# STREAM FORM AND FUNCTION

Streams and rivers are complex and dynamic (constantly changing) systems with a fundamentally basic function – to move **water and sediment** efficiently from the upstream watershed to points downstream. Despite this seemingly simple function, the processes by which streams maintain an efficient system of water and sediment delivery can seem complex and difficult to understand. The perpetual change to maintain this efficiency is known as **dynamic equilibrium**.

Understanding channel processes is important so that we are able to infer the cause and effect of channel change, and if warranted, to implement projects that work with the natural channel processes to maintain or improve the balance inherent to the system. Designing projects to work with the natural channel processes offers potential long-term benefits to both the landowner and to the stream system. Understanding opportunities, potential limitations, and probable outcomes of a range of project alternatives requires considering stream form and function.

Stream morphology (form) and stream processes (function) are closely related. The goal of this chapter is to introduce stream morphology (often referred to as **channel form** – or the physical expression of the stream on the landscape) and the interrelated stream processes (**stream function** – or the mechanisms by which the channel moves water and sediment) that allow for interpretation of the natural and anthropogenic influences that may be affecting both the form and function of stream channels.

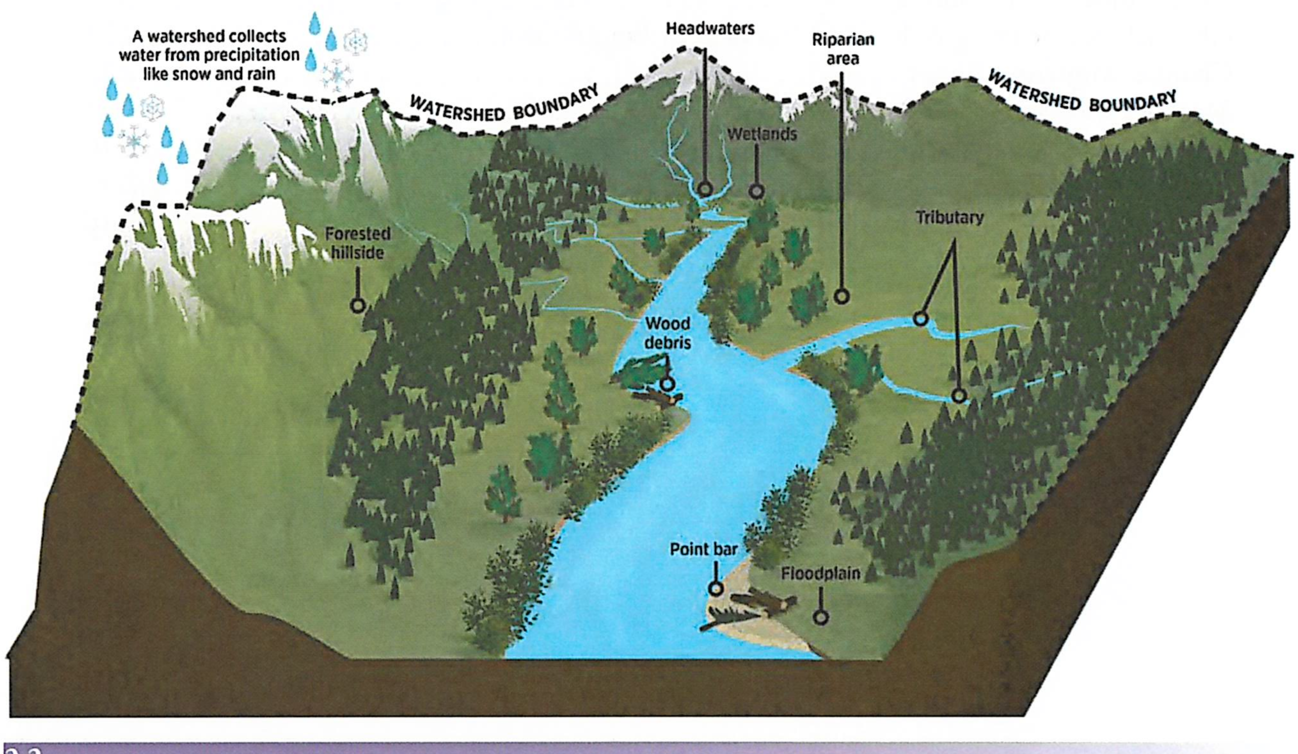
### *Contents*

# WATERSHEDS

A **watershed** is an area of land bounded on all sides that drains to a specific outflow point, such as a lake or a larger stream. The land that drains water to that outflow point is the watershed for that location. The confluence of streams and rivers is the point at which the area of a watershed expands. A watershed may consist of surface water including lakes, streams, and wetlands as well as the underlying groundwater. Watersheds can range in size from a small headwater tributary to the Missouri River drainage, Montana's largest watershed. A larger watershed is made up of several smaller watersheds. Hydrologic Unit Codes (HUC) are one way that watershed sizes are classified.

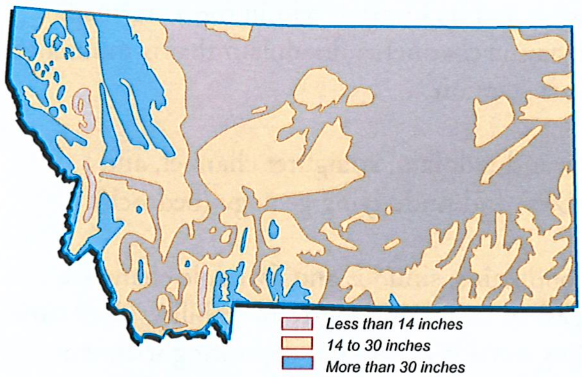
A watershed collects, stores, and transports water, sediment, and organic material that shape and define the streams and rivers within them.

- Water - From precipitation and stored in snowpack, groundwater, and vegetation until it evaporates from the ground, transpires through vegetation, or flows downstream in the form of channel runoff
- Sediment - From the upland ground surfaces and streambanks during rainfall or snowmelt runoff, deposits on pointbars and floodplains
- Organic material - From plants and animals across the watershed, provides nutrients for aquatic life and structure to stream channels in the form of large woody debris



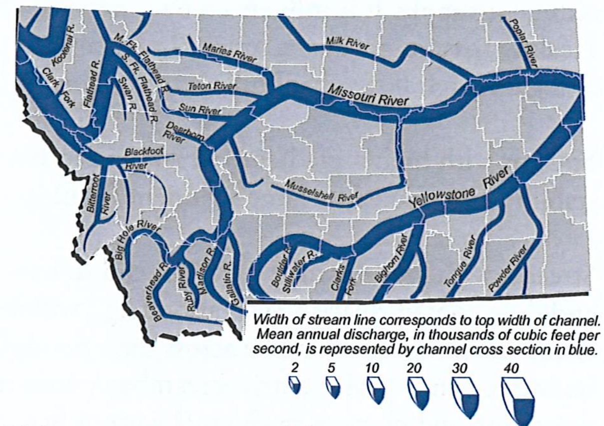
# GEOLOGY AND CLIMATE

## *Average Annual Precipitation*

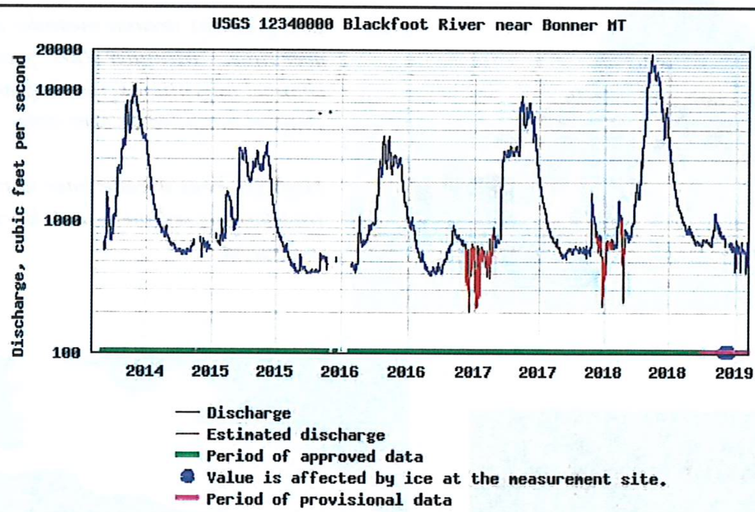



*Montana is a fairly arid state, with much of the precipitation falling in the form of snow. Spring runoff from melting snow drives a lot of channel forming processes*

## *Average Annual Runoff*




*Higher precipitation west of the continental divide results in more water flowing out of the state annually in the Clark Fork than in the Missouri River.*




*A hydrograph displays discharge of water ($Q_W$) over time. Peak discharge usually occurs in late spring, during snowmelt and spring rains. $Q_W$ tapers over the summer and becomes more dependant on stored groundwater.*

Stream channels are formed by the flow of water and sediment delivered from its watershed.

Streamflow is controlled by local climatic conditions and weather events, primarily by the amount of precipitation that falls in a watershed as rain or snow. Much of the streamflow in Montana occurs in late spring and early summer when snow melts from high elevations. These spring runoff events also move a lot of sediment and debris that drive channel form. The majority of precipitation that falls in a watershed flows out. However, some is lost to evaporation and transpiration and some is stored in groundwater, wetlands, or manmade reservoirs. The release of stored water can have significant effects on streamflow during the late summer months.

Underlying geology within a watershed dictates the path of flow, streambed and streambank material, rates of erosion, and permeability of soils. Land cover and land use dictate the quality and quantity of water leaving a watershed.

# STREAM CHANNEL FORM

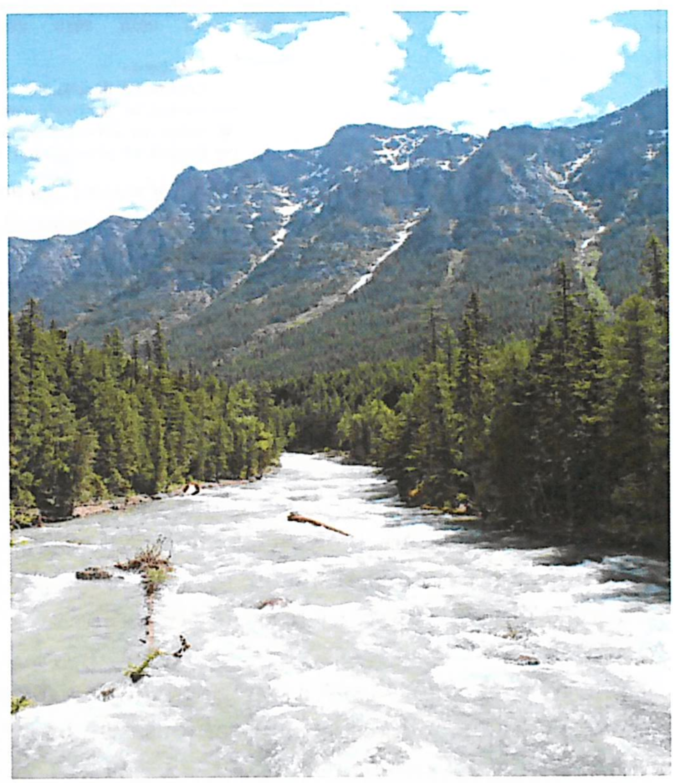
Channel form is not static but maintains a dynamic equilibrium that is in balance with its water and sediment supply. It is influenced by watershed characteristics and its location within the watershed. Healthy streams are characterized by a stable but often dynamic channel, a floodplain that is inundated at regular high flows (bankfull), and streamside (riparian) vegetation.

Streams with higher gradient (>4%) tend to have a narrower floodplain, straighter channel, and stability maintained by large sediment (boulders and cobbles) and underlying geology (bedrock).

Streams with lower gradient (<2%) tend to have broad floodplains, sinuous and dynamic channels, and deep rooted riparian vegetation (e.g., willows or sedges) to maintain long-term stability. Over time channels will naturally move across their floodplain eroding outside bends and depositing sediment on inside bends (point bars). Streambank erosion increases due to factors such as removal of riparian vegetation and changes to channel pattern (e.g., channelization).

*Low gradient streams meander across their floodplain over time. "Meander scars" provide evidence of past channel migration across its floodplain, where the old channel has filled in over time.*

*High gradient streams have narrower floodplains, transporting sediment and debris to the lower watershed.*



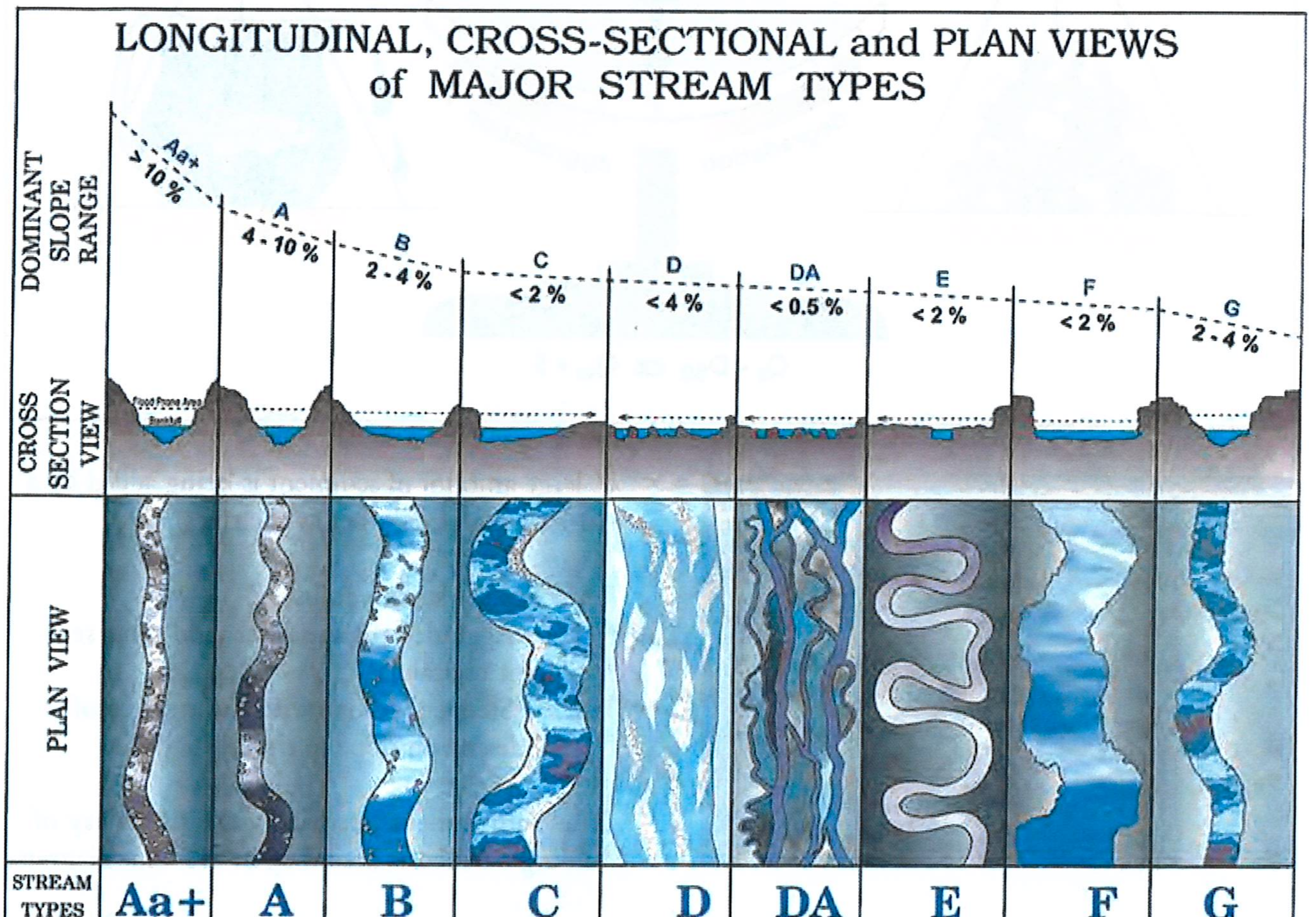
# STREAM CHANNEL FORM

## Dimension, Pattern, and Profile

Stream channel form is dictated by processes including the water and sediment discharge as well as the geologic setting. Channel form develops and maintains a dynamic equilibrium that is dictated by the supply of water, sediment, and debris from its watershed. Channel form is often expressed in three primary measures:

- **Dimension:** Displayed as a cross section view of a stream, this characteristic illustrates water depth at different stages relative to streambank height.
- **Pattern**: Displayed in plan view (from above), this characteristic illustrates a stream's sinuosity or length within a valley. Also referred to as planform.
- **Profile**: Displayed as a view of the average dominant slope range along the bankfull water surface or as a more detailed measurement of the stream bottom depth relative to bankfull water surface.

Rosgen stream types are a useful way to discuss stream and river systems defined by these three characteristics. Typical Montana streams begin high in steep mountain terrain as A type channels, gradually transitioning to B and then C channels as they reach the valley bottom. Significant training is necessary to accurately classify stream types; however, a general understanding of dimension, pattern and profile can help understand how a stream may function. A complete description and examples of Rosgen stream types can be found in Appendix 1.




STREAM FORM AND FUNCTION

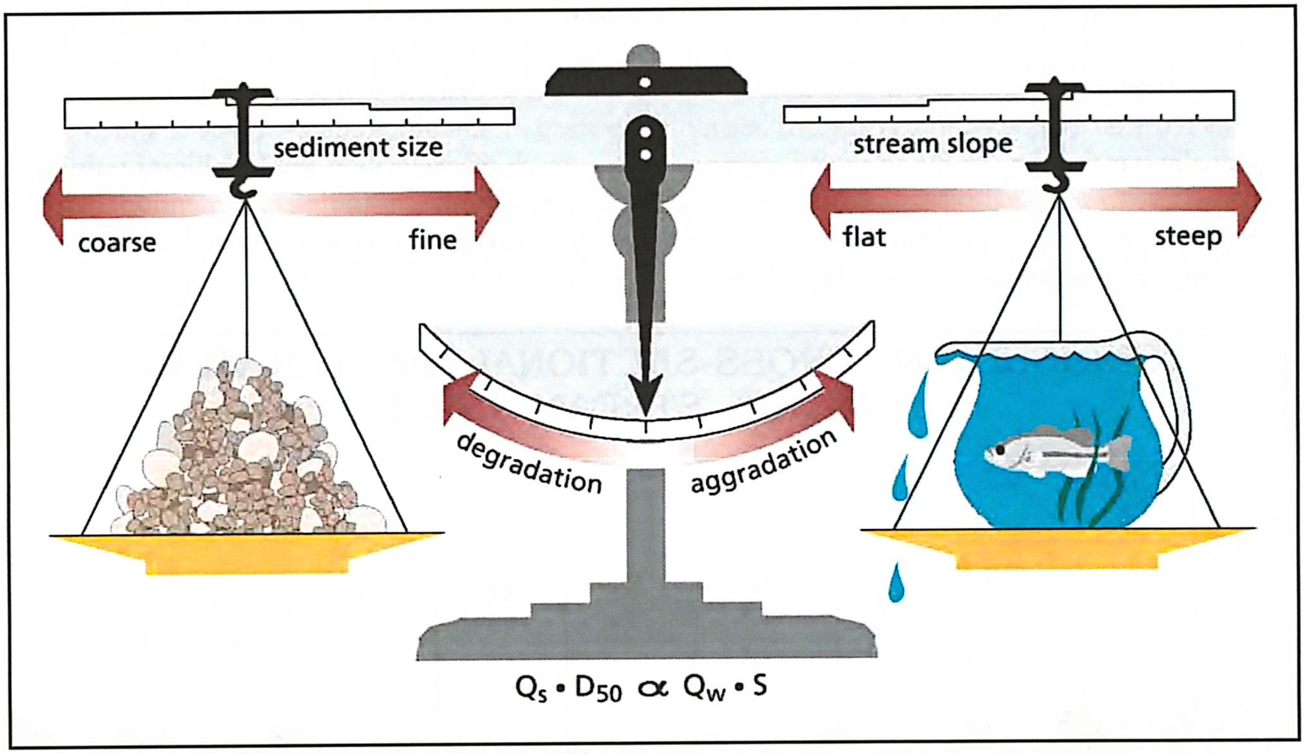
# THE LANE DIAGRAM

## Lane's Diagram – Don't Leave Home Without It!

Lane's relationship shows stream process is a function of four main factors:

- Sediment discharge (Qs)
- Sediment particle size (D50)
- Streamflow (Qw)
- Stream slope (S)

Lane's relationship suggests that a channel will be maintained in dynamic equilibrium when changes in sediment load and bed-material size are balanced by changes in streamflow or channel gradient. A change in one of these factors causes changes in one or more of the other variables, in this way a stable form tends to re-establish.



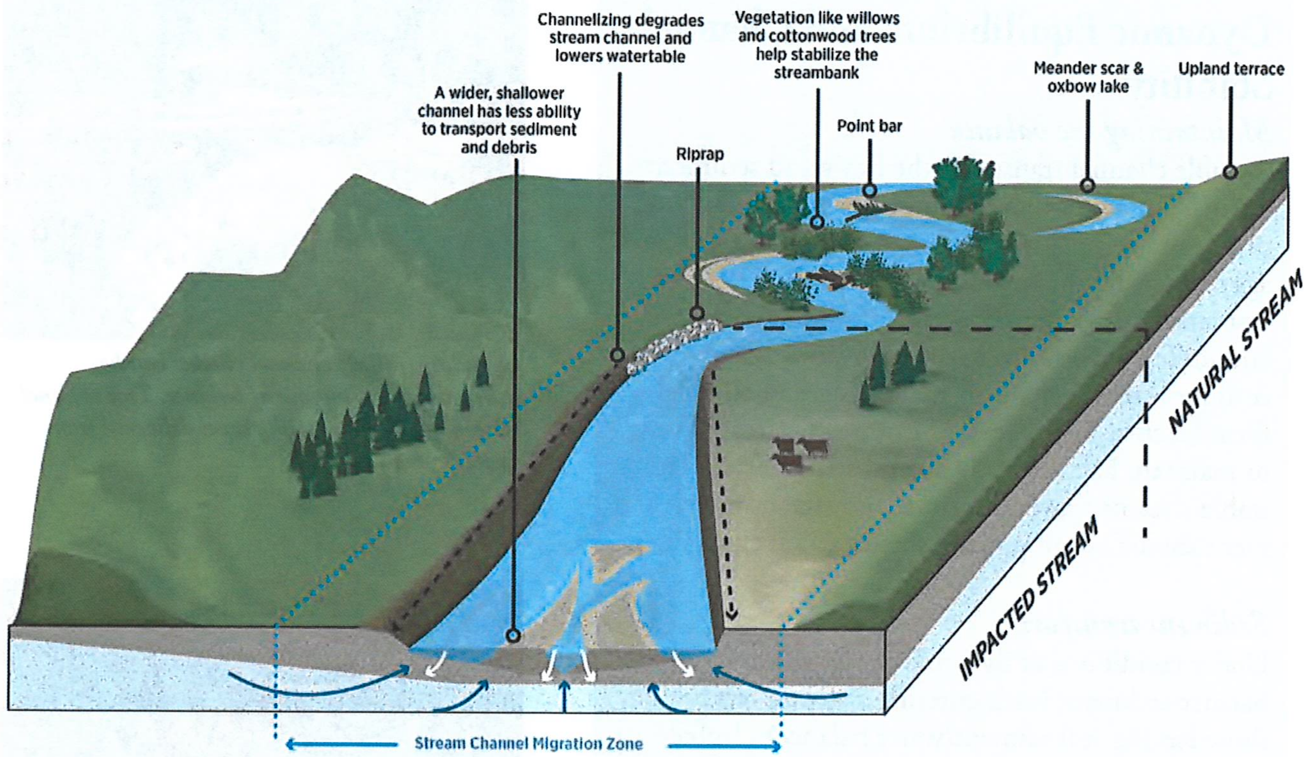

A large amount of sediment is being added by a 30-foot high bank (below the trees).

How has the stream adjusted?

1. Aggraded the meander (add more sediment to scale).
2. Steepened slope with meander cutoff (slide stream slope to right).

These adjustments are part of the river's way of finding balance as described in the Lane diagram.

# APPLYING THE LANE DIAGRAM




## Lane's Diagram – Examples of its Application

### *Channel is straightened to increase agricultural production.*

- Stream slope is now steeper due to loss in stream length
- Steeper channel moves larger sediment causing degradation or downcutting
- Water cannot access the floodplain during high flow due to downcutting causing increased bank erosion; groundwater level is lowered
- Excess fine sediment from bank erosion accumulates downstream where channel is less steep, causing the downstream channel to aggrade
- Aggradation leads to more downstream bank erosion

### *Changes in stream flow. Water is diverted year round.*

- Less water in the channel reduces the power to moves sediment downstream leading to aggradation
- Aggradation leads to bank erosion and channel widening

**CAUTION**

Maintaining riparian vegetation and stream channel connection to its floodplain are critical for ensuring long-term dynamic channel stability.

# BANK AND CHANNEL STABILITY

## Dynamic Equilibrium and Channel Stability

### *Maintaining the balance*

A stable channel transports the flows and sediment in such a manner that the dimension, pattern, and profile of the river is maintained without either aggrading (filling) or degrading (scouring). Stream systems naturally tend towards minimum work and uniform distribution of energy, or "dynamic equilibrium." This means that changes in channel form (such as bank erosion) can be the stream's way to maintain balance in water and sediment. Even stable streams move over time, and stream management should accommodate these natural changes.

### *Sediment transport*

Under conditions of dynamic equilibrium, streams balance sediment loads entering a stream reach with those leaving it (sediment/water balance). Imbalance results in either aggradation or degradation. When more sediment enters a reach than leaves it, aggradation will occur as the stream's transport capacity is exceeded. In contrast, degradation occurs when a stream has excess energy and more sediment leaves a reach than enters it. Bank instability problems are frequently apparent where streams are aggrading or degrading.

### *Channel shape varies to keep the balance*

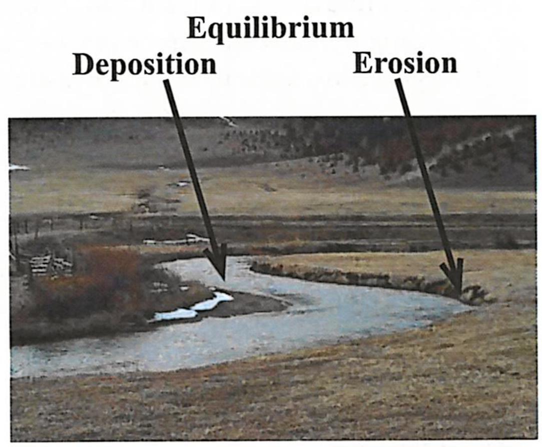
The ability of a stream to carry its sediment load largely depends on cross-section shape and channel slope. A channel cross section that maintains a stable geometry and channel slope will generate enough force to transport sediment and convey water through the reach. Channel geometry adjusts to accommodate sediment input and discharge.

### *Land use makes a difference*

Stream management can influence how the stream responds to flood events. Both human and natural factors can cause substantial changes in channel stability. Maintaining riparian vegetation is highly beneficial to stream function.

*Aggrading (filling) channel reaches can be indicative of streams out of balance. This channel has completely filled with gravel delivered from upstream reaches.*

*Degrading (scouring/downcutting) channels are common when streams have been straightened.*




*Scour and deposition still occur in equilibrium channels and can be accelerated by removal of vegetation. Note the lack of riparian vegetation on the outside meander.*

# BANK AND RIPARIAN VEGETATION

## Healthy vegetation promotes healthy river channels

### *Vegetation serves many functions*

Riparian vegetation is an integral and important component of a healthy stream environment. Trees, shrubs, grasses, and other plants with deep roots help to stabilize banks, regulate water temperature and nutrient levels, filter sediment, and provide overhead cover and food for fish and other organisms.

### *Vegetation is crucial in stabilizing some channels*

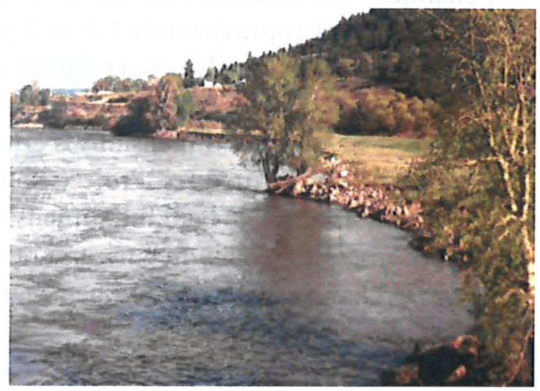
Riparian vegetation along otherwise unconfined stream channels is especially significant for maintaining a stable stream corridor. Streams with high bedload transport rates are very sensitive to upstream changes in water and sediment supply. The channel may move laterally, eroding the banks. Woody vegetation slows lateral channel movement and reduces overbank flood velocities in the floodplain.

### *Clearing riparian areas is costly*

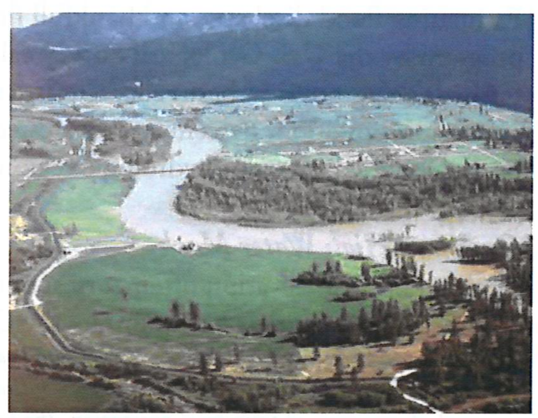
Land management activities that reduce riparian vegetation (such as conversion of riparian to lawns, fields, or livestock grazing) can result in bank erosion even during moderate flows. When this occurs, a series of channel adjustments may lead to a change in channel type, for example from a single threaded channel to a multiple threaded, over-widened, braided channel. Accelerated bank erosion and channel migration are seen in more sensitive channel types.

Good stream management should include a plan for monitoring and eliminating or reducing noxious weeds, while reseeding with native plants to protect against erosion.

*Remnant willows are found in many floodplains converted to agricultural uses.*

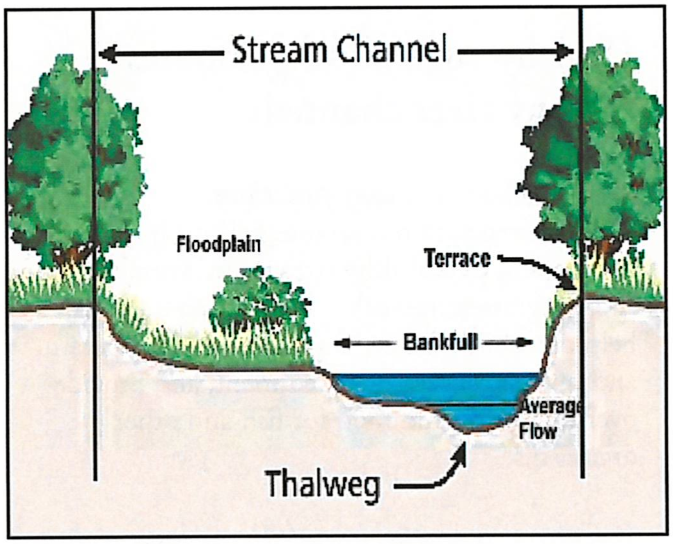


*Assisted by rip-rap, a single tree does what it can. Note the absence of mature replacement trees in the floodplain.*



*Replacement trees are colonizing the expanding point bar floodplain. The channel is moving several feet per year (20+ feet in 1997, alone), much to the dismay of the landowner.*

# FLOW CHARACTERISTICS




An understanding of both peak flow and low flow conditions is required when designing channels and in-stream structures. In particular, designing river projects around bankfull dimensions is standard practice for alluvial channels.

## Discharge and Channel Geometry

### *Bankfull Discharge*

Bankfull discharge is defined as the discharge at which channel maintenance processes are the most effective. That is, the discharge that moves sediment, forms or removes bars, forms or changes meanders, and generally does the work that results in the average characteristics of the channel. The bankfull flow has an average return interval of approximately 1.5 to 2 years, although this number can vary to 1.1 to 2 years or more. In Montana, this primarily occurs during spring snowmelt runoff.

Understanding bankfull dimensions is critical for the design of channel cross sections, culverts, bridges, and other instream structures. Projects should be designed to maintain sediment transport and convey water. Replicating stable bankfull dimension of width, depth, and slope will help ensure that sediment transport processes remain in a natural range. Substantial deviation from bankfull dimensions may lead to increased bank erosion, stream bed aggradation or degradation, and structural failure.

The average flood event (usually with a recurrence interval of about 1.5 to 2 years) is associated with channel adjustments, especially in streams with reaches that are not structurally controlled, such as portions of the Bitterroot or Yellowstone rivers. Adjustments may include lateral scour, channel abandonment (avulsion and formation of meander cut-off chutes), pool filling, channel straightening, and local changes in slope.

Estimating flood discharge and bankfull flow can be accomplished using an interactive, online software program by the U.S. Geological Survey called StreamStats. This provides flow estimates for ungaged watersheds using physical basin characteristics including variables such as drainage area, stream slope, mean annual precipitation, percentage of forested area, elevation and other factors. Predictive equations have been developed for eight hydrologic regions in Montana.

### *Ordinary High Water Mark*

Bankfull flow or elevation often corresponds to the "ordinary high water mark", which is important for jurisdictional purposes. For example, the Clean Water Act 33 CFR 328.3(e) states:

> ***The term ordinary high water mark means that line on the shore established by the fluctuations of water and indicated by physical characteristics such as a clear, natural line impressed on the bank, shelving, changes in the character of soil, destruction of terrestrial vegetation, the presence of litter and debris, or other appropriate means that consider the characteristics of the surrounding areas.***

The definition of high water mark may equally pertain to other permitting.

# FIELD INDICATORS OF BANKFULL FLOW

## USGS Gage Records

Bankfull elevation can be determined from U.S. Geological Survey (USGS) gage station records, through flood frequency analysis and development of hydraulic geometry, or from the following principal indicators:

### *Point Bar Indicators*

Point bars can be used as an approximation of bankfull elevation. The point bar is the sloping surface that extends into the channel from the depositional side of a meander. The top of the point bar is at the level of the floodplain because floodplains generally develop from the extension of point bars as a channel moves laterally by erosion and deposition over time. Depositional, flat features are the best indicator of bankfull elevation.

### *Vegetation Indicators*

The bankfull elevation is usually marked by a change in vegetation, such as the change from point bar gravel to forbs, herbs, or grass. Shrubs and willow clumps are sometimes useful but can be misleading. Willows may occur below bankfull stage, but alders are typically above bankfull. Confirm vegetational indicators with depositional features.

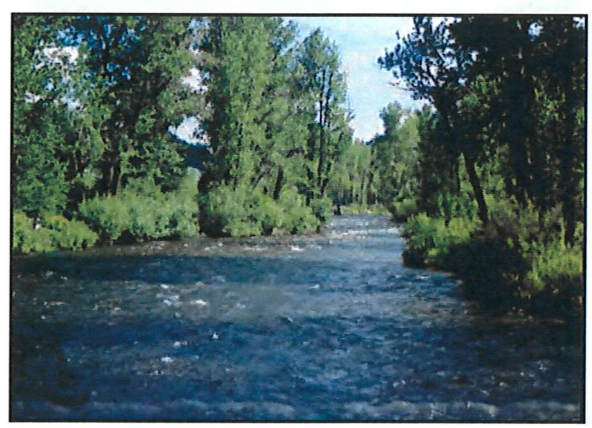
### *Topographic Breaks*

A topographic break is often evident at bankfull elevations. The stream bank may change from a sloping bar to a vertical bank, or from a vertical bank to a horizontal plane on top of the floodplain. Bankfull is often marked by a change in the size distribution of sediment and soil materials at the surface.

Generally, bankfull stage corresponds to the mean high watermark referenced under the state's 310 permit.

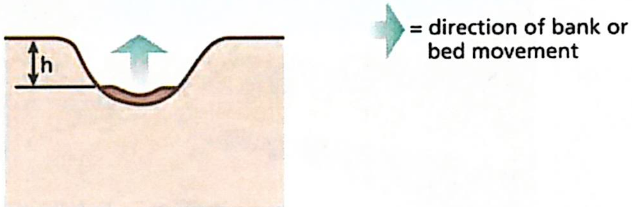

*The tops of point bars can provide a good indicator of bankfull dimensions in the field.*

*This bridge stringer is also a good indicator of bankfull. Projects should avoid this situtation, which traps debris.*

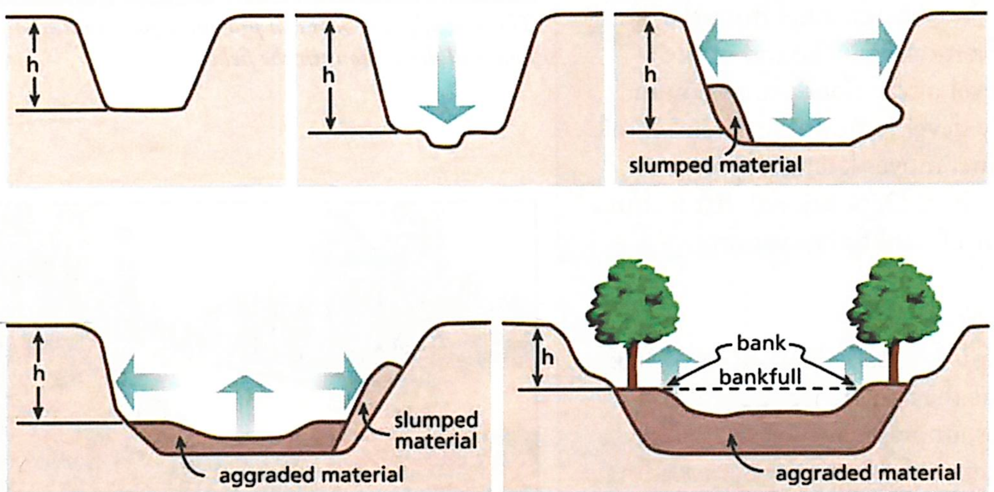


*Bankfull is not always obvious and can be difficult to visualize in some channel types.*

# CHANNEL DOWNCUTTING & RE-ESTABLISHMENT OF EQUILIBRIUM

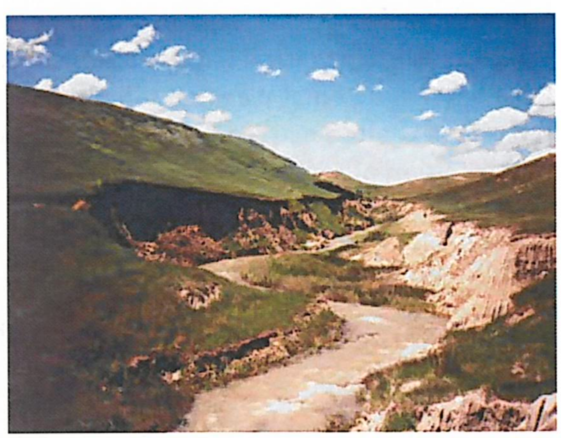



*In response to channelization, or imposed higher flows, the channel downcuts and begins to widen (E type to G to F).*




*As the channel re-establishes equilibrium at a new elevation, the new floodplain is colonized by riparian vegetation (C type to E type). This process can take decades or more to complete.*

*This channel has downcut severely due to excessive flow introduced for irrigation (Rosgen G type).*



*Downstream in the drainage, a new equilibrium channel with meanders, point bars, and floodplain is beginning to develop (F channel moving to C).*

# CHANNEL MIGRATION ZONES

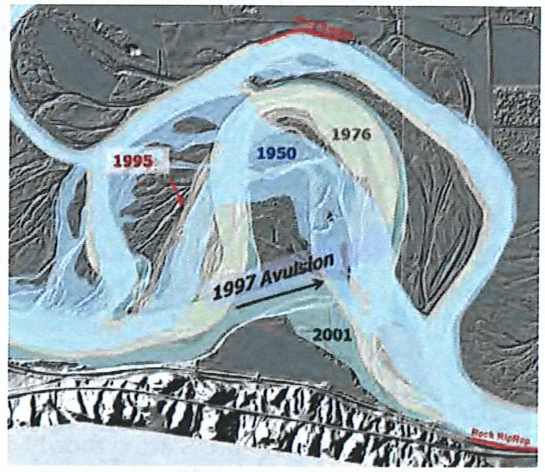
The area within which a river channel is likely to move over a period of time is often referred to as the channel migration zone (CMZ). The migration of river channels includes processes of lateral scour/deposition, avulsions, and sometimes erosion of terraces. CMZs are related to floodplain mapping.

## A Channel Migration Zone is composed of:

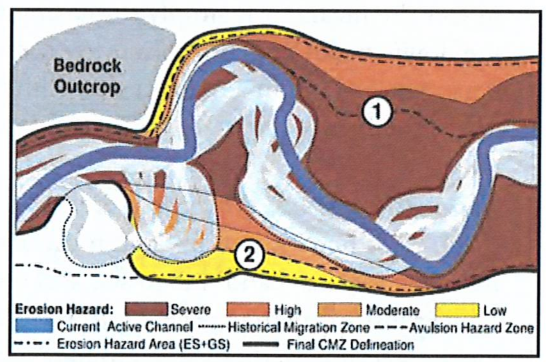
- Historic Migration Zone (HMZ) – the area of historic channel occupation, usually defined by the available photographic record. This can be thought of as the cumulative footprint of the channel as seen in available historic imagery.
- Erosion Hazard Area (EHA) – the area outside the HMZ susceptible to channel occupation due to channel migration or mass wasting. This is the area that, based on historic rates of migration, the river may occupy over the period of the CMZ.
- Avulsion Hazard Zone (AHZ) – floodplain areas geomorphically susceptible to abrupt channel relocation. These are often swales, historic channels, or bendways that are not captured by the EHA.
- Restricted Migration Area (RMA) – areas of CMZ isolated from the current river channel by constructed bank and floodplain protection features (also known as the Disconnected Migration Area, or DMA)

## Considerations for Project Design

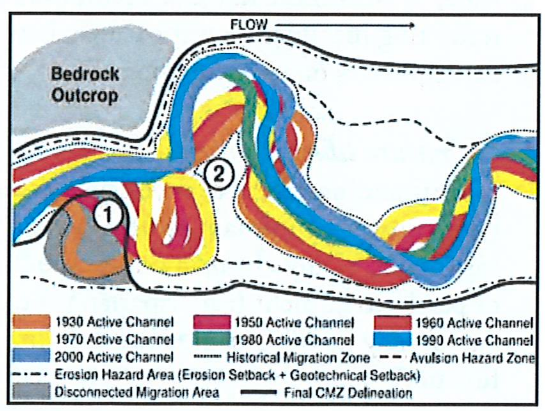
- Maintain the natural process of channel migration. Restriction of floodplains, and encroachment/development within CMZ can have unintended negative consequences for landowners and adverse impacts to river systems.
- Channel and project design should take into consideration location within the CMZ, and endeavor not to impair or encroach on natural processes in a manner that will cause adverse impacts.




*The Yellowstone River is particularly active within its floodplain. Channel migration studies are being developed for the Lower Yellowstone and Lower Missouri, among other locations.*




*Zones of varying risk are defined based on historic channel patterns, topography, and floodplain characteristics.*




*Delineation of historic patterns of channel plan form helps define the CMZ.*

# MEANDER MOVEMENT AND BANK EROSION

## Meanders evolve naturally over time

Meandering channels in rivers systems naturally evolve shape and position in the floodplain. The relative stability of meanders is a result of both environmental and often human factors. Meanders shift position in response to changes in the sediment supply/water balance, impacts from upstream reaches, land use such as grazing or clearing of floodplain vegetation, and large scale channel adjustment related to changing environmental conditions. Healthy riparian vegetation provides bank stability and slows channel migration.

### *Meanders move downstream*

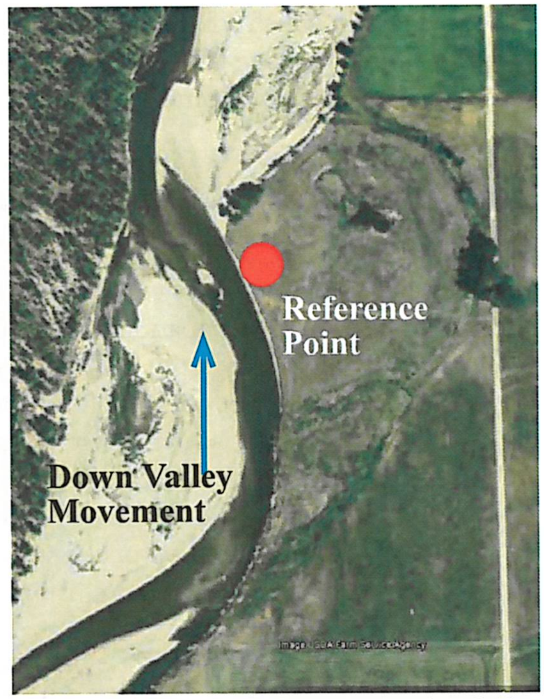
The highest erosive forces are typically at the lower third of the meander. This causes the meander to migrate in the downstream direction. To the observer standing at a fixed point downstream, this may appear that the bank is eroding laterally when in fact the meander is simply displacing its shape in the downstream direction. In other cases, meanders may develop in a manner that shifts laterally across the floodplain.

### *Restoration is sometimes possible*

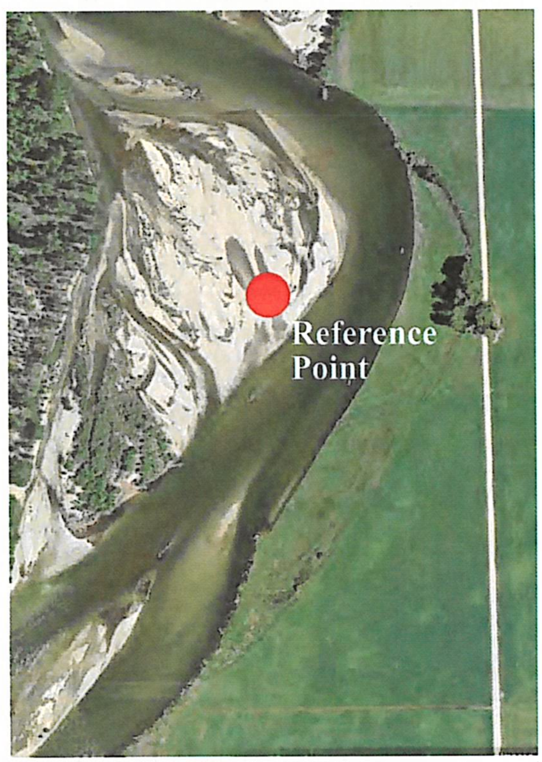
If causes of bank instability and meander movement are localized and due to site specific factors such as loss of riparian vegetation, restoration using bioengineering methods that emulate and restore natural conditions may be appropriate. If meander movement and channel adjustments are system wide, or within the range of natural variability, restricting meander movement may have negative consequences on river function.

### *Let nature take its course*

Understanding meander development and underlying causes is important to develop appropriate treatments, if any. In many cases, the "no action" or passive treatment (e.g., riparian protection, setbacks) may be the best alternative to maintain river function.




*Bitterroot River meander 1995 eroding hay field on right bank.*




*Bitterroot River meander (2014) has moved several hundred feet downstream and laterally over 20 years.*

# CHANNEL CUTOFF (AVULSION)

## Channel cutoff is a common process in alluvial channels

Highly sinuous, meandering streams often form fairly stable channels. Floodplain and bank vegetation is key in maintaining stability. Natural channel migration occasionally cuts a meander, forming an abandoned oxbow. Meander "cutoffs" are a natural part of stream channel process, but can be accelerated by poor stream management. Extensive rip-rap to constrain the channel may lead to meander cutting up or down stream. Removal of beaver can also increase the probability of meander cutting.

### *Sediment sources are important*

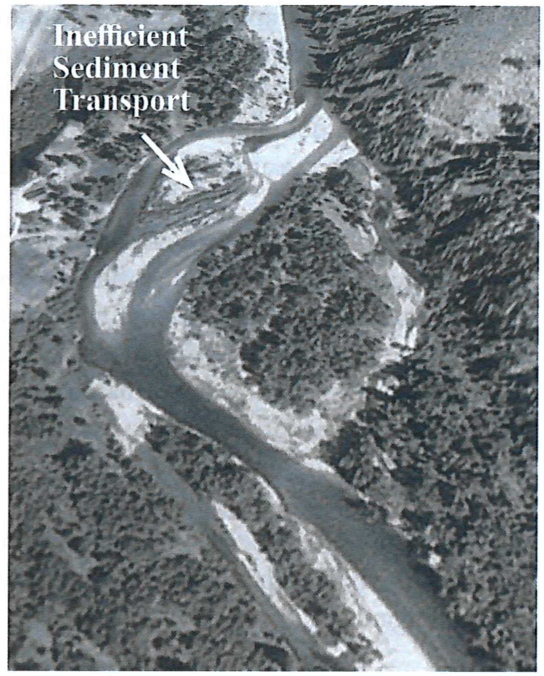
Excess sediment from upstream erosion contributes to meander cutoffs. Many meanders are cut off because stream energy is insufficient to carry incoming sediment through a bend. When a sediment plug forms at the entrance to a meander bend, the stream may cut through the floodplain or point bar.

### *Restoration requires balancing sediment and stream flows*

When a meander is abandoned, the channel responds by increasing its slope, velocity, and its ability to carry sediment. This may cause accelerated bank cutting and erosion downstream. In some cases, a stable meander pattern can be re-established, but only after developing a strategy to balance sediment and water transport through the reach.

### *Let nature take its course*

In most cases, allowing natural meander cutoffs to occur without intervention may be the best strategy for ensuring long-term river health. Meanders evolve and "age" as a natural adjustment. Although it is not always easy to determine what "natural" is, it is seldom wise to work against a river's natural process.




*Bitterroot River meander in 1995 showing sediment deposition in left channel.*


*Bitterroot River channel cutoff in 2014. Sediment has deposited on the left meander channel. Note rip-rap in left channel to protect home.*

# ROLE OF LARGE WOODY DEBRIS

In addition to water and sediment, Montana's streams and rivers transport large woody debris (LWD) from blowdown trees or channel migration into floodplain areas. LWD can have a major effect on stream form and function.

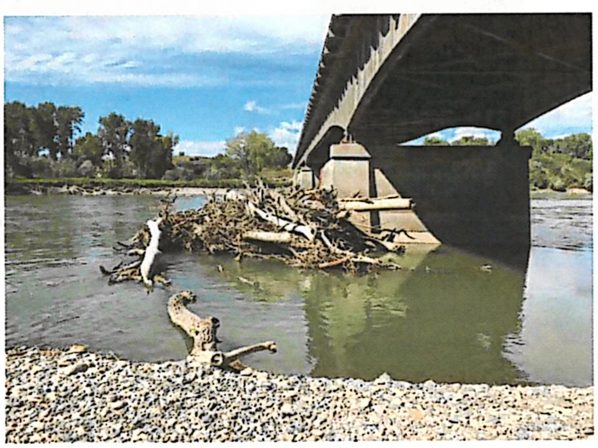
LWD accumulation is considered an important component of healthy aqautic systems. It provides stability to different channel types by capturing and retaining sediment. LWD accumulates on gravel bars or streambanks providing habitat for fish and other aquatic life by creating pools and providing overhead cover.

Over time, LWD degrades providing organic material for riparian plants and nutrients for aquatic organisms.

Loss of woody riparian vegetation and roads adjacent to streams further limits LWD sources and accumulation in streams, altering channel development and stability.

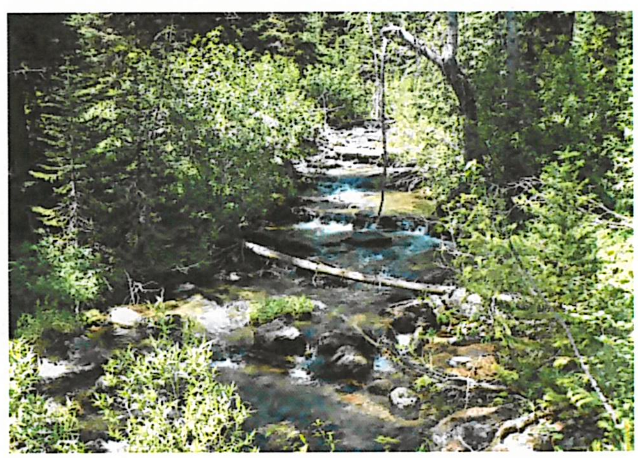
Removal of LWD by landowners, recreationists, or others can further degrade habitat and stream function.

LWD can also pose problems when it accumulates against bridges, structures, or against banks changing the flow of water to important infrastructure.



*Stream channels evolved with native tree communities. Loss of large trees such as cedars from historical logging has resulted in changes in local and downstream channel stability.*

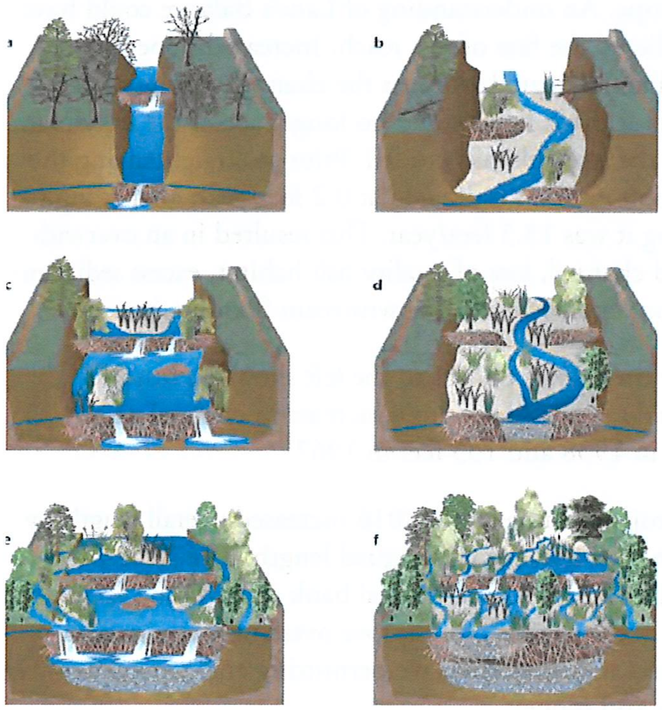
*Extensive blowdown from forest fires is an important mechanism for providing LWD, resulting in chanel shifts and creation of new habitat.*



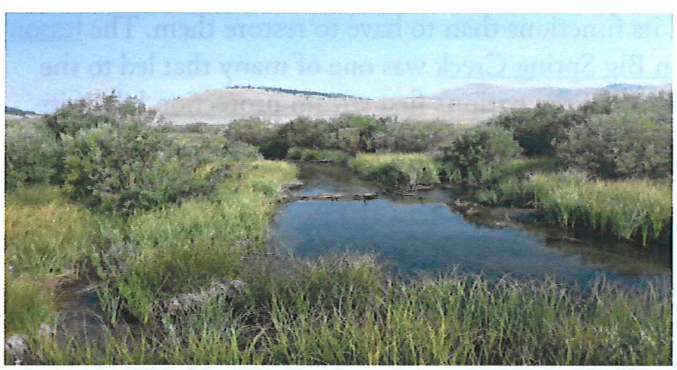
*Trees fall across steep, narrow mountain streams and maintain grade control and step pool habitat.*

# ROLE OF BEAVER DAMS

Beavers were once abundant on Montana rivers and streams. Beaver dams helped shape the landscape and continue to play an important role in maintaining stream stability, groundwater storage, and riparian plant communities on many streams. Their effects, however, vary from stream to stream. Loss or removal of beaver dams can have significant and potentially undesirable channel changes that include downcutting, lowering of the water table, and loss of associated riparian vegetation.



*Sequence of incised channel recovery as a result of colonization by beavers.*



## Beaver Dam Effects on Incised Streams

(a) Beaver will dam streams within narrow incised channels during low flows, but stream power is often too high during runoff, which results in blowouts.

(b) During high flows dams blow, and an inset floodplain forms.

(c) The widened inset floodplain results in lower stream power, enabling beaver to build wider, more stable dams.

(d) Beaver ponds fill up with sediment and are temporarily abandoned. Accumulated sediment provides good establishment sites for riparian vegetation. This process repeats.

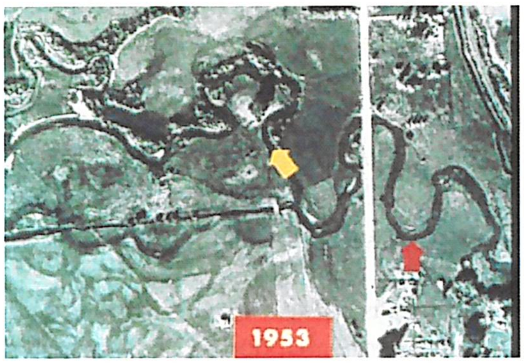
(e) Eventually, the beaver dams raise the water table sufficiently to reconnect the stream to its former floodplain.

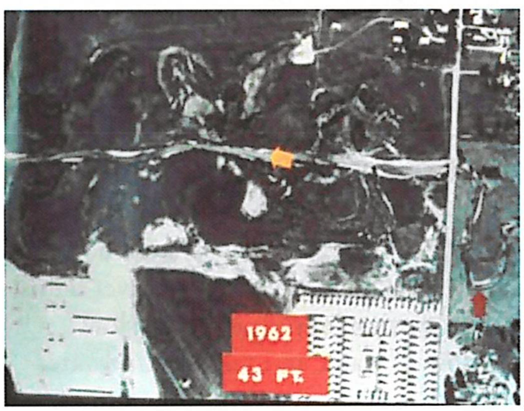
(f) Over time, vegetation and sediment fill the ponds, and the stream ecosystem develops a high level of complexity as beaver dams, live vegetation, and dead wood slow the flow of water and raise groundwater levels. The result is a diverse system of multithread channels and wetlands that saturate the entire valley.

Note that this process can take decades to occur and is susceptible to changes in management.

*the beaver abounds on these Rivers* - *Sergeant John Ordway, August 8th, 1805 while travelling west with the Lewis and Clark expedition through the Missouri River headwaters*

# CASE STUDY - BIG SPRING CREEK



*Aerial imagery sequence of Big Spring Creek. Photo to the right is from 2017 following channel reconstruction.*

Big Spring Creek is a meandering, Rosgen C type, channel that runs through Lewistown. A portion of the stream, west of highway 191 was straightened to increase agricultural production. Channelization reduced the length of this reach from 6,000 feet in 1938 to 2,000 feet in 1962. The loss in length resulted in an increase in slope. An understanding of Lane's Balance could have predicted the fate of this reach. Increased slope resulted in channel degradation. As the channel continued to degrade, high flows could no longer access the floodplain and the streambanks eroded. Prior to straighteneing the erosion rate was estimated at 0.2 feet/year; after straightening it was 13.5 feet/year. This resulted in an overwidened channel, loss of quality fish habitat, excess sedimentation, and increase in downstream flooding impacts.

The time series photos to the left show the historic straightened and resulting increase in channel width; 25 feet in 1938 and 133 feet in 1967.

A project completed in 2016 increased overall length by 60%, still short of the original length. The project recreated floodplain, used natural bank stabilization features and grade controls to improve overall functions. The project required extensive permitting and proved costly in time and money.

While the final result of the 2016 project improved the resource for fish and the community of Lewistown, it serves as a lesson in resource protection and promoting natural stream function. It is easier to maintain a stream and its functions than to have to restore them. The lesson from Big Spring Creek was one of many that led to the creation of the nation's first stream protection bill of its kind in 1963, the Montana Stream Protection Act (124 Permit), followed in 1975 by Montana Natural Streambed and Preservation Act (310 Permit).