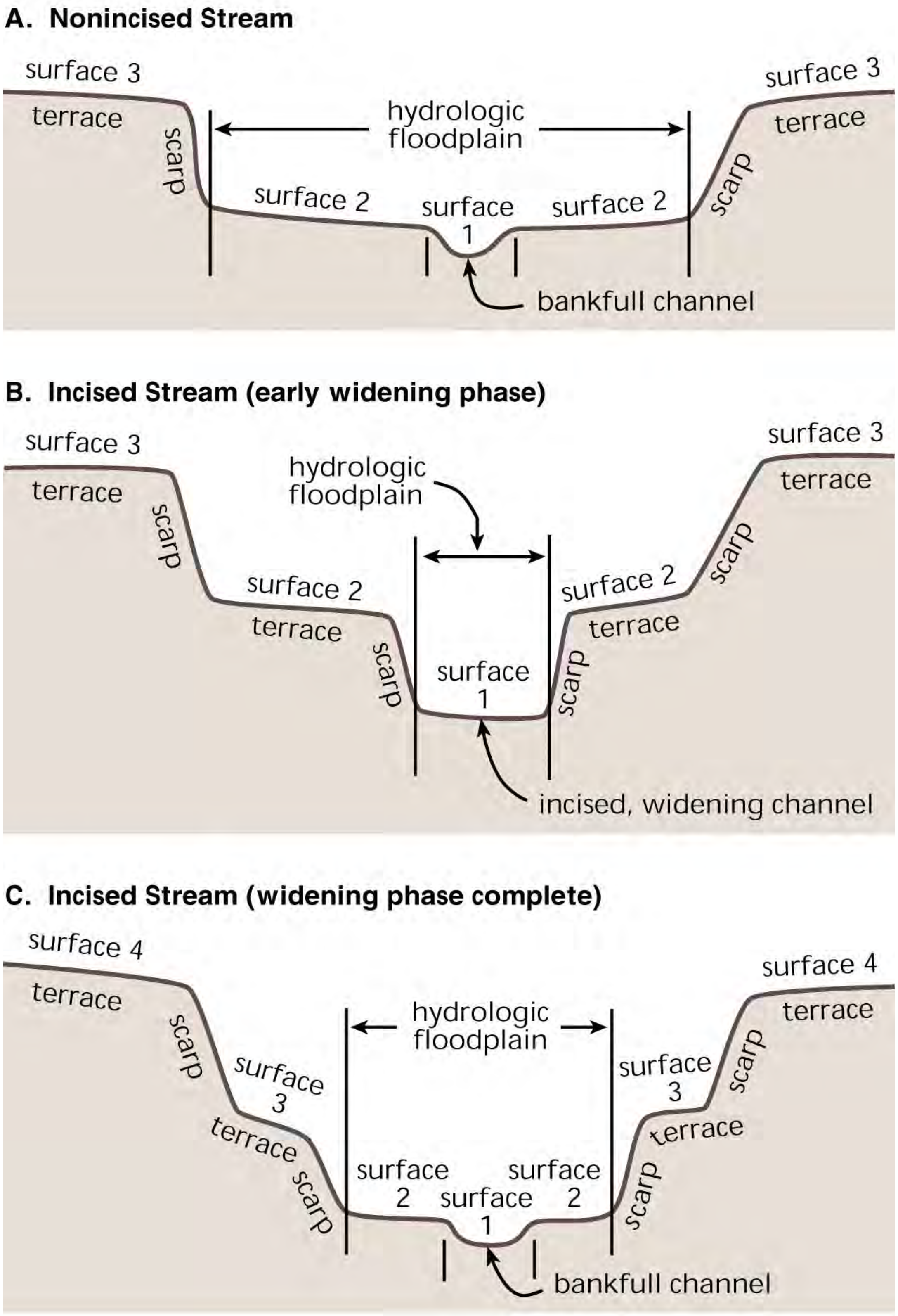
Sediment discharge (Qs)

When silts and sands, gravels, cobbles or even boulders have been moved by the streamflow, we call them ***sediment***. ***Sediment discharge*** is the amount of sediment moving past a particular point over some interval of time, and is usually measured in tons per year. ***Bedload*** is sediment that moves along the bottom of the channel, while ***washload*** is sediment that is suspended up in the water. Measuring sediment discharge is one way to determine if a stream is stable or not. If the amount of sediment coming into a reach of stream doesn't roughly equal the amount leaving the reach in the same time period, the form of the reach will have to change.

Entrenchment

When a reach of stream is straightened or narrowed, the power of the streamflow is increased, and it may cut down into its bed, so that flood flows can't spill out into the floodplain. When this happens, we say that the reach has ***incised***, and that the channel has become ***entrenched***. Entrenchment can be low, moderate or extreme. When even large flood flows are confined to the narrow channel of the stream, they can become very deep, and therefore very erosive. The result may be that the stream gullies down even deeper into the bed. Eventually the banks may become too high and steep, and they may erode away on one or both sides, widening the channel. Eventually, the channel may widen enough to allow a new floodplain to develop inside the entrenched banks (see the figure below). This is one way that streams evolve over time.

Entrenchment may also occur as a result of building berms that prevent the stream from using its natural floodplain during large flows, or if the amount of water the stream is forced to carry increases significantly as a result of storm drainage associated with land development.



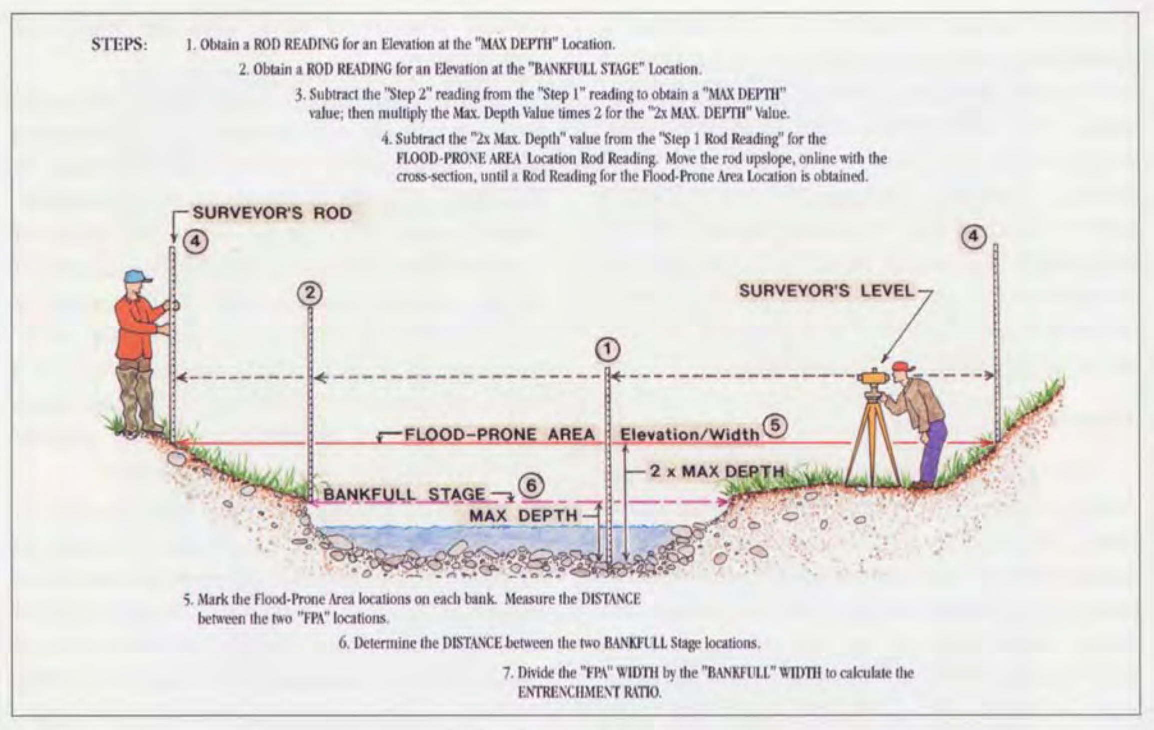
A. Nonincised Stream

B. Incised Stream (early widening phase)

C. Incised Stream (widening phase complete)

Fig. 1.24 -- Terraces in (A) nonincised and (B and C) incised streams. Terraces are abandoned floodplains, formed through the interplay of incising and floodplain widening.
In Stream Corridor Restoration: Principles, Processes, and Practices (10/98).
Interagency Stream Restoration Working Group (15 federal agencies)(FISRWG).

One method of measuring entrenchment was developed by hydrologist David Rosgen. His ***Entrenchment Ratio*** compares the stream's width at bankfull flow with its width at twice the maximum depth at bankfull flow:



STEPS:

1. Obtain a ROD READING for an Elevation at the "MAX DEPTH" Location.
2. Obtain a ROD READING for an Elevation at the "BANKFULL STAGE" Location.
3. Subtract the "Step 2" reading from the "Step 1" reading to obtain a "MAX DEPTH" value; then multiply the Max. Depth Value times 2 for the "2x MAX. DEPTH" Value.
4. Subtract the "2x Max. Depth" value from the "Step 1 Rod Reading" for the FLOOD-PRONE AREA Location Rod Reading. Move the rod upslope, online with the cross-section, until a Rod Reading for the Flood-Prone Area Location is obtained.
5. Mark the Flood-Prone Area locations on each bank. Measure the DISTANCE between the two "FPA" locations.
6. Determine the DISTANCE between the two BANKFULL Stage locations.
7. Divide the "FPA" WIDTH by the "BANKFULL" WIDTH to calculate the ENTRENCHMENT RATIO.

D. Rosgen's measure of entrenchment from Rosgen 1996.

Applying the Science of Stream Form and Function to Stream Management

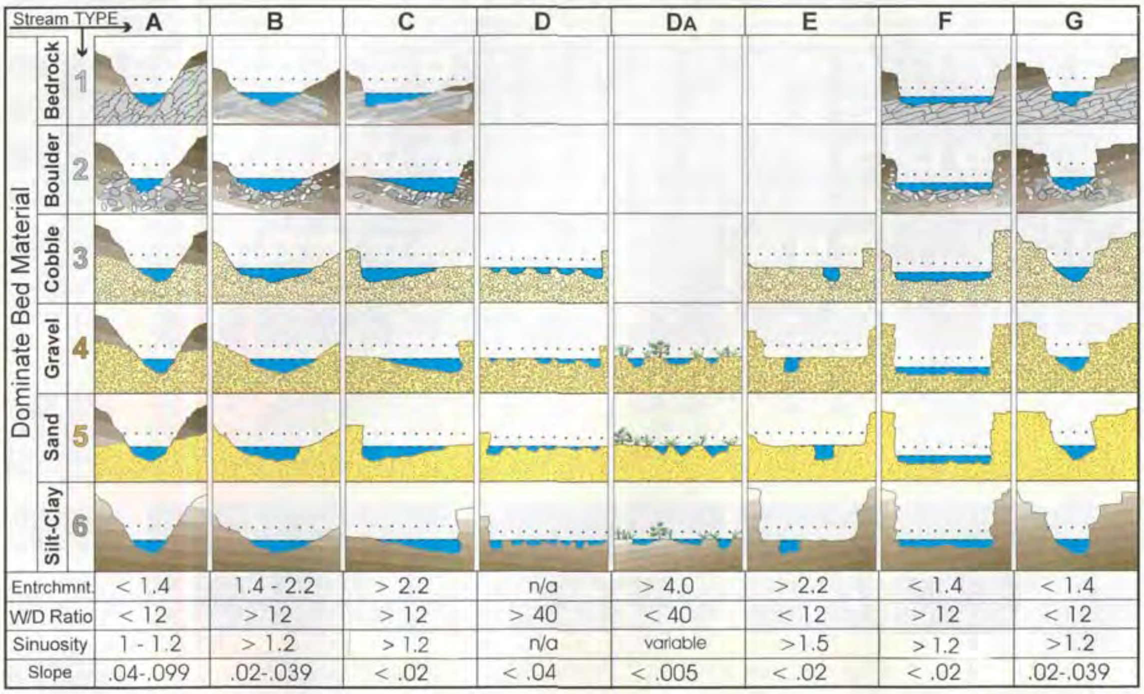
By carefully analyzing all these characteristics of stream form, stream managers can get a fairly good idea about the relative stability of a stream, reach by reach, over its whole length. By understanding the relationship between the stream's form and its function, managers can prioritize severely unstable stream reaches for treatment, and can apply different management strategies appropriately, and more cost effectively. Analysis of stream morphology can also make for more successful design of stream restoration projects; designers identify and survey stable stream reaches and then use their form characteristics as a design template for restoration projects.

Classifying Streams by their Form

One useful tool for stream managers, also developed by Dave Rosgen, is a system for classification of different stream reaches on the basis of their form. Rosgen's system gives letter and number designations to different stream types, depending on their combination of five characteristics:

1) Entrenchment ratio
2) Ratio of width to depth
3) Slope
4) Sinuosity
5) Bed material size (D_{50})

Different combinations of these characteristics result in a great number of different stream types, from A1 through G6 (see Figure XX; read letter designation across the top, number down the left side). These letter/number designations provide a sort of shorthand for summing up the form of a stream reach.



	A	B	C	D	DA	E	F	G
Entrchmnt.	< 1.4	1.4 - 2.2	> 2.2	n/a	> 4.0	> 2.2	< 1.4	< 1.4
W/D Ratio	< 12	> 12	> 12	> 40	< 40	< 12	> 12	< 12
Sinuosity	1 - 1.2	> 1.2	> 1.2	n/a	variable	>1.5	> 1.2	>1.2
Slope	.04-.099	.02-.039	< .02	< .04	< .005	< .02	< .02	.02-.039

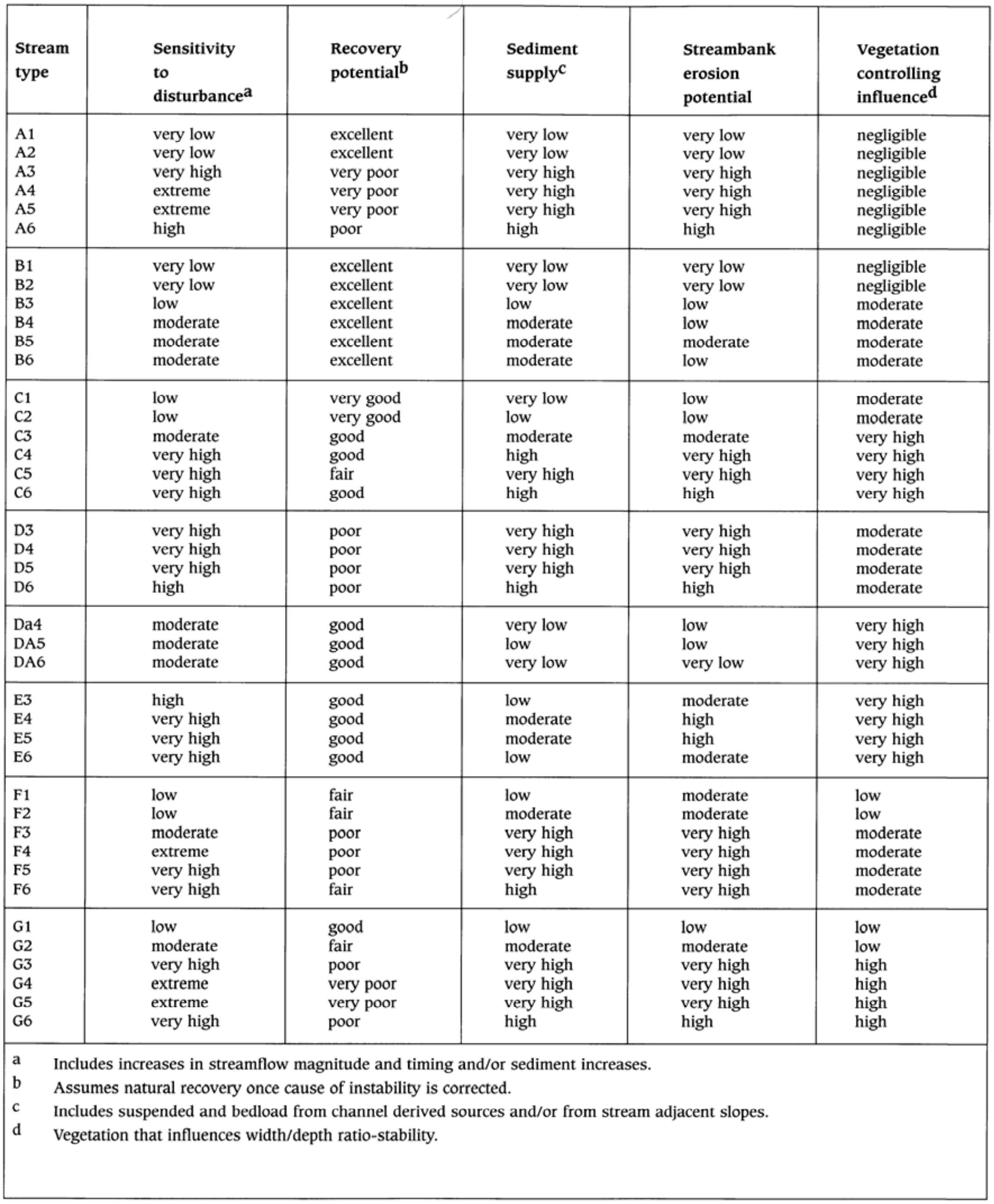
From Rosgen 1996.

So, for example, a B3 stream type has a cobble dominated bed, has a moderate amount of accessible floodplain, is more than 12 times as wide as it is deep, is moderately sinuous, and drops between 2 and 4 feet for every 100 feet of stream length. How does a B3 differ from an F3? An F3 is more entrenched, meaning that it can’t spill out onto its floodplain during storm flows, and it’s also less steep, dropping less than 2 feet for every 100 feet of stream length. How is a B3 different from a G4? Not only is the G4 more entrenched, like the F3, but also has a smaller width-to-depth ratio than a B3, and a finer, gravel-dominated bed.

As we have discussed above, each of these different forms functions a little differently from the next, especially with regard to the stream’s ability to transport its sediment effectively. By classifying the different stream types in a watershed, then, different management strategies can be targeted to each section of stream. Rosgen (1994) has created a table (see Table 2), which suggests how the different stream forms can be interpreted with regard to a number of management issues.

Throughout this management plan you will find references to these stream types. It is important to emphasize that these are only very general management interpretations, and that the stream types are included as a convenient, “shorthand” summary of the morphology of a reach. To produce reasonably reliable conclusions about how a stream reach is likely to behave in the future, the actual surveyed conditions at each reach must also be considered in the context of the conditions found in adjoining reaches upstream and downstream, historical information taken from aerial photography and additional field studies of soils, vegetation and watershed land use.

Table 2. Stream forms and their associated management issues (Rosgen, 1994).



Stream type	Sensitivity to disturbance[a]	Recovery potential[b]	Sediment supply[c]	Streambank erosion potential	Vegetation controlling influence[d]
A1	very low	excellent	very low	very low	negligible
A2	very low	excellent	very low	very low	negligible
A3	very high	very poor	very high	very high	negligible
A4	extreme	very poor	very high	very high	negligible
A5	extreme	very poor	very high	very high	negligible
A6	high	poor	high	high	negligible
B1	very low	excellent	very low	very low	negligible
B2	very low	excellent	very low	very low	negligible
B3	low	excellent	low	low	moderate
B4	moderate	excellent	moderate	low	moderate
B5	moderate	excellent	moderate	moderate	moderate
B6	moderate	excellent	moderate	low	moderate
C1	low	very good	very low	low	moderate
C2	low	very good	low	low	moderate
C3	moderate	good	moderate	moderate	very high
C4	very high	good	high	very high	very high
C5	very high	fair	very high	very high	very high
C6	very high	good	high	high	very high
D3	very high	poor	very high	very high	moderate
D4	very high	poor	very high	very high	moderate
D5	very high	poor	very high	very high	moderate
D6	high	poor	high	high	moderate
Da4	moderate	good	very low	low	very high
DA5	moderate	good	low	low	very high
DA6	moderate	good	very low	very low	very high
E3	high	good	low	moderate	very high
E4	very high	good	moderate	high	very high
E5	very high	good	moderate	high	very high
E6	very high	good	low	moderate	very high
F1	low	fair	low	moderate	low
F2	low	fair	moderate	moderate	low
F3	moderate	poor	very high	very high	moderate
F4	extreme	poor	very high	very high	moderate
F5	very high	poor	very high	very high	moderate
F6	very high	fair	high	very high	moderate
G1	low	good	low	low	low
G2	moderate	fair	moderate	moderate	low
G3	very high	poor	very high	very high	high
G4	extreme	very poor	very high	very high	high
G5	extreme	very poor	very high	very high	high
G6	very high	poor	high	high	high

[a] Includes increases in streamflow magnitude and timing and/or sediment increases.

[b] Assumes natural recovery once cause of instability is corrected.

[c] Includes suspended and bedload from channel derived sources and/or from stream adjacent slopes.

[d] Vegetation that influences width/depth ratio-stability.

References

Rosgen, D.L. 1994. A classification of Natural Rivers. Catena 22: 169-199.

Rosgen, D.L. 1996. Applied River Morphology. Wildland Hydrology, Pagosa Springs, Colorado.