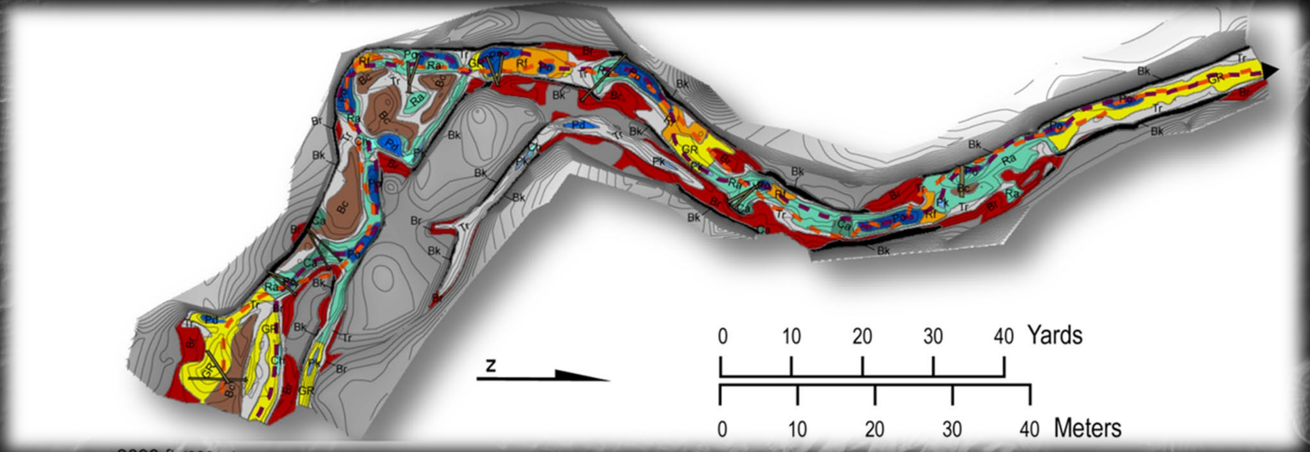
WATS 6840 – Ecohydraulics
Module 3: Fluvial Geomorphology

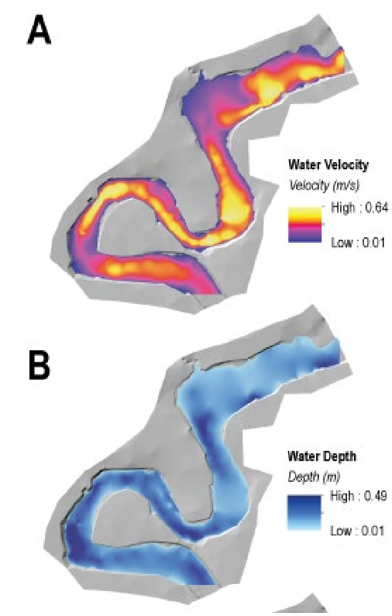


UtahState University
DEPARTMENT OF WATERSHED SCIENCES

Joe Wheaton & Nick Bouwes

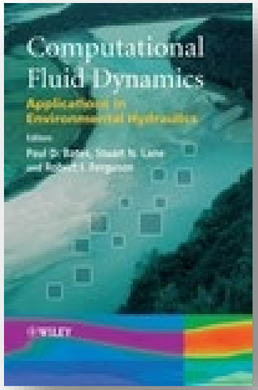
For Ecohdyraulics, What do I need to know about hydraulics?

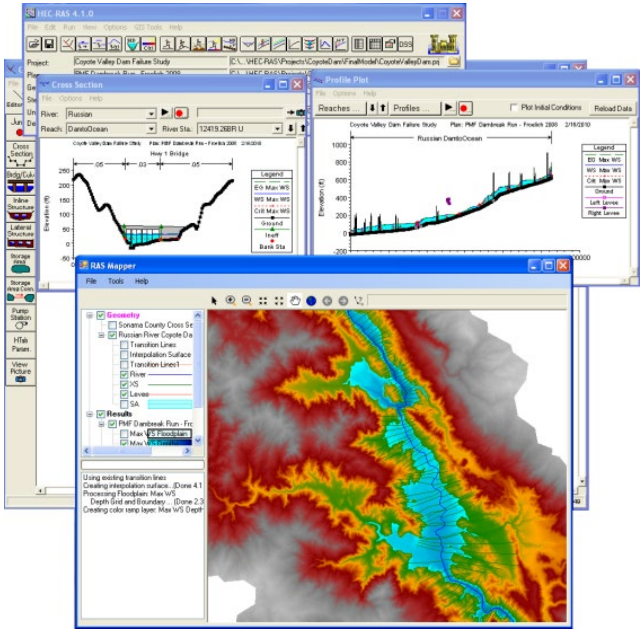
- That flow fields (comprised of patterns of velocity and depth) can be modeled from a force-balance perspective if I have:
  - **Discharge** (flow) coming in (magnitude of driving force - external)
  - **Topography** (boundary to hold and route water through channel and riverscape) – sets up driving forces from potential energy / slope - internal and "steering"
  - **Roughness** (flow resistance)
- Two-dimensional or three-dimensional models of hydraulics are necessary to resolve patterns of physical habitat "at a scale relevant to fish"
- Resolution & quality of topography are fundamental
- How good are patterns of velocity & depth?
- Am I looking at **steady-state** or **dynamic** (time varying) simulation?
- Is "discretization" of space (and time) appropriate for biotic questions being asked?

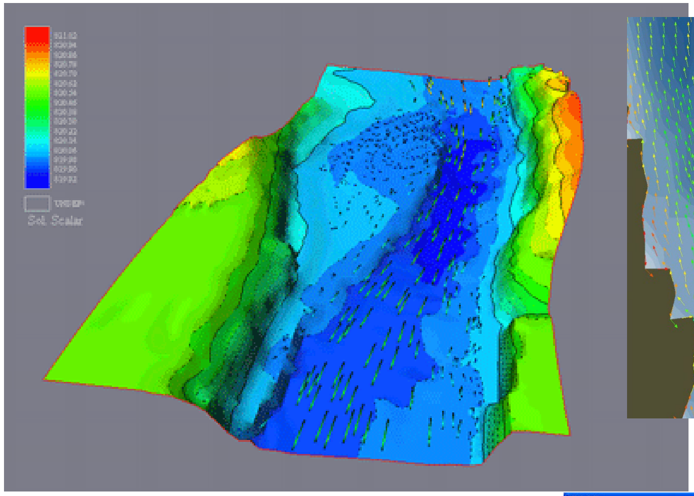


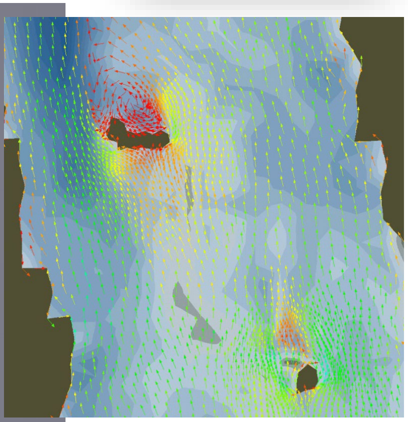
Hydraulics Is Not… But Depends On

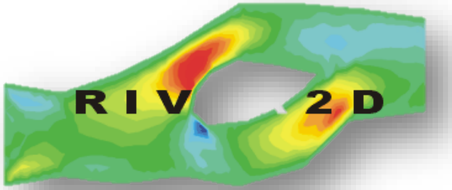
- Hydraulics is f(climate, hydrology, geology, geomorphology)
- But hydraulics ≠ climate, hydrology, geology, geomorphology
- What does hydraulics =?
- What are the primary hydraulic variables?
  - Velocity & Depth

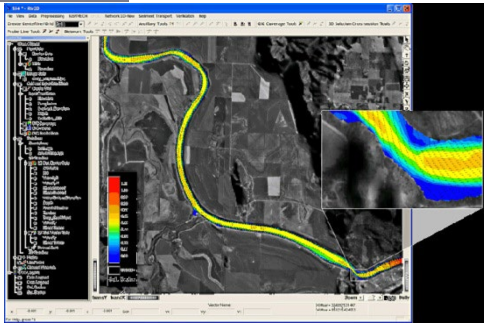








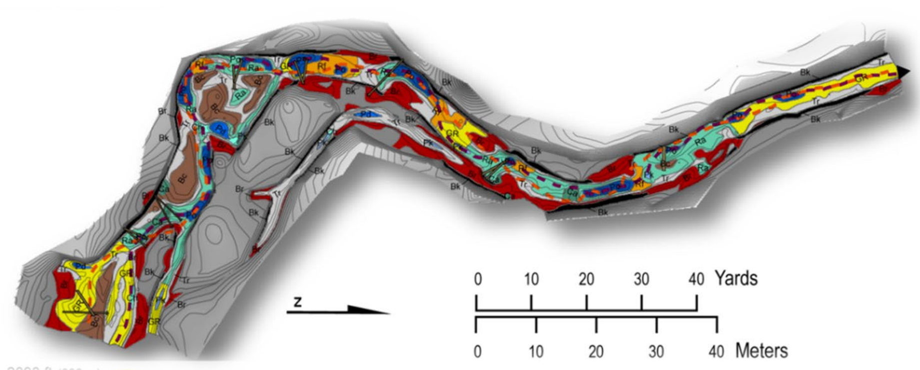




Purpose of This Lecture

Geomorphology – *The study of landforms and processes that shape them.*

- Crash-course on the 'form' side of **geomorphology**, as those forms represent physical habitat
- Help you understand the **building blocks** of riverscapes
- Introduce you to the tools and terminology to help you **map riverscapes** at both reach scale and network scale

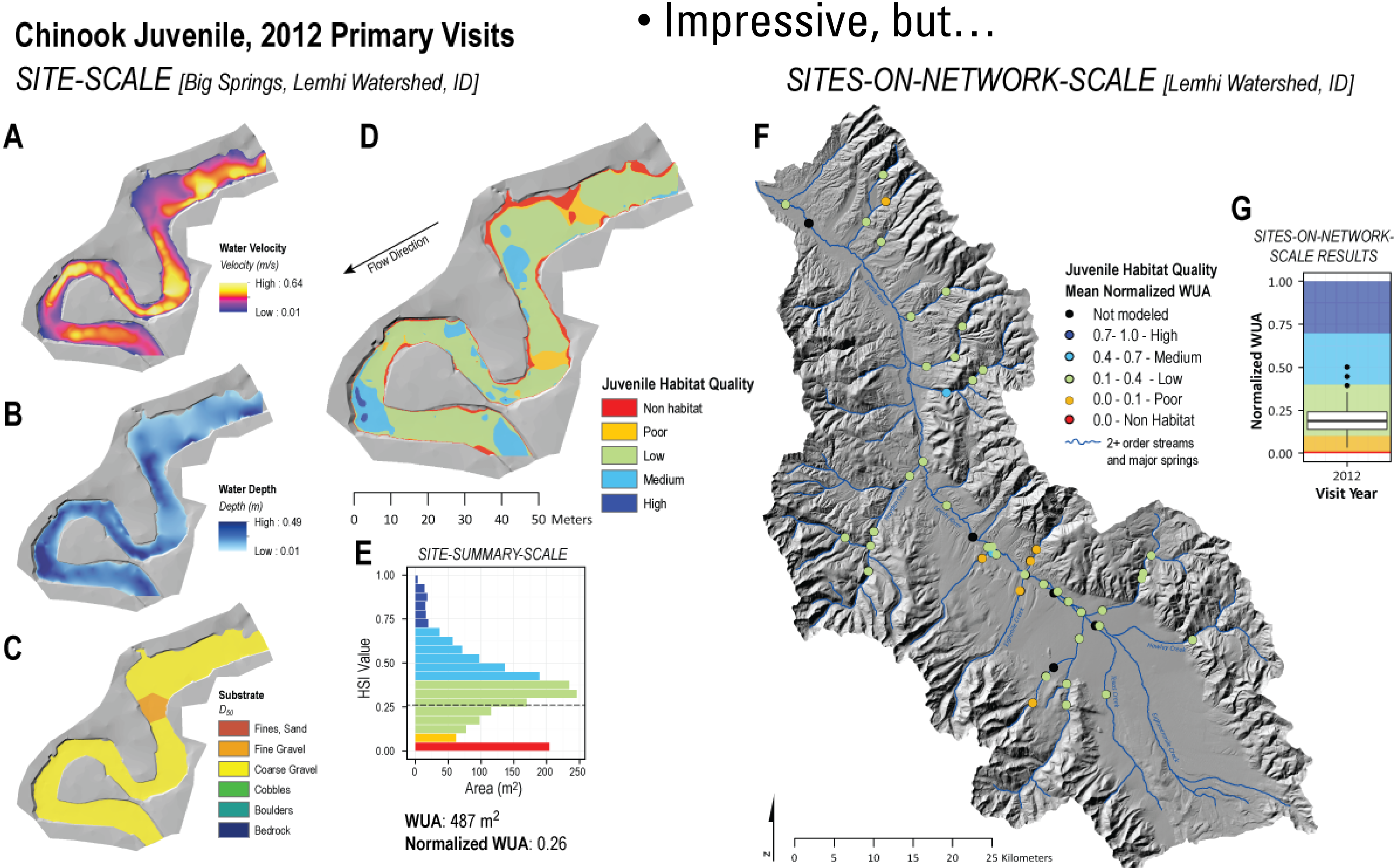


Similar Crash Course we cover in
WATS 5350 – Capstone II

Full Course in Detail
WATS 5150 – Fluvial Geomorphology

RECALL: Example Of Outputs @ Site Summary Scale

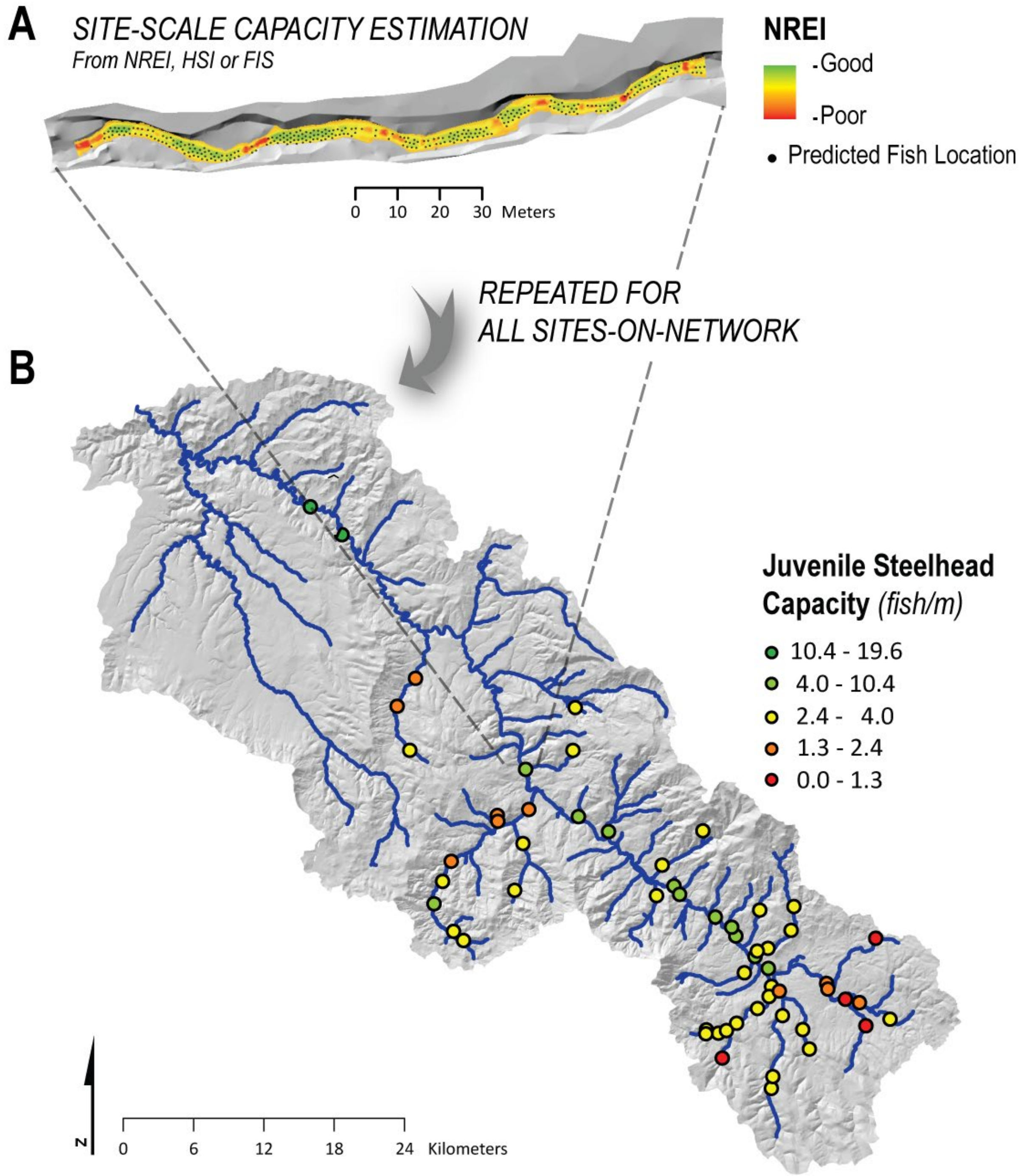
- Impressive, but…



From: Wheaton et al. (2017) ESPL – Ecohydraulics Special Issue; DOI: 10.1016/j.geomorph.2015.07.010

RECALL: All FHM

- The FHM are a vehicle for producing site-specific, species and life-stage specific capacity estimates.
- Capacity is our fish-habitat relationship currency

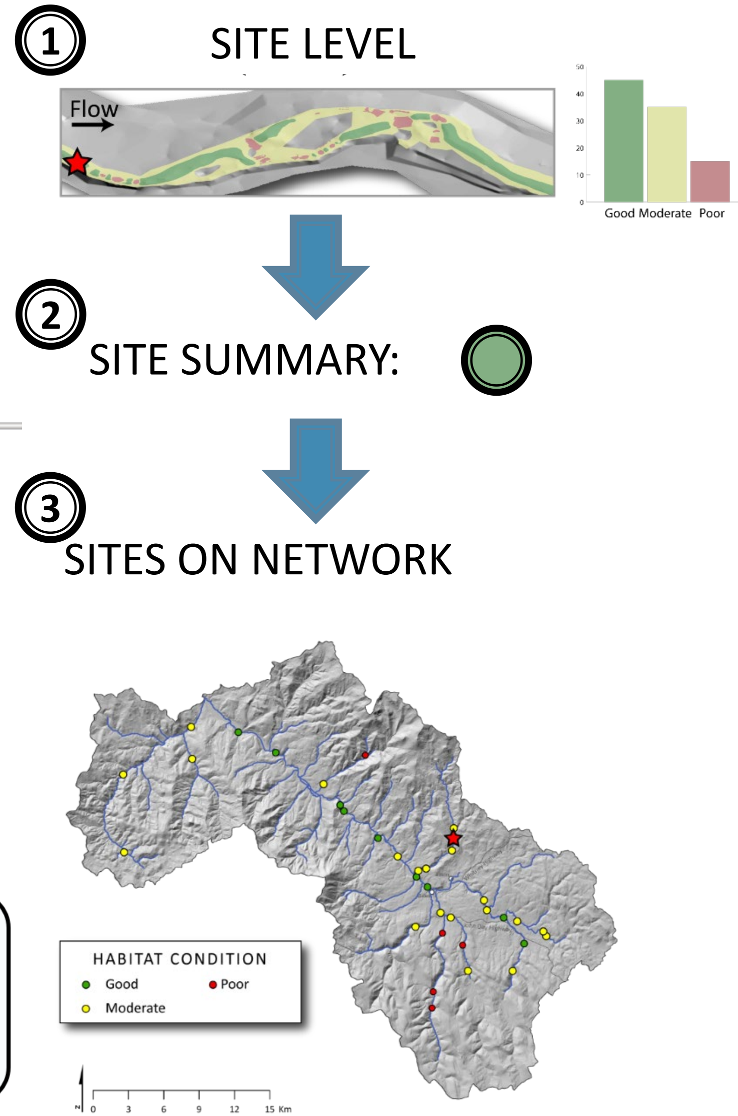


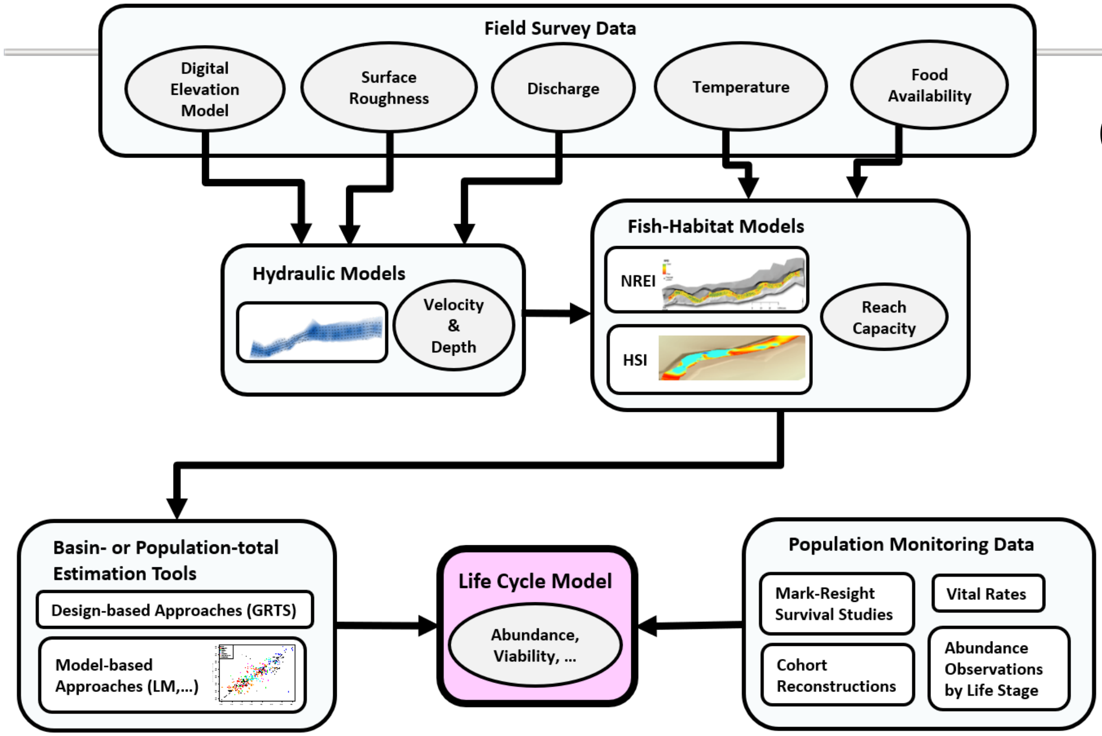
From: Wheaton et al. (2017) ESPL – Ecohydraulics Special Issue; DOI: 10.1016/j.geomorph.2015.07.010

RECALL: In the end… all that gives me is dots

@ Every Site (800+)

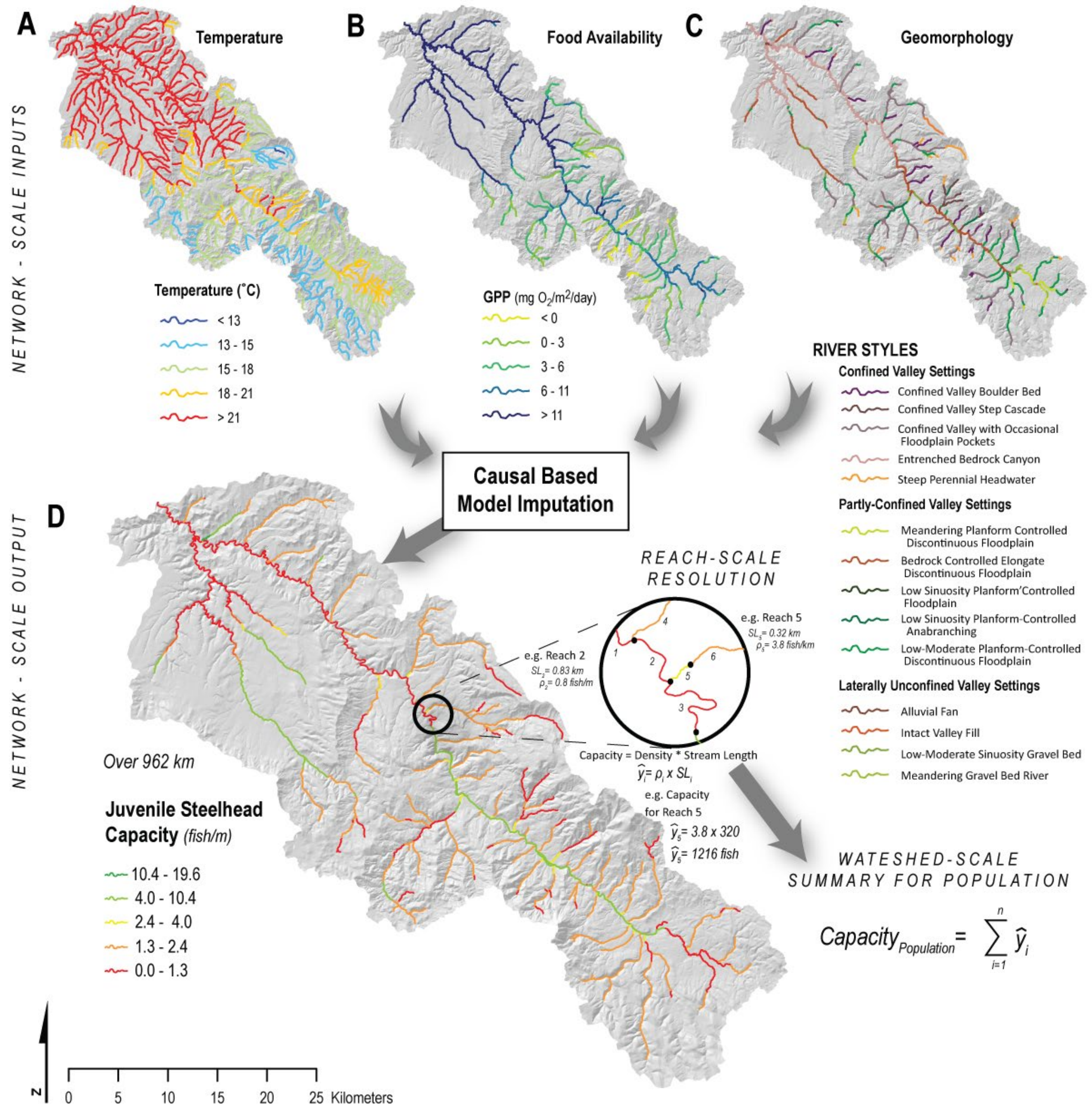
- HSI for spawning (Adult) capacity
- NREI estimates for Juvenile Capacity





RECALL:
Magic Step

- Imputation
- This step is one of our biggest development hurdles…
- Can we predict site level summary from network level output?



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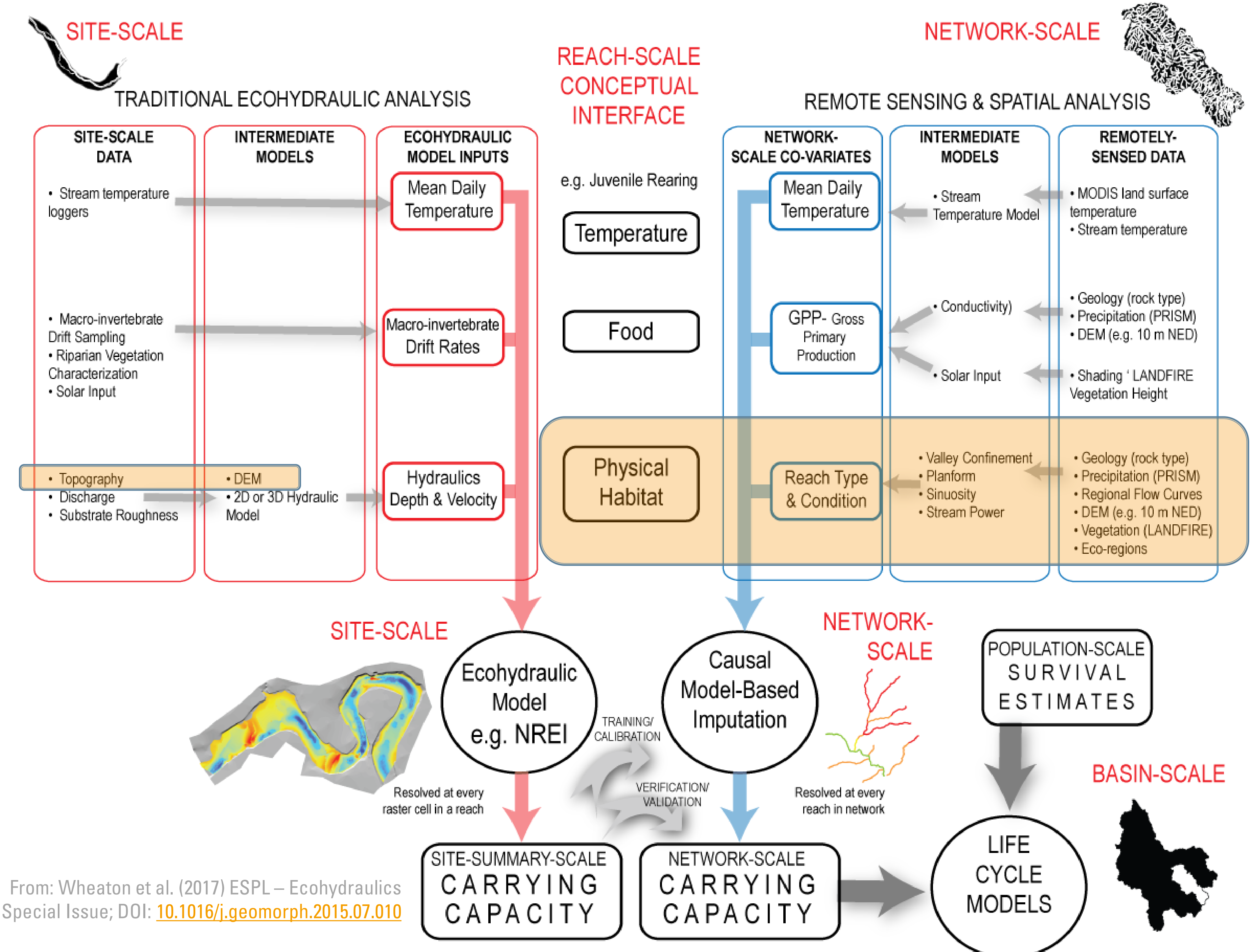

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Geomorphology & Habitat

I. Reach Types

II. Building Blocks
   - I. Margins (entry into Valley Setting)
   - II. Geomorphic Units
   - III. Structural Elements

III. Habitat

Geomorphic Reach Types?

MONTGOMERY AND BUFFINGTON

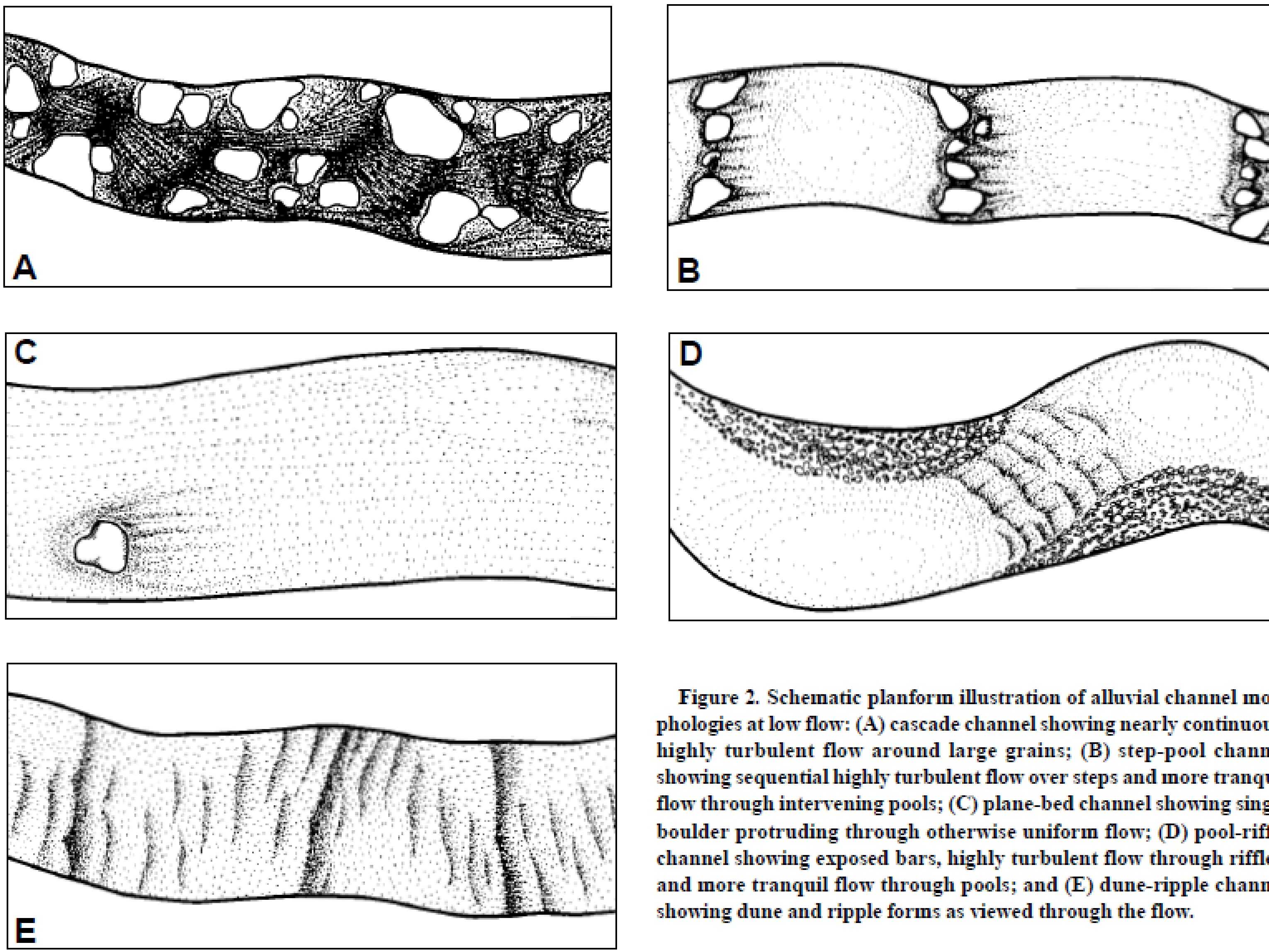


Figure 2. Schematic planform illustration of alluvial channel morphologies at low flow: (A) cascade channel showing nearly continuous, highly turbulent flow around large grains; (B) step-pool channel showing sequential highly turbulent flow over steps and more tranquil flow through intervening pools; (C) plane-bed channel showing single boulder protruding through otherwise uniform flow; (D) pool-riffle channel showing exposed bars, highly turbulent flow through riffles, and more tranquil flow through pools; and (E) dune-ripple channel showing dune and ripple forms as viewed through the flow.

Nested-Hierarchal Scales

1. 'Reach Types' or 'River Styles' are flavors of riverscapes
2. Flavor based on physiography:
   1. Climate
   2. Geology
   3. Ecology
3. River Style predicts what you will find at finer-scale (i.e. habitat)

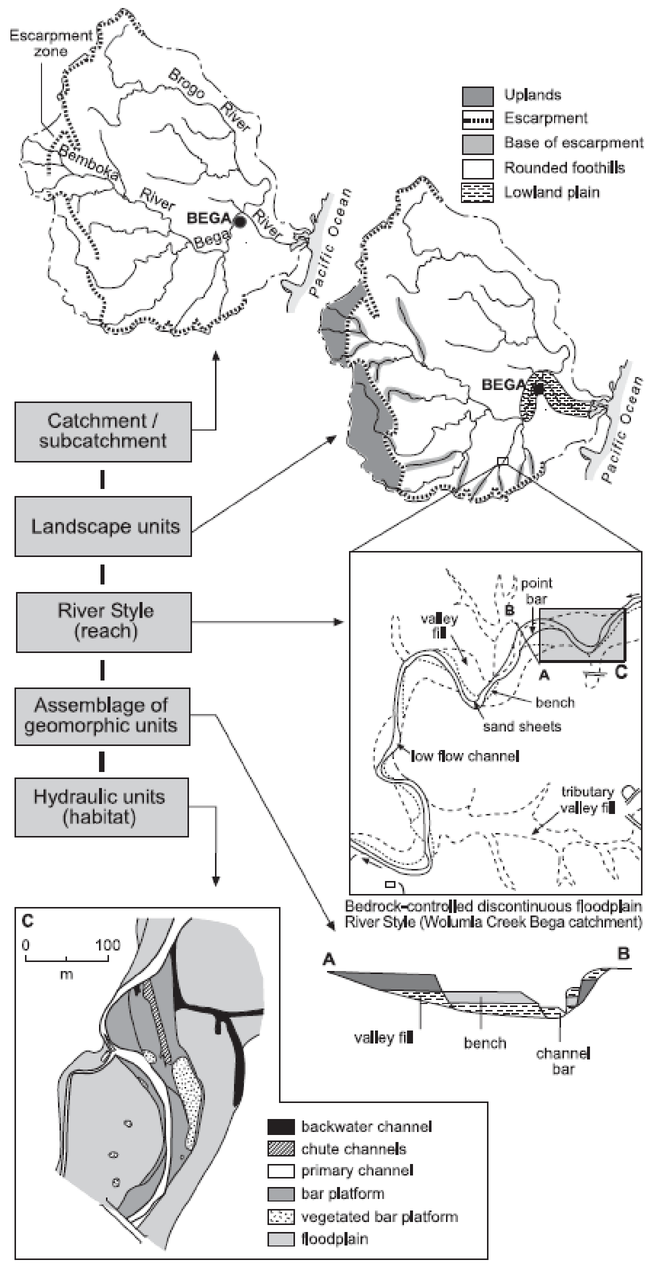
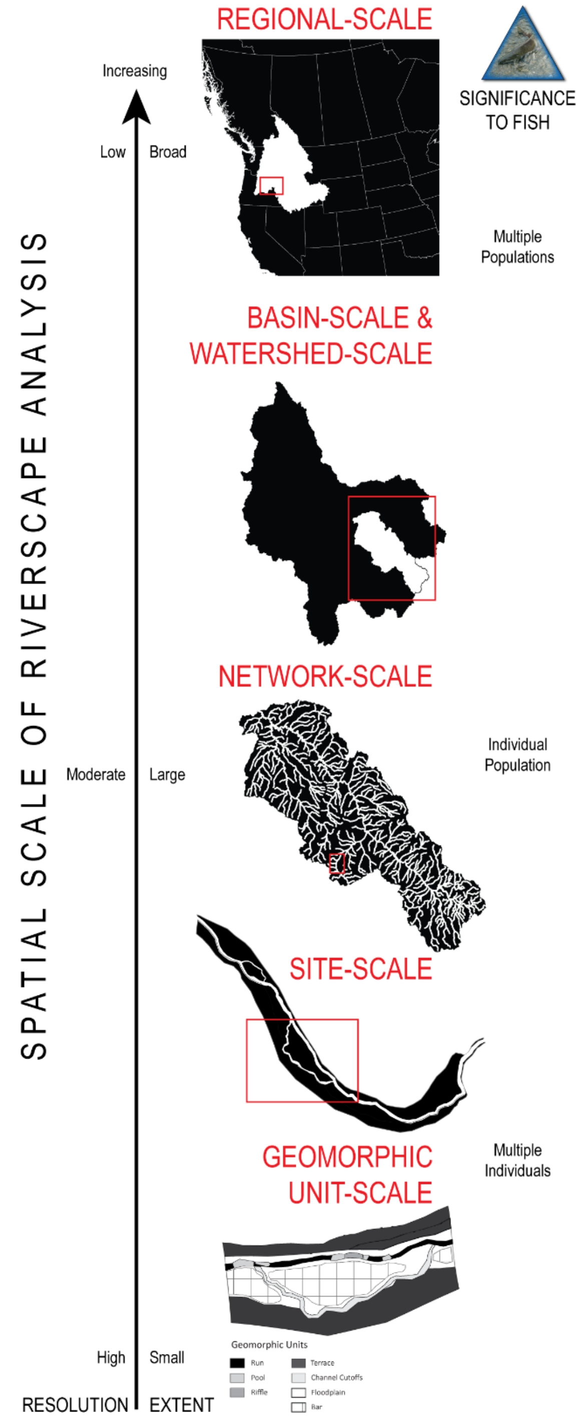


Figure from: Brierley & Fryirs (2005)

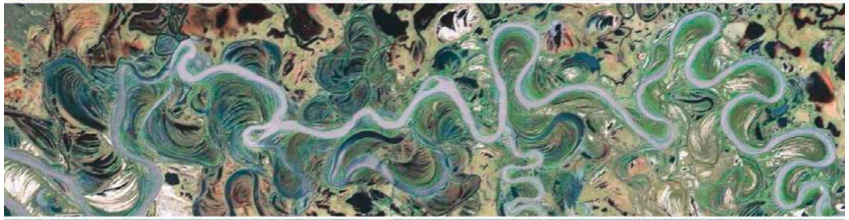


Some Different Flavors Or





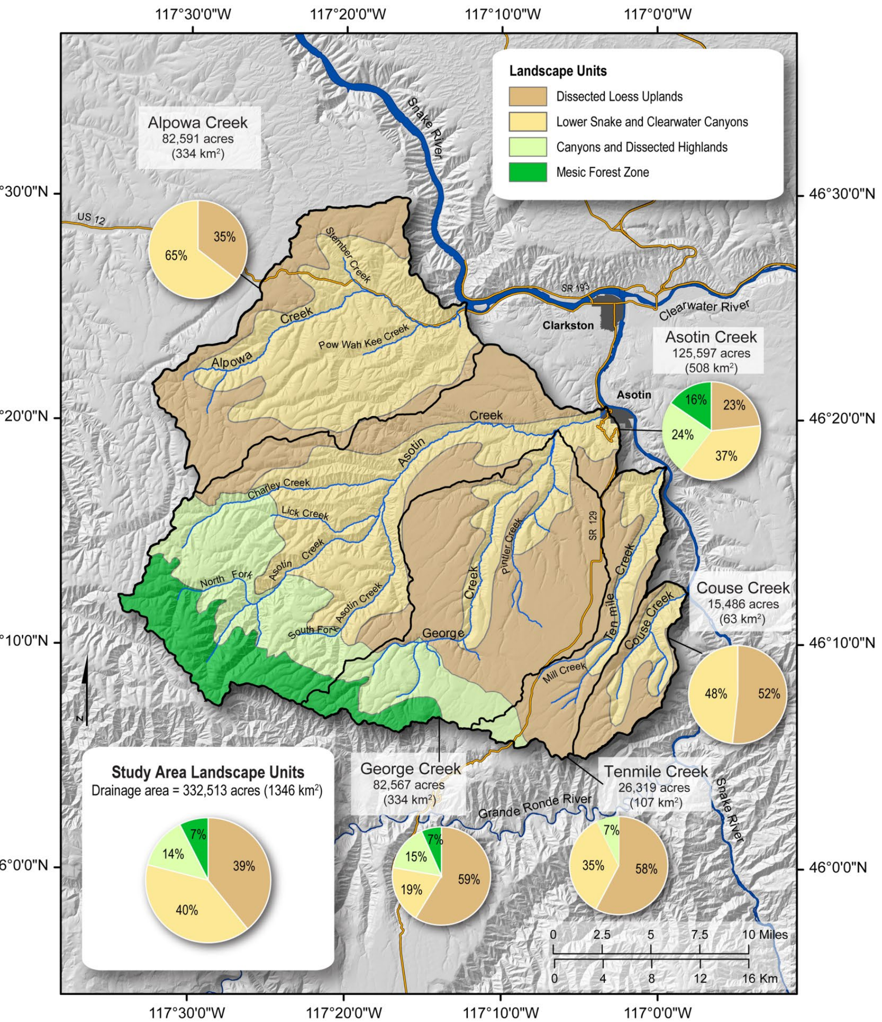






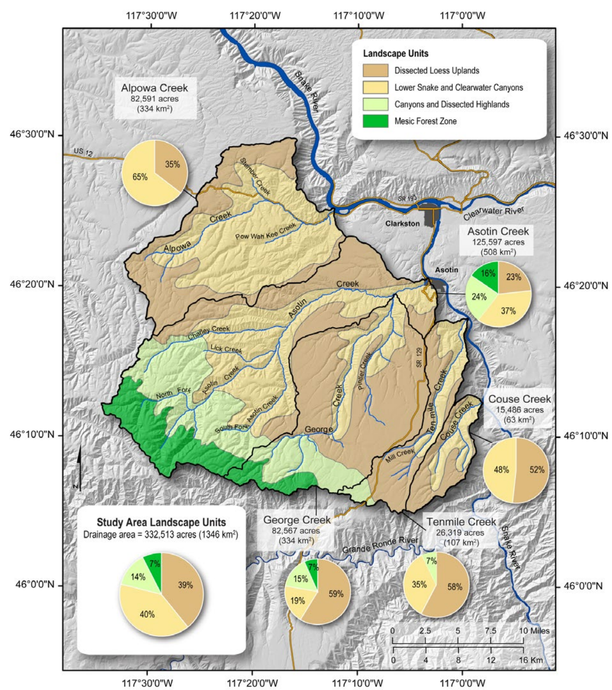
- Photos From Gary Brierley

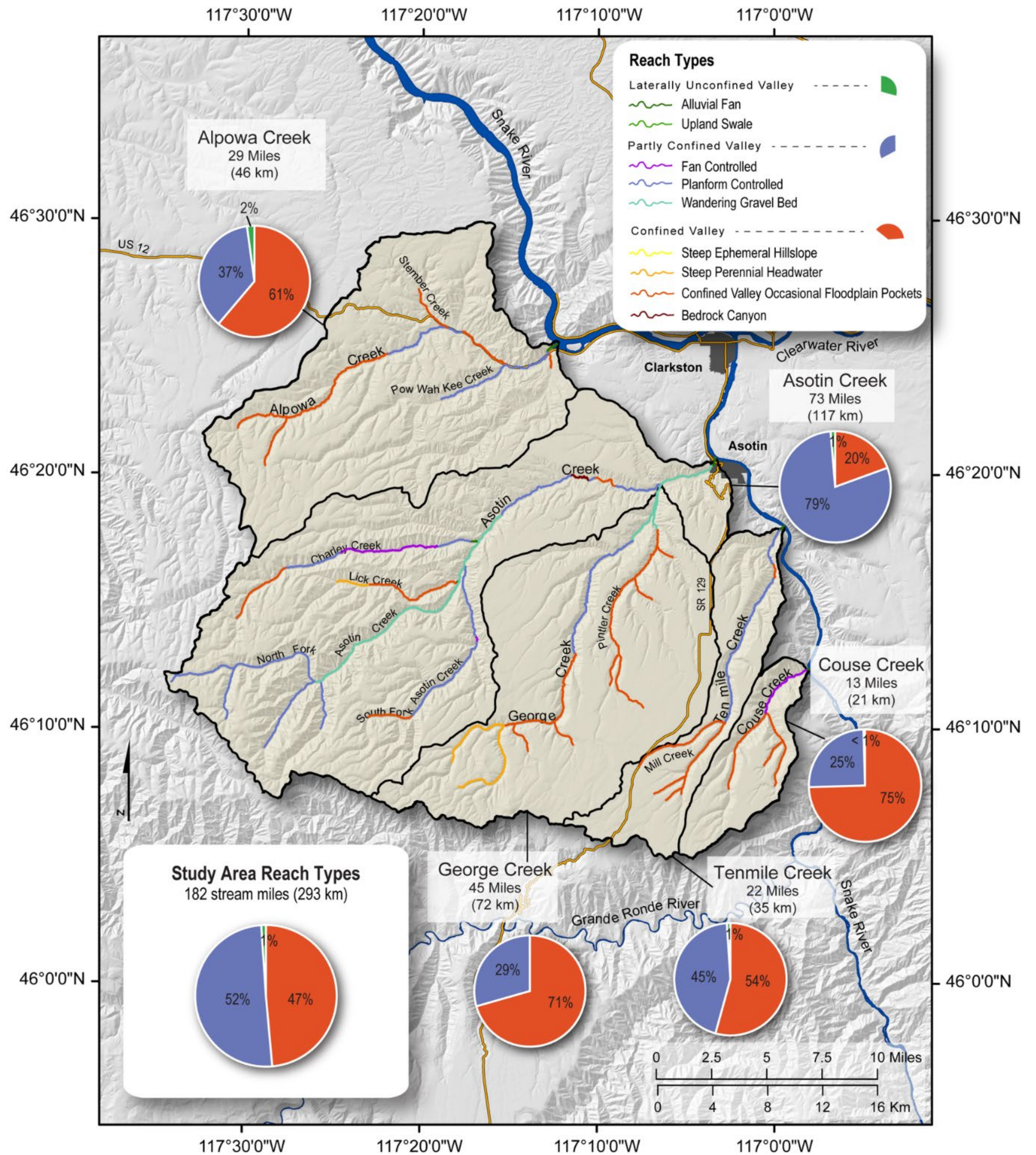
Eco-regions & Landscape Units Matter



Flavors of Stream

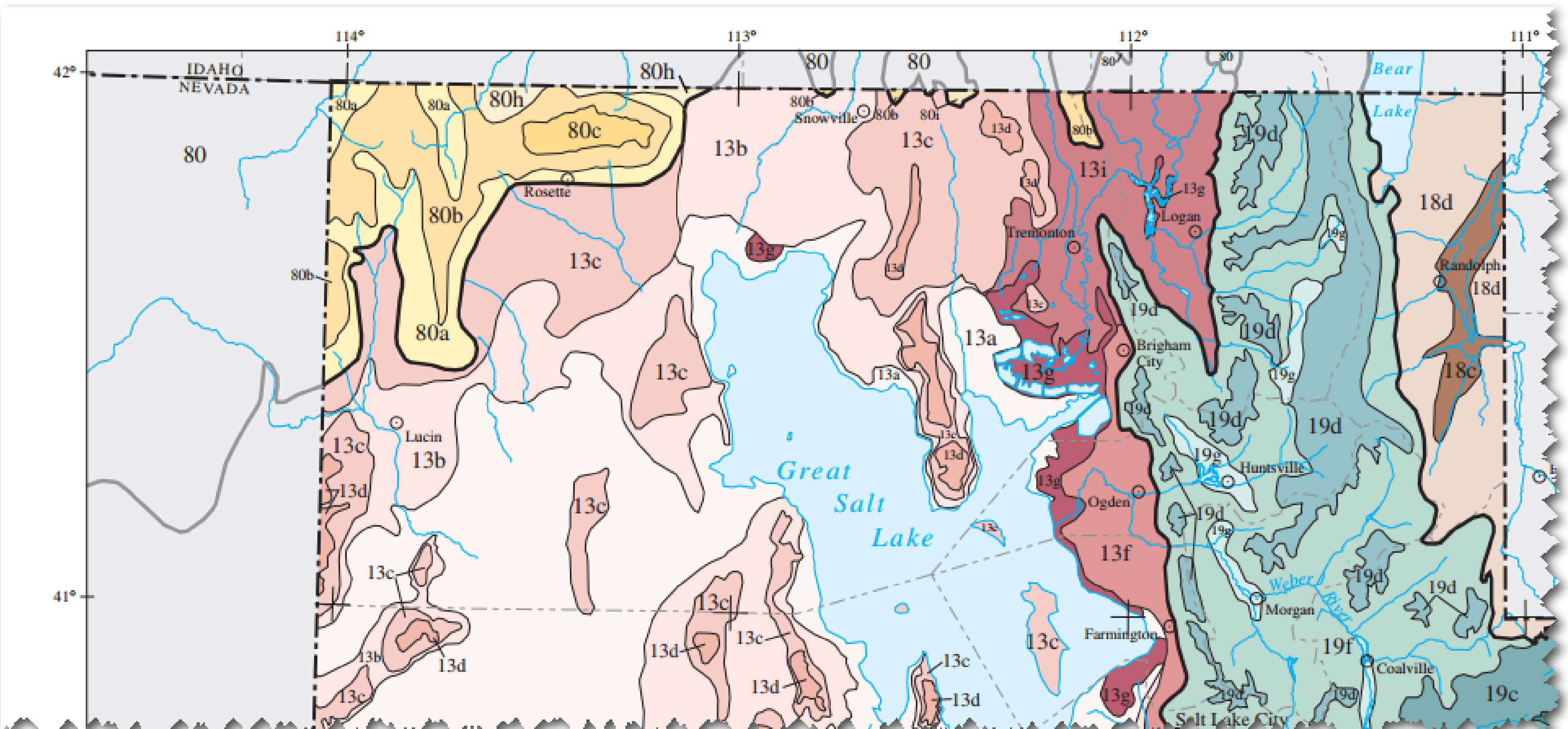
- Map systematically based on:
  - Landscape Units
  - Valley Setting





Detailed Enough to Differentiate Landscape Units

- The types of streams that occupy and cross these vary systematically



Ecoregion Descriptions… LU's?

Land use includes logging, seasonal grazing, and recreation.

19f The **Semiarid Foothills** ecoregion is found between about 5,000 and 8,000 feet elevation. Widely spaced juniper and pinyon typically occur in a matrix of sagebrush, grama grass, mountain mahogany, and Gambel oak. Maple-oak scrub is common in the north but, southward, it is gradually replaced by pinyon-juniper woodland at lower elevations and ponderosa pine at upper elevations. Overall, the vegetation is distinct from Ecoregion 19g, which is lower and drier, and Ecoregions 19d and 19e, which are higher and wetter. Livestock grazing is common. Some rangeland has been cleared of trees and reseeded to grasses.

19g The unforested **Mountain Valleys** ecoregion contains terraces, flood plains, alluvial fans, and hills. It is

19. Wasatch and Uinta Mountains

Ecoregion 19 is composed of high, glaciated mountains, dissected plateaus, foothills, and intervening valleys. It includes the extensively glaciated Uinta Mountains, the Wasatch Range, and the Wasatch Plateau. Agricultural valleys occur especially in the eastern part of the Wasatch Range. The Wasatch Front is steeper, more rugged, and wetter than more easterly parts of the Wasatch Range. Alkaline dust from the Great Basin does not buffer high elevation surface waters against acidification. Streams draining the quartzite-dominated Uinta Mountains and portions of the Wasatch Front that are underlain by acidic intrusive volcanics tend to be non-alkaline, low in nutrients, and low in total dissolved solids. Above an elevation of about 11,000 feet, alpine meadows, rockland, and talus slopes occur and are especially widespread in the Uinta Mountains. Between about 8,000 and 11,000 feet elevation, subalpine forests, Douglas-fir forests, and aspen parkland are widespread with ponderosa pine and limber pine also occurring on the high volcanic plateaus. Between approximately 5,000 and 8,000 feet elevation, juniper-pinyon woodland and mountain mahogany-oak scrub communities occur, with the latter more prevalent in the north than in the south. Lodgepole pine is less widespread and summer livestock grazing is more common than in the Middle Rockies (17). Unlike in the maritime-influenced Northern Rockies (15), Pacific indicator tree species such as grand fir are absent from Ecoregion 19. The ecoregion is used for logging, recreation, homes, and summer grazing.

19a The **Alpine Zone** occurs on mountain tops above timberline, about 11,000 feet elevation. It is especially extensive in the Uinta Mountains. Glacial features dominate the landscape. Meadows and rockland are common and contrast with the dense forests of neighboring, lower ecoregions. Ecoregion 19a is higher and receives more precipitation than other parts of Ecoregion 19. Runoff from its deep snow pack is a major source of summer water for lower, more arid ecoregions. Soils are mostly Inceptisols. They have a cryic temperature regime and are often stony, shallow, and acidic. Ecoregion 19a is used for seasonal grazing and recreation.

19b The wet, glaciated **Uinta Subalpine Forests** ecoregion contains high elevation mountains, glaciated basins that drop into deep canyons, and many lakes. Elevations range from 10,000 feet to timberline, about 11,000 feet. Ecoregion 19b is higher, wetter, more extensively glaciated, and less rugged than Ecoregion 19c but does not receive as much precipitation as the higher Alpine Zone (19a). Its Inceptisols and Alfisols support Engelmann spruce, lodgepole pine, and subalpine fir. Such subalpine forests are far more extensive in the Uinta Mountains than in the less massive Wasatch Range. Logging, seasonal grazing, and recreational activity are important land uses. Snow melt provides water to lower, more arid ecoregions.

19c The **Mid-elevation Uinta Mountains** ecoregion is glaciated and forested. It occupies the elevational zone between 8,000 and 10,000 feet in the Uinta Mountains. Here Douglas-fir, ponderosa pine, aspen parkland, and, in the north, lodgepole pine grow. The vegetation is distinct from the lower juniper-pinyon woodlands of Ecoregions 20c and 20g and the higher, wetter Uinta Subalpine Forests (19b) and Alpine Zone (19a). Ecoregion 19c's terrain is more rugged than Ecoregion 19b. Its deep canyons contain many good quality, perennial streams that are fed by meltwater from the high Uinta Mountains. They provide water to lower, more arid ecoregions.

19d The partially glaciated **Wasatch Montane Zone** consists of forested mountains and plateaus underlain by sedimentary and metamorphic rocks. It is lithologically distinct from the igneous rocks of Ecoregion 19e. Douglas-fir and aspen parkland are common and Engelmann spruce and subalpine fir grow on steep, north-facing slopes. Vegetation is unlike the lower juniper-pinyon woodland and mountain brush of Ecoregion 19f or the alpine meadows of Ecoregion 19a. Perennial streams provide water to lower, more arid regions.

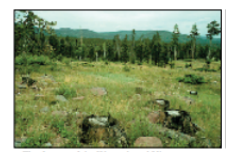
19e The **High Plateaus** ecoregion is largely capped by flat-lying igneous rock and is lithologically distinct from the Wasatch Montane Zone (19d). Elevations usually range from about 8,000 to 11,000 feet and are accompanied by differences in precipitation and temperature. The subalpine fir, Engelmann spruce, Douglas-fir, and aspen communities of plants and animals are widespread but the ponderosa pine community also occurs at lowest elevations. The vegetation is unlike the juniper-pinyon woodland and mountain brush found at lower elevations in Ecoregion 19f and the meadows that occur at higher elevations in Ecoregion 19a. Land use includes logging, seasonal grazing, and recreation.

19f The **Semiarid Foothills** ecoregion is found between about 5,000 and 8,000 feet elevation. Widely spaced juniper and pinyon typically occur in a matrix of sagebrush, grama grass, mountain mahogany, and Gambel oak. Maple-oak scrub is common in the north but, southward, it is gradually replaced by pinyon-juniper woodland at lower elevations and ponderosa pine at upper elevations. Overall, the vegetation is distinct from Ecoregion 19g, which is lower and drier, and Ecoregions 19d and 19e, which are higher and wetter. Livestock grazing is common. Some rangeland has been cleared of trees and reseeded to grasses.

19g The unforested **Mountain Valleys** ecoregion contains terraces, flood plains, alluvial fans, and hills. It is affected by cold temperatures and has a short growing season. Potential natural vegetation is mostly Great Basin sagebrush. It is distinct from the juniper-pinyon woodland and mountain mahogany-oak scrub of Ecoregion 19f. Today, irrigated cropland, irrigated pastureland, and rangeland are common. Turkey farms, feedlots, and dairy operations occur locally. Land use contrasts with that of nearby high plateaus and mountains.

Cutthroat trout are found in the streams of the Wasatch and Uinta Mountains (19).
Photo: Bob Lillie

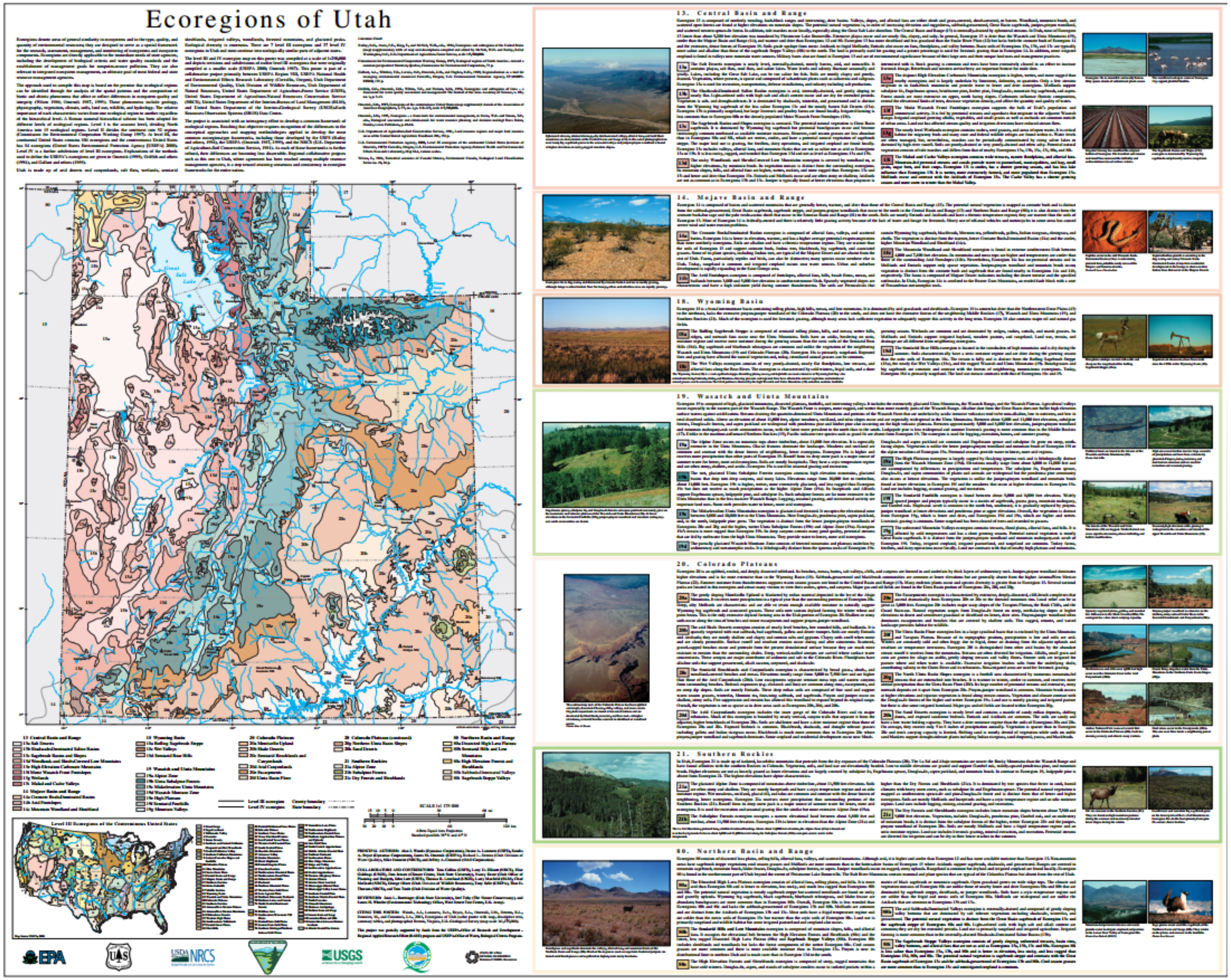
High areas near treeline receive large amounts of precipitation and have been extensively glaciated. Cirques, tarns, moraines, and rockland are common and are used for recreation and seasonal grazing.



The forests of the Wasatch and Uinta Mountains (19) are logged. Timber harvest can cause significant erosion, stream turbidity, and habitat modification.

Seasonal, high elevation cattle grazing is widespread in the meadows and forests of the upper Wasatch and Uinta Mountains (19).

Ecoregions of Utah – Level IV



- ftp://ftp.epa.gov/wed/ecoregions/ut/ut_front.pdf

River Styles Tree & Fruit?

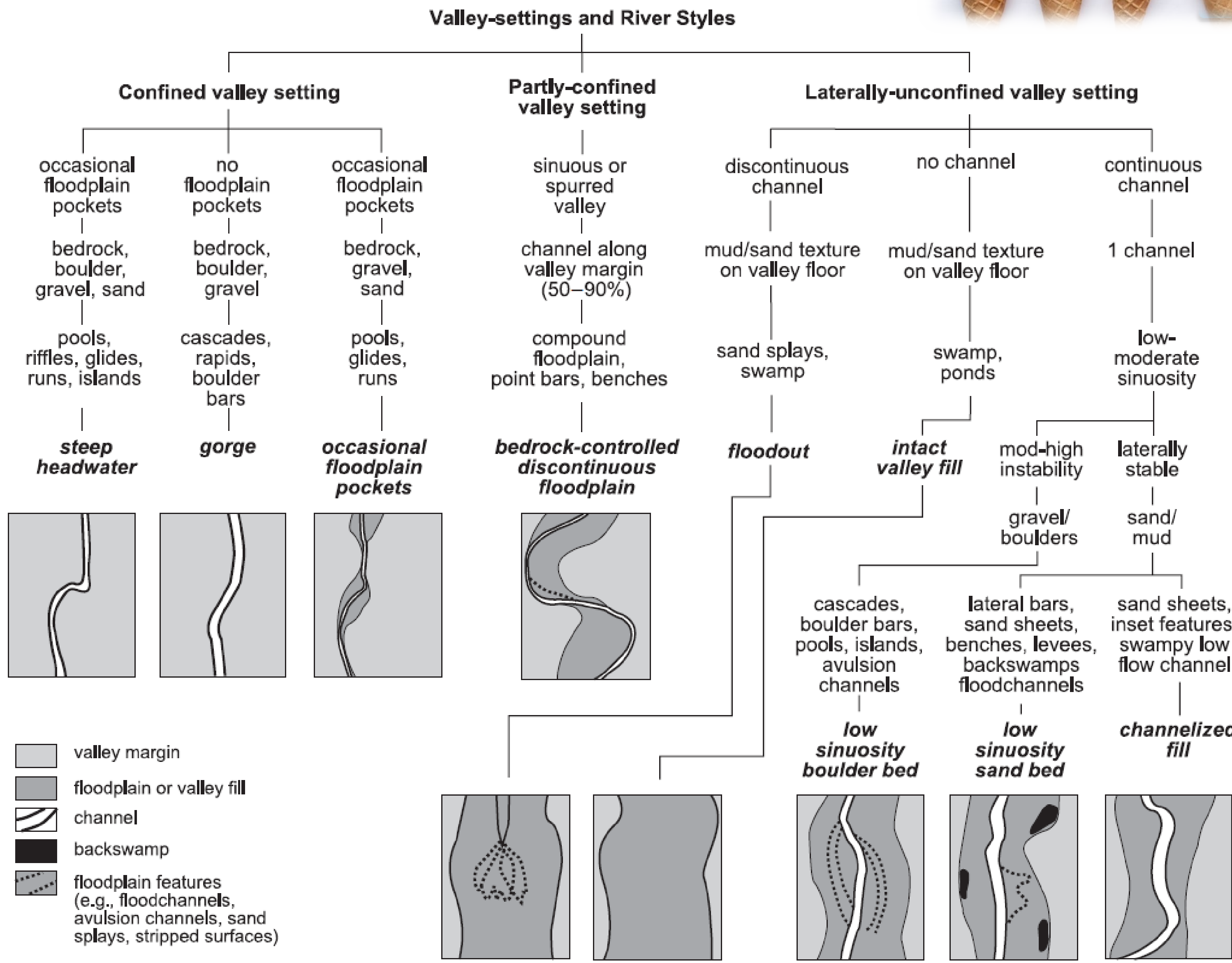
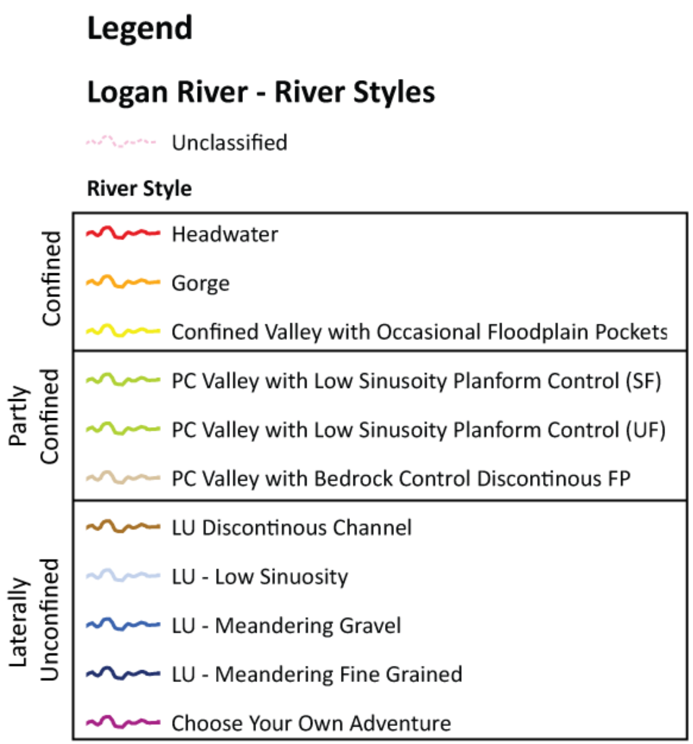
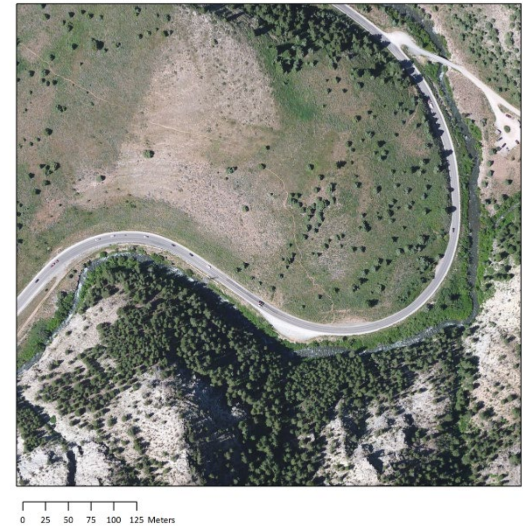


Figure 9.10 The Bega catchment River Styles tree (from Fryirs, 2001)

Exercise 1

- What 3 flavors?
- Optionally Download KMZ of Logan River Styles





https://restoration-usu.github.io/WATS-5340-5350/Course_Topics/WATS_5350/03_Design_Geomorphic_Principles.html

Geomorphology & Habitat

I. Reach Types

II. Building Blocks
   I. Margins (entry into Valley Setting)
   II. Geomorphic Units
   III. Structural Elements

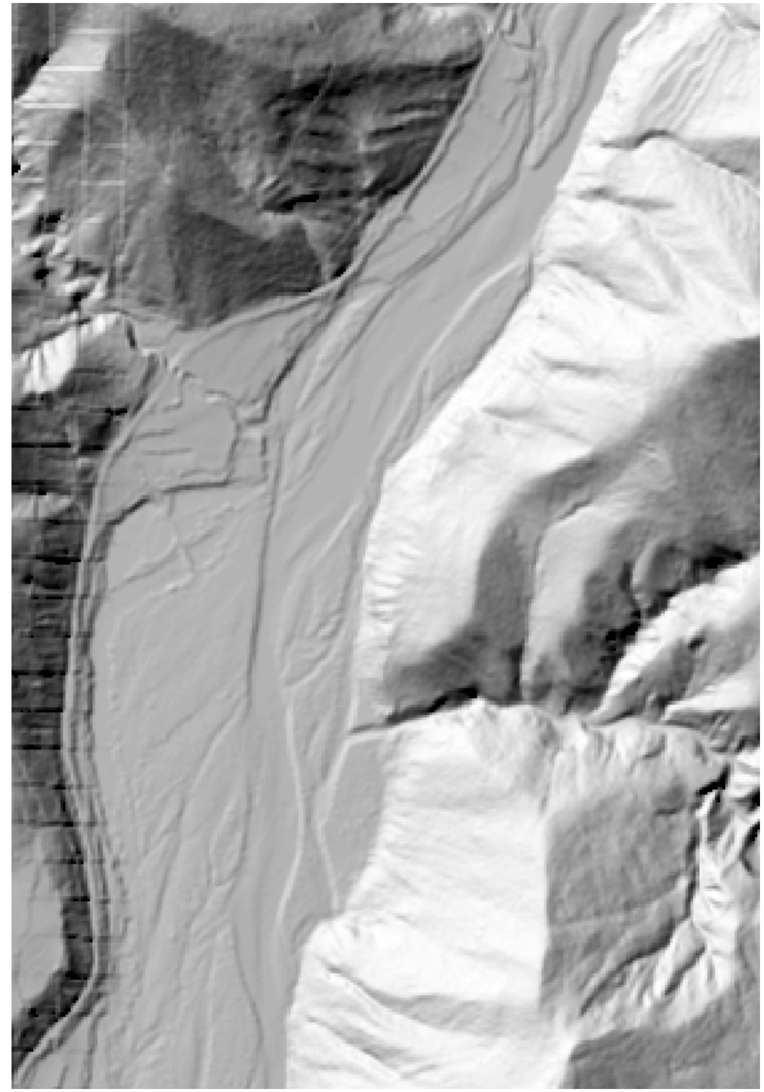
III. Habitat

If I Took You to an Overlook…

- And I asked you to draw a map…
- What would you draw?

For Real, What Would You Draw?

- If I gave you an aerial photo?



- Would you draw something different from a DEM?

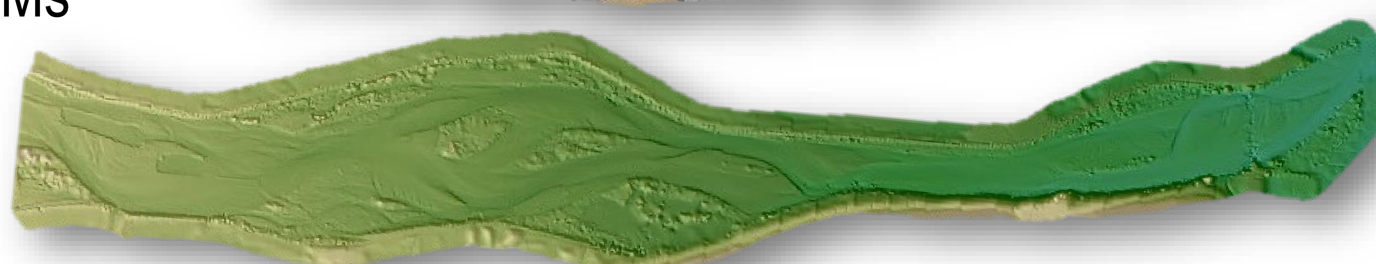
Technology Buys us Beautiful, HR, Digital Maps…

From point clouds

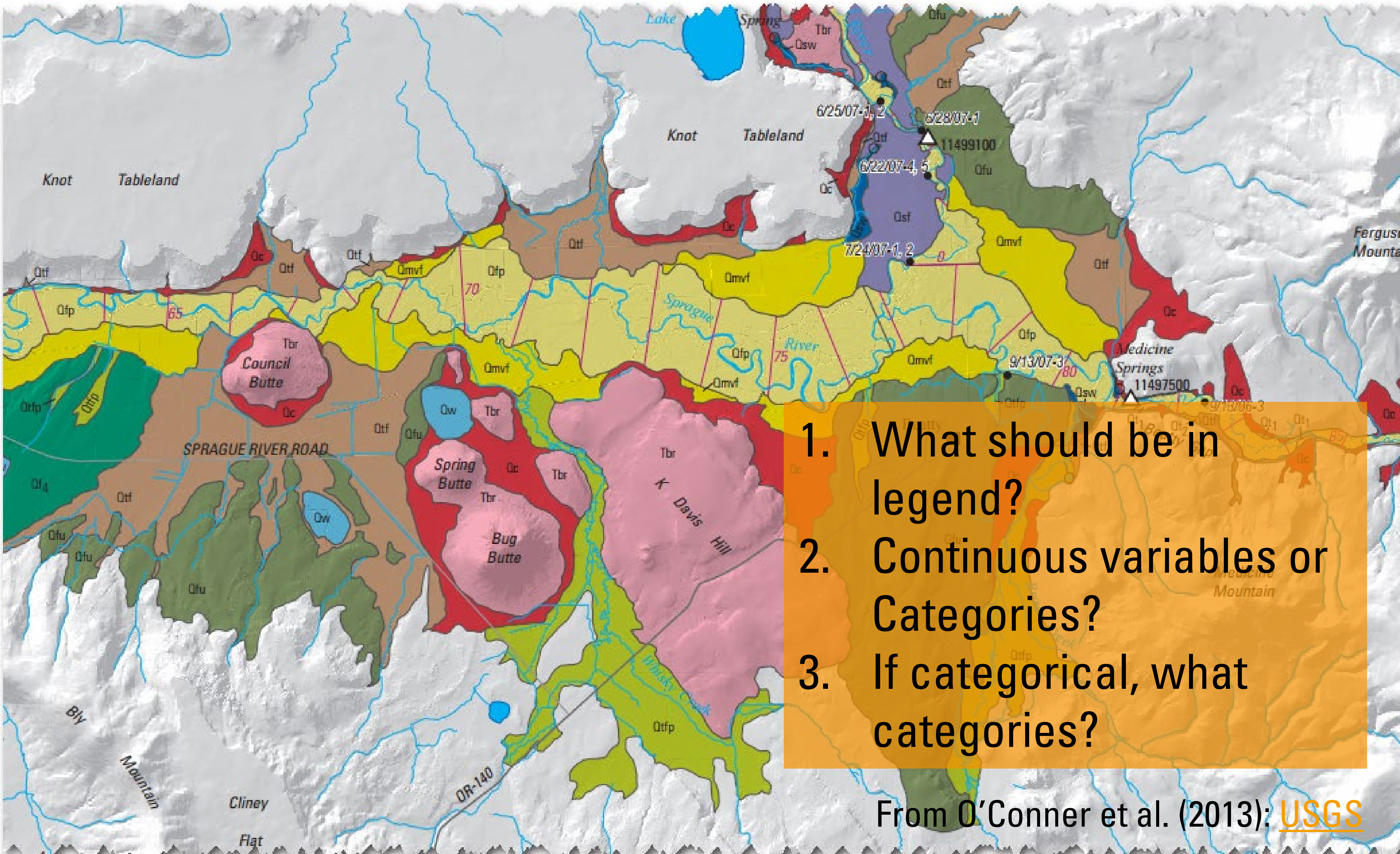
- But then what?
- What can you do with these base maps?

To Aerial Images

& DEMs



What are the components of a geomorphic map?



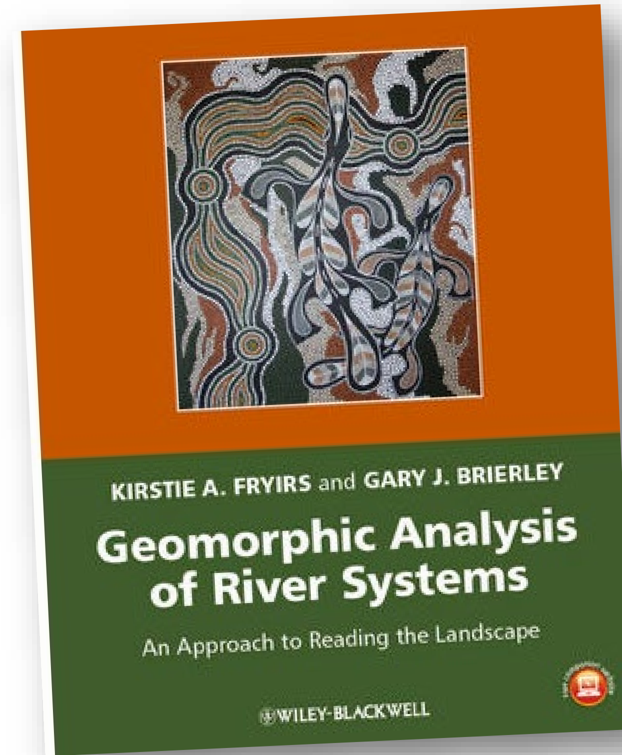
1. What should be in legend?
2. Continuous variables or Categories?
3. If categorical, what categories?

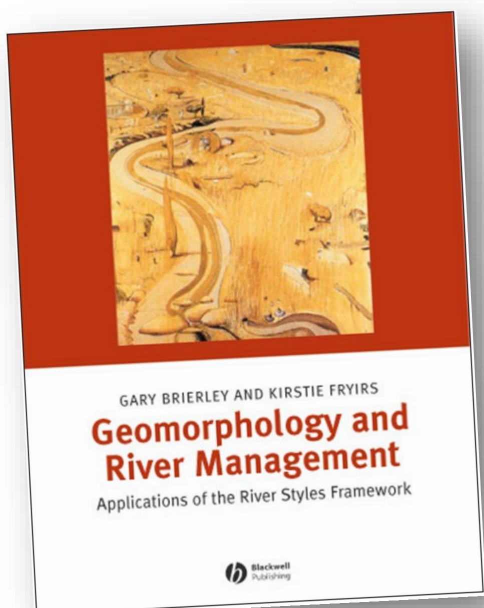
From O'Conner et al. (2013): USGS

Reading The Riverscape

- Most important underlying principle behind fluvial taxonomy effort was to ‘read’ the riverscape
- How can we find a common ‘language’ without reinventing wheel?

What we learn in WATS 5150 - Fluvial





- Brierley G and Fryirs K. 2005. Geomorphology and River Management: Applications of the River Styles Framework. Blackwell Publishing: Victoria, Australia, 398 pp.
- Fryirs KA and Brierley GJ. 2013. *Geomorphic Analysis of River Systems: An Approach to Reading the Landscape, First Edition. Blackwell Publishing Ltd.: Chichester, U.K., 345 pp.*

Geomorphology & Habitat

I. Reach Types

II. Building Blocks

    I. Margins (entry into Valley Setting)
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From: Wheaton et al. (2015) – Geomorphology; DOI: 10.1016/j.geomorph.2015.07.010

Margins

- A border or edge between distinct regions used to define a riverscape's setting

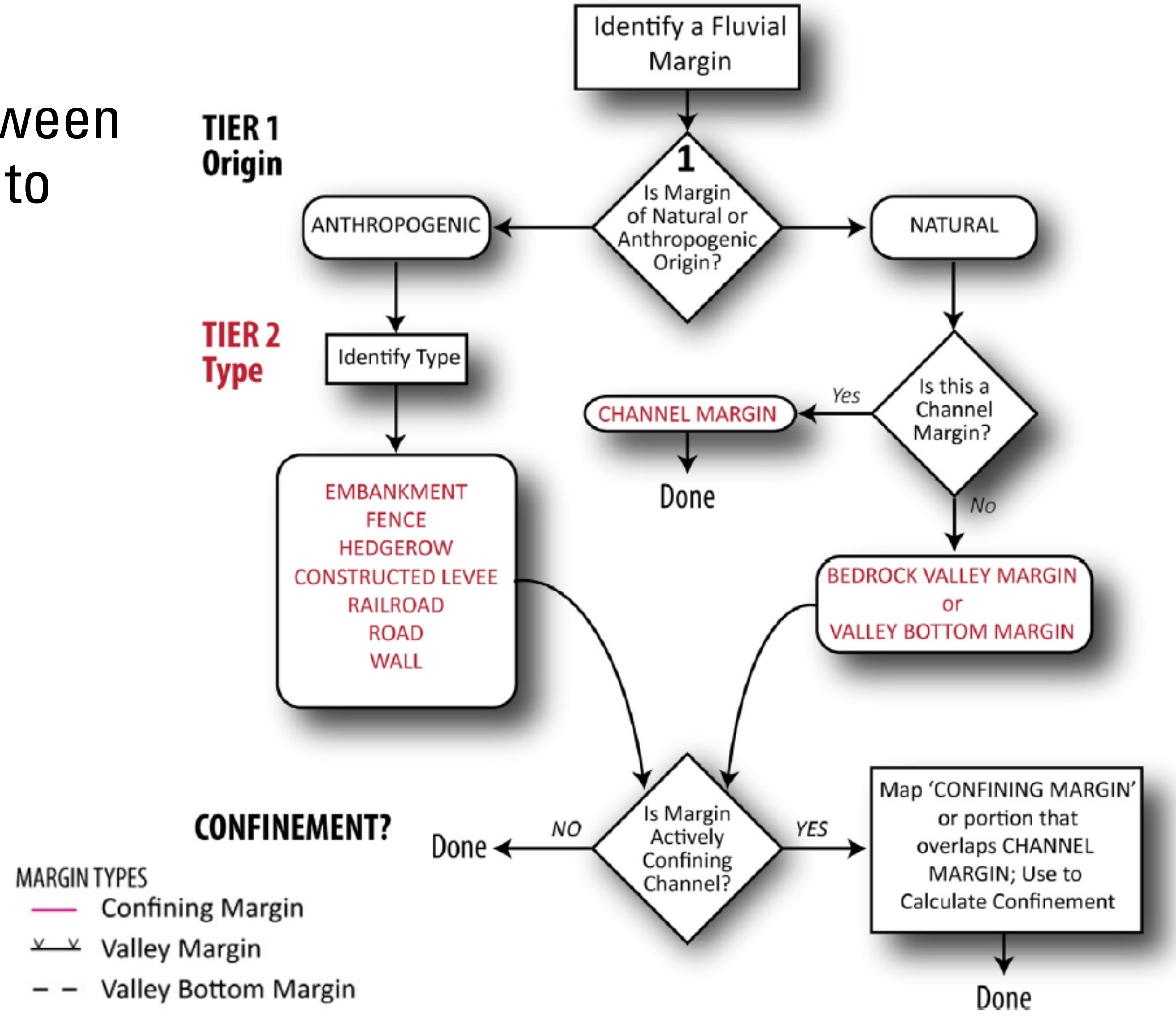
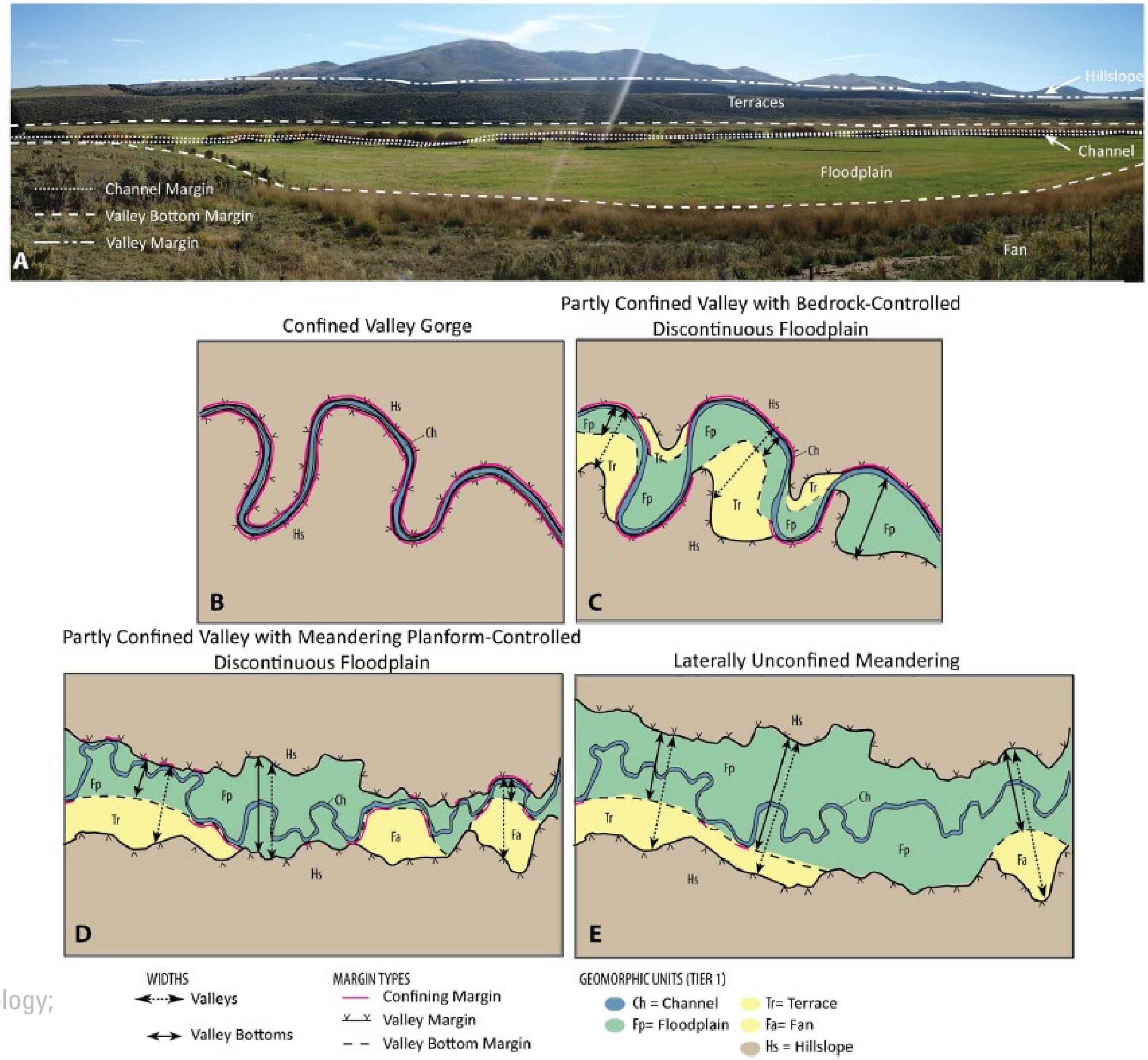


Fig. 1. Tiered fluvial margins classification framework.

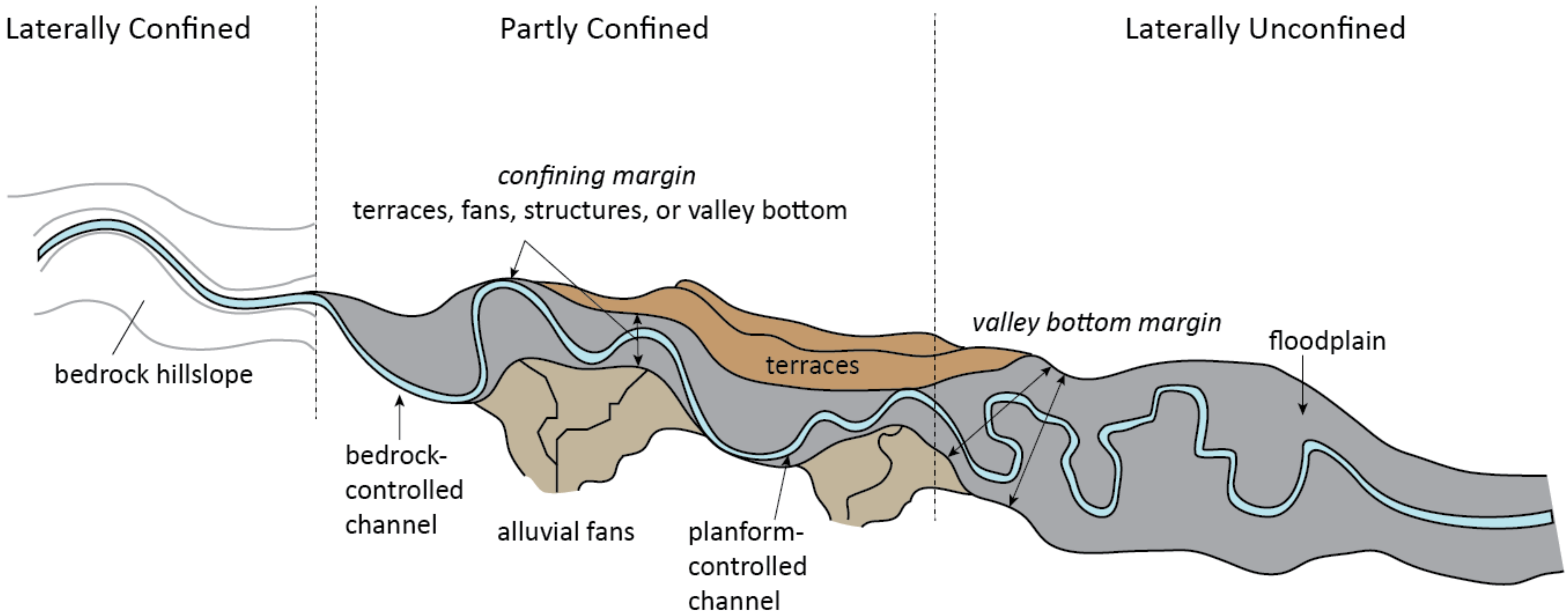
Valley Margins in Different Settings

- Interesting thing is identifying where different margins overlap
- Fundamental control on channel's capacity to adjust
- Differentiates reach types
- Sets up planform steering of flows



From: Wheaton et al. (2015) – Geomorphology; DOI: [10.1016/j.geomorph.2015.07.010](https://doi.org/10.1016/j.geomorph.2015.07.010)

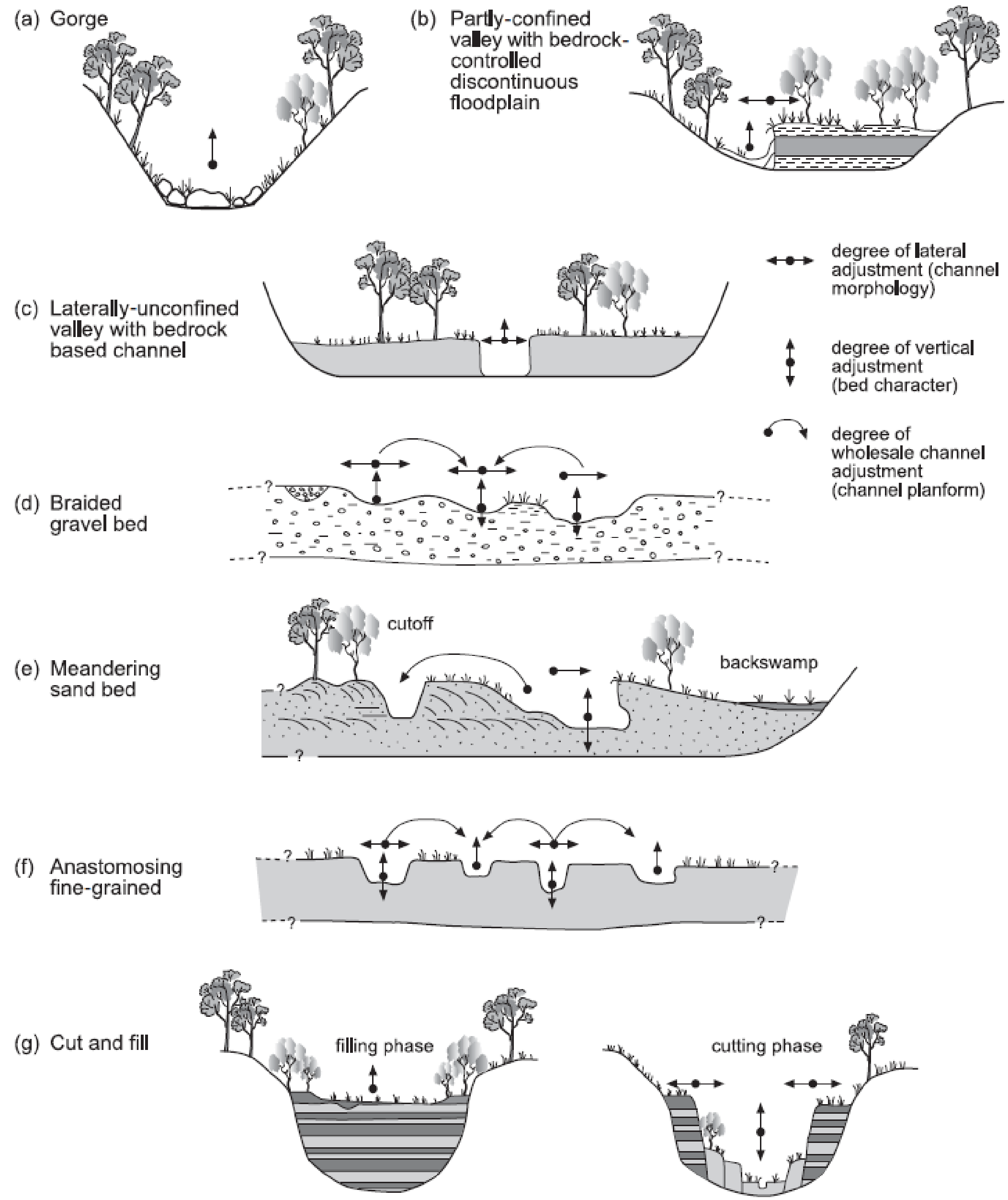
VALLEY SETTING CONTINUUM



From: O'Brien et al. (2015)

NATURAL CAPACITY FOR ADJUSTMENT

- Plausible limits on what adjustments are possible
- Geomorphic context matters
  - Confinement
  - Sediment Supply
  - Flow Regime
  - Vegetation
  - Land use
  - History



From Brierley & Fryirs (2005)

Definition of Valley Confinement

- The percent length of a reach that is in contact with a confining margin on *either* of its banks
- i.e. – where channel margin intersects valley bottom margin

$$C_{VB} = \left(\sum_{DS}^{US} CL_{EB} @ C_{M} \Big/ CL_{T} \right) \times 100$$

From: Fryirs et al. (2015) – ESPL;
DOI: [10.1002/esp.3893](10.1002/esp.3893)

EARTH SURFACE PROCESSES AND LANDFORMS
Earth Surf. Process. Landforms (2016)

Published online in Wiley Online Library
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An approach for measuring confinement and assessing the influence of valley setting on river forms and processes

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ESPL
Earth Surface Processes and Landforms

ABSTRACT: Valley setting and confinement (or lack thereof) are primary controls on river character and behaviour. Although there are various proxies for valley confinement, direct measures that quantify the nature and extent of confinement are generally lacking and/or inconsistently described. As such they do not lend themselves to consistent analysis over large spatial scales. Here we clearly define forms of confinement to aid in quantification of degrees of confinement. Types of margin that can induce confinement are differentiated as a valley margin, valley bottom margin, and/or anthropogenic margin. Such margins sometimes overlap and share the same location, and in other situations are separated, giving immediate clues as to the valley setting. We apply this framework to examples from Australia, United States and New Zealand, showing how this framework can be applied across the spectrum of river diversity. This method can help to inform interpretations of reach-scale river behaviour, highlighting the role of antecedent controls on contemporary forms and processes. Clear definitions of confinement are shown to support catchment-scale analysis of river patterns along longitudinal profiles, and appraisals of the geomorphic effectiveness of floods and sediment flux in catchments (e.g. process zone distribution, lateral sediment inputs and (dis)connectivity). Copyright © 2015 John Wiley & Sons, Ltd.

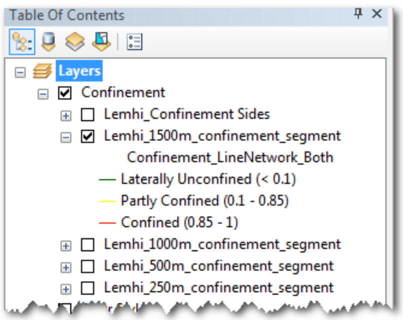
KEYWORDS: valley confinement; fluvial corridor; river planform; antecedence; river structure and function

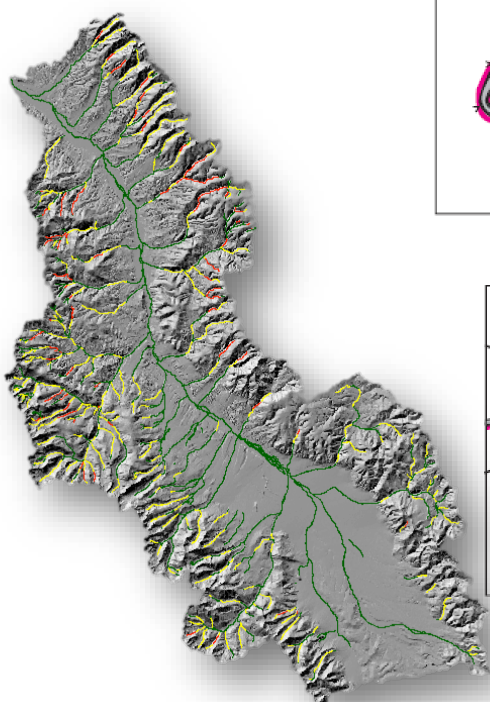
Introduction

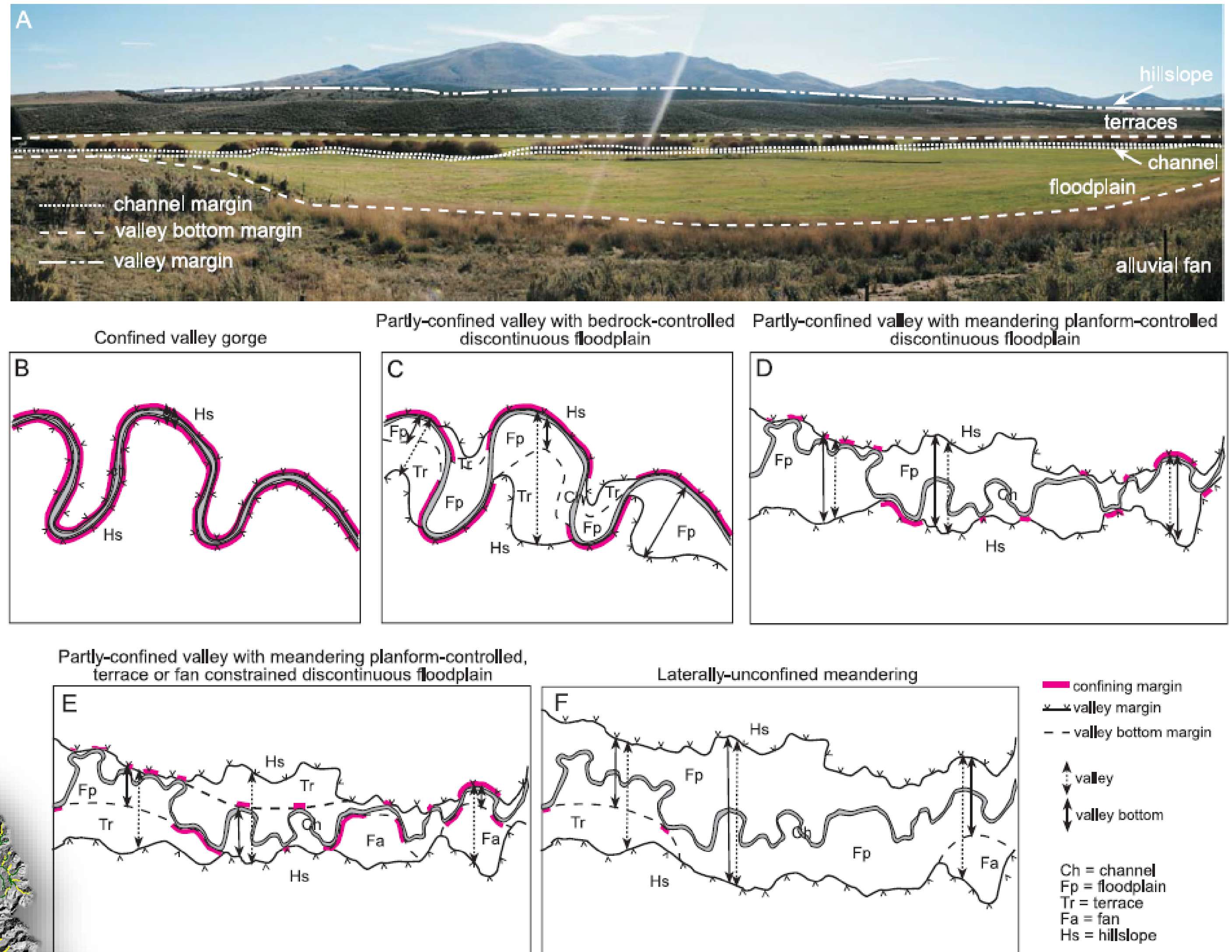
Along with gradient, discharge and sediment regime, valley confinement is a primary control on river morphology. Definitions of valley setting are typically based on the distribution of genetic floodplain along river courses, defined by Nanson and Croke (1992) as the largely horizontally-bedded alluvial landform adjacent to a channel, separated from the channel by banks, built of sediment transported by the present flow-regime, and reformed by contemporary processes. Kellerhals and Church (1989), Rosgen (1994, 1996) and Polvi *et al.* (2011) use the entrenchment ratio, defined as the ratio of flood prone width (i.e. width of the valley over the genetic floodplain) to bankfull channel width as a measure of flow confinement. In application of the Rosgen (1994, 1996) channel classification framework, the flood-prone width is approximated as the width measured at an elevation that is twice the maximum depth of the bankfull channel. However, these are not direct measures of valley confinement. Alternatively, Lewin and Brindle (1977) use degrees of confinement to describe the extent to which bedrock influences valley confinement, but this approach is not quantified. Also, Schumm (1985), Brierley and Fryirs (2005) and Fryirs and Brierley (2013) use the position of the channel on the valley floor to define ranges of confinement that can be used to differentiate valley settings (Figure 1). Very few of these schemes work across the range of river diversity, or consider the relative role of bedrock versus other confining features (e.g. ancient alluvium, or anthropogenic features) in differentiating between river types (Fotherby, 2009; Fryirs and Brierley, 2010). The lack of a consistent and conceptually sound approach for the analysis of valley confinement limits our capacity to interpret the impact it has on reach-scale river behaviour and catchment-scale patterns of river types.

Previous authors have used quantitative measures as proxies for valley setting (e.g. Johansen *et al.*, 2013; Beechie and Imaki, 2014). However, these approaches do not adequately discriminate between situations in which the active channel is in contact with potential confining margins, and the type of confining margin the channel abuts against. The increasing availability of high resolution digital elevation models (DEMs) presents an opportunity for systematic analyses of these relationships (e.g. Leviandier *et al.*, 2012; Parker *et al.*, 2012; Roux *et al.*, 2015). However, before automated procedures become firmly embedded in the literature, it is important to give careful consideration

Continuum of Confinement







From: Fryirs et al. (2015) – ESPL;
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Geomorphology & Habitat

I. Reach Types

II. Building Blocks
   I. Margins (entry into Valley Setting)
   II. Geomorphic Units
   III. Structural Elements

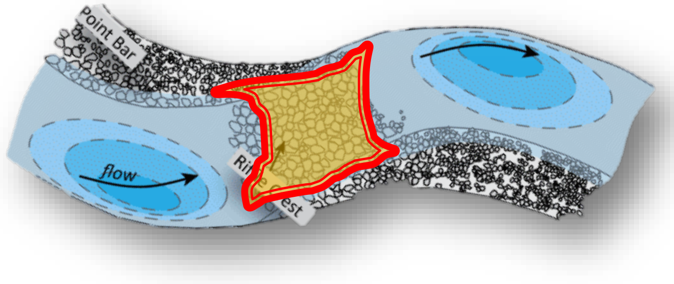
III. Habitat

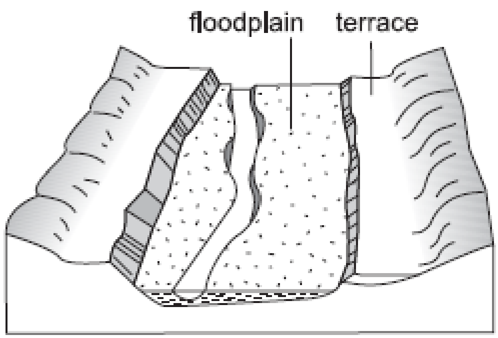
Geomorphic Unit Definition

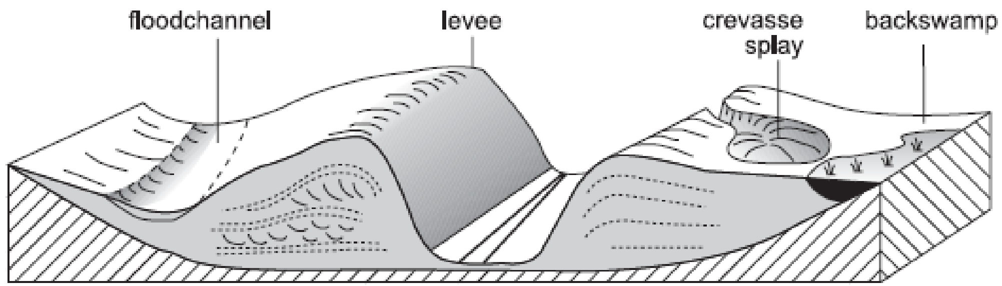
- A geomorphic unit is a landform that is a byproduct of erosion and deposition of sediment
- Fluvial geomorphic units are the result of fluvial (by water) erosion and deposition

For mapping purposes:

- GU’s are spatially continuous areas that can be topographically defined
- GU’s can be represented on a cell-by-cell basis by probabilistic or fuzzy membership in a class (e.g. probability of being a bar)
- GU’s are often represented as polygons



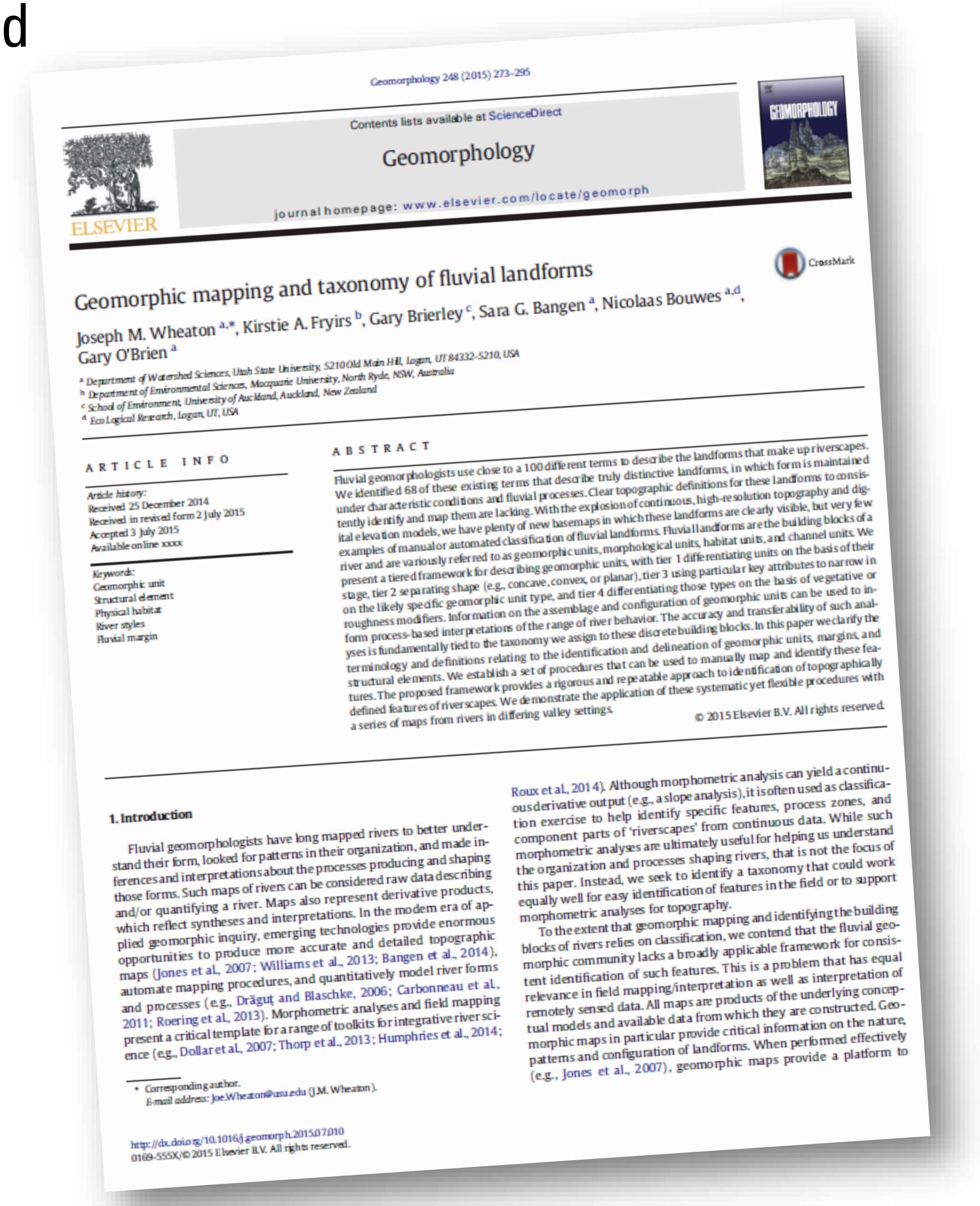




Figures from: Brierley and Fryirs (2005)

Surely, someone had already done this?

- In glacial, hillslope, coastal and aeolian geomorphology, the landforms are fairly consistently defined
- In fluvial, we found over 100 different terms to describe geomorphic units, of which 68 were actually distinctive…
- The legend should include a) margins, b) geomorphic units, and c) structural elements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Geomorphic mapping and taxonomy of fluvial landforms

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A B S T R A C T

Fluvial geomorphologists use close to a 100 different terms to describe the landforms that make up riverscapes. We identified 68 of these existing terms that describe truly distinctive landforms, in which form is maintained under characteristic conditions and fluvial processes. Clear topographic definitions for these landforms to consistently identify and map them are lacking. With the explosion of continuous, high-resolution topography and digital elevation models, we have plenty of new basemaps in which these landforms are clearly visible, but very few examples of manual or automated classification of fluvial landforms. Fluvial landforms are the building blocks of a river and are variously referred to as geomorphic units, morphological units, habitat units, and channel units. We present a tiered framework for describing geomorphic units, with tier 1 differentiating units on the basis of their stage, tier 2 separating shape (e.g., concave, convex, or planar), tier 3 using particular key attributes to narrow in on the likely specific geomorphic unit type, and tier 4 differentiating those types on the basis of vegetative or roughness modifiers. Information on the assemblage and configuration of geomorphic units can be used to inform process-based interpretations of the range of river behavior. The accuracy and transferability of such analyses is fundamentally tied to the taxonomy we assign to these discrete building blocks. In this paper we clarify the terminology and definitions relating to the identification and delineation of geomorphic units, margins, and structural elements. We establish a set of procedures that can be used to manually map and identify these features. The proposed framework provides a rigorous and repeatable approach to identification of topographically defined features of riverscapes. We demonstrate the application of these systematic yet flexible procedures with a series of maps from rivers in differing valley settings.

1. Introduction

Fluvial geomorphologists have long mapped rivers to better understand their form, looked for patterns in their organization, and made inferences and interpretations about the processes producing and shaping those forms. Such maps of rivers can be considered raw data describing and/or quantifying a river. Maps also represent derivative products, which reflect syntheses and interpretations. In the modern era of applied geomorphic inquiry, emerging technologies provide enormous opportunities to produce more accurate and detailed topographic maps (Jones et al., 2007; Williams et al., 2013; Bangen et al., 2014), automate mapping procedures, and quantitatively model river forms and processes (e.g., Drăguţ and Blaschke, 2006; Carbonneau et al., 2011; Roering et al., 2013). Morphometric analyses and field mapping present a critical template for a range of toolkits for integrative river science (e.g., Dollar et al., 2007; Thorp et al., 2013; Humphries et al., 2014; Roux et al., 2014). Although morphometric analysis can yield a continuous derivative output (e.g., a slope analysis), it is often used as classification exercise to help identify specific features, process zones, and component parts of 'riverscapes' from continuous data. While such morphometric analyses are ultimately useful for helping us understand the organization and processes shaping rivers, that is not the focus of this paper. Instead, we seek to identify a taxonomy that could work equally well for easy identification of features in the field or to support morphometric analyses for topography.

To the extent that geomorphic mapping and identifying the building blocks of rivers relies on classification, we contend that the fluvial geomorphic community lacks a broadly applicable framework for consistent identification of such features. This is a problem that has equal relevance in field mapping/interpretation as well as interpretation of remotely sensed data. All maps are products of the underlying conceptual models and available data from which they are constructed. Geomorphic maps in particular provide critical information on the nature, patterns and configuration of landforms. When performed effectively (e.g., Jones et al., 2007), geomorphic maps provide a platform to

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From: Wheaton et al. (2015) – Geomorphology; DOI: 10.1016/j.geomorph.2015.07.010

Four Primary Motivations for Better Identifying Geomorphic Units

1. Geomorphic Units are building blocks of a reach
2. Geomorphic Units comprise fish habitat -> Build stronger fish habitat relationships
3. Geomorphic Units are readily derivable from topography, if we have clearer topographic definitions
4. Geomorphic Unit Assemblages are predictable by reach type & condition

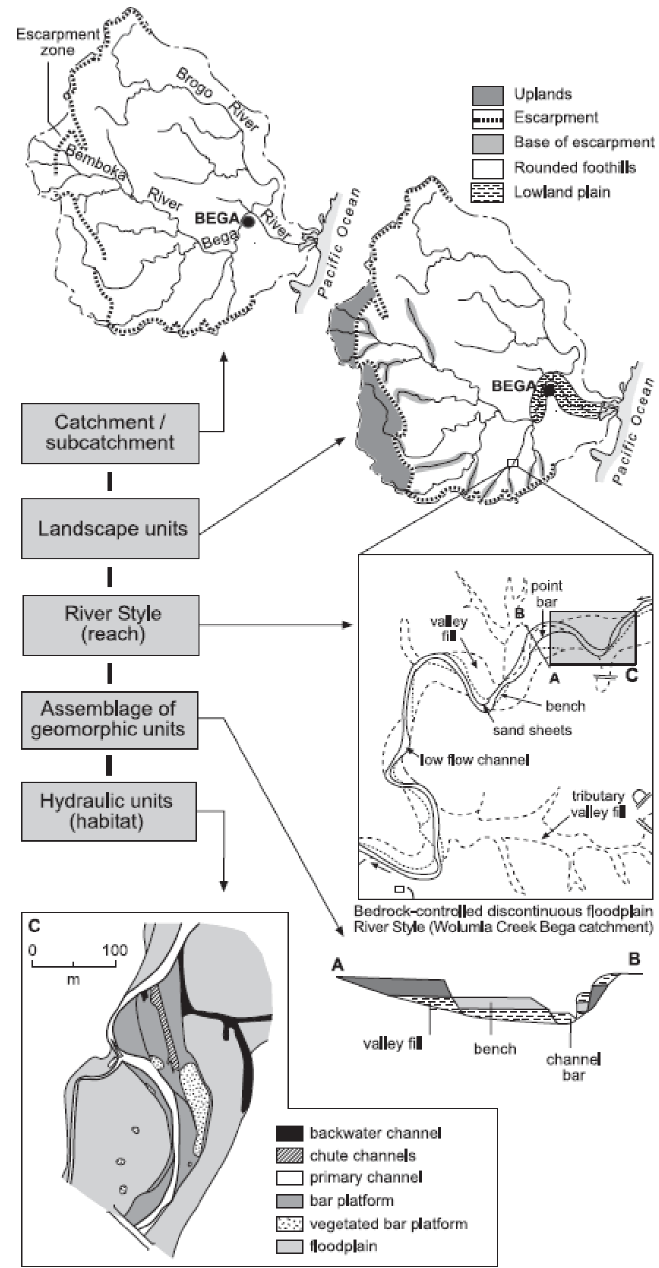
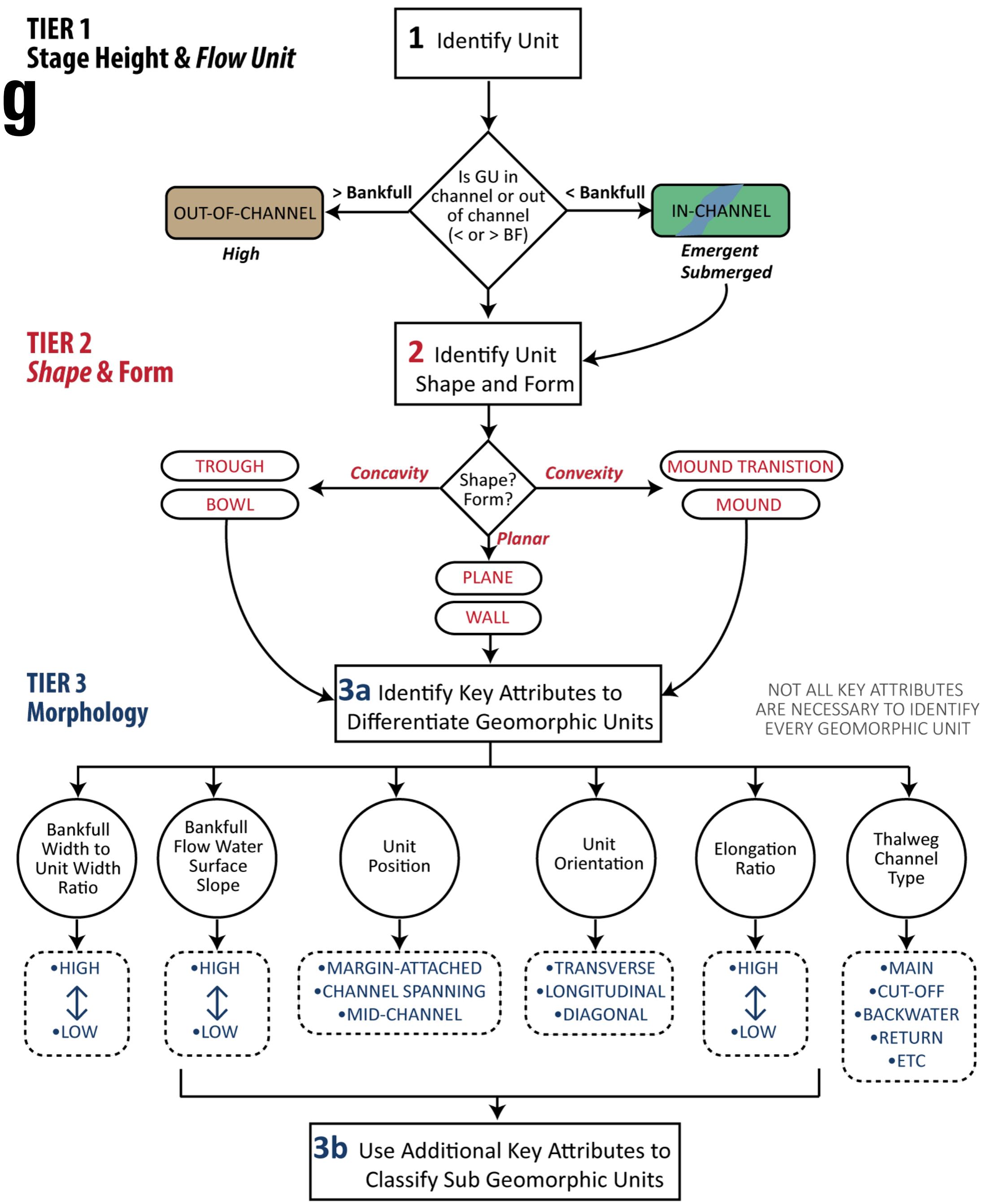


Figure from: Brierley & Fryirs (2005)

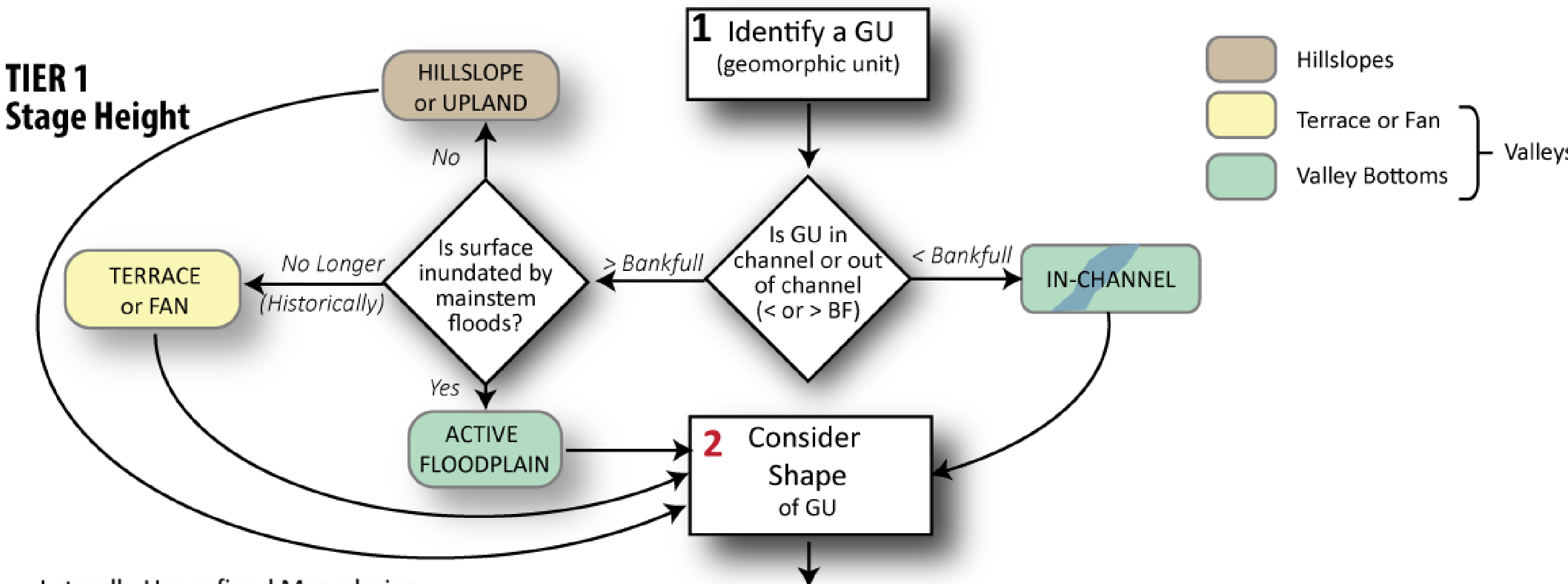
Taxonomy for Mapping Fluvial Landforms

- Four Tiers
  - Stage Height
  - Shape / Form
  - Morphology
  - Roughness/Vegetation
- Over 100 fluvial geomorphic units found in literature, of which 68 are distinctive (3b)
- Clearer, *topographically* based definitions

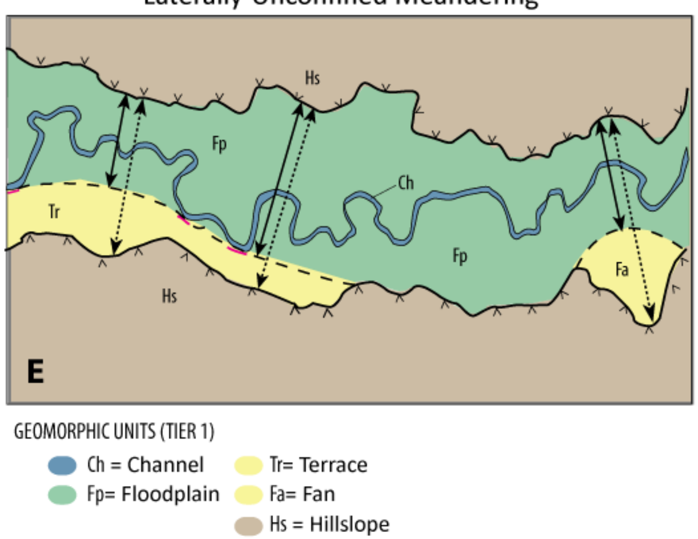
From: https://riverscapes.github.io/pyGUT/
Wheaton et al. (2015) – Geomorphology; DOI: 10.1016/j.geomorph.2015.07.010



Tier 1 – Stage Height -> Leads To Geomorphic Map



Laterally-Unconfined Meandering



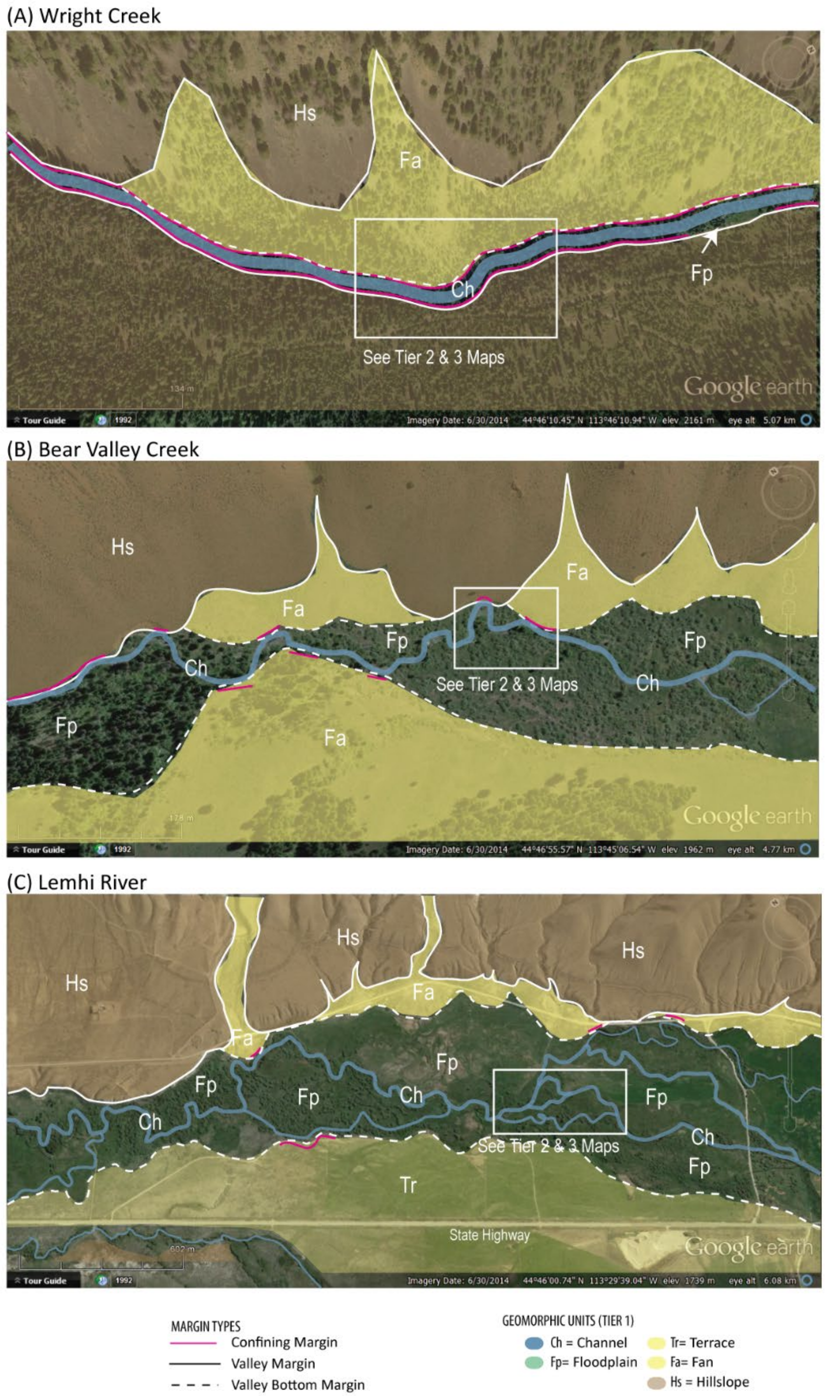
- The building blocks of a Valley?

vs.

- The building blocks of a Valley Bottom?

Tier 1 Applied

- Contrasting valley settings show different distributions of tier 1 geomorphic Units…

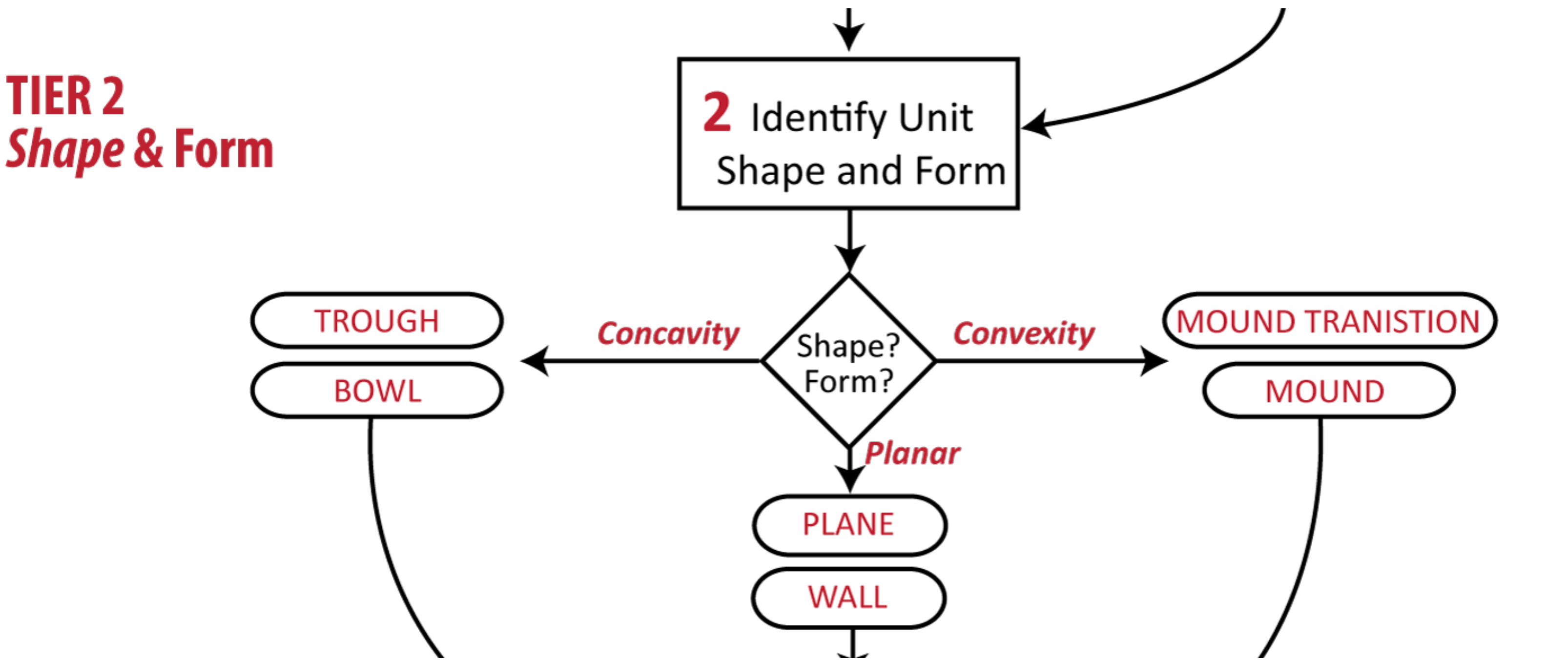


From: Wheaton et al. (2015) – Geomorphology; DOI: 10.1016/j.geomorph.2015.07.010

Tier 2 – Shape & Form

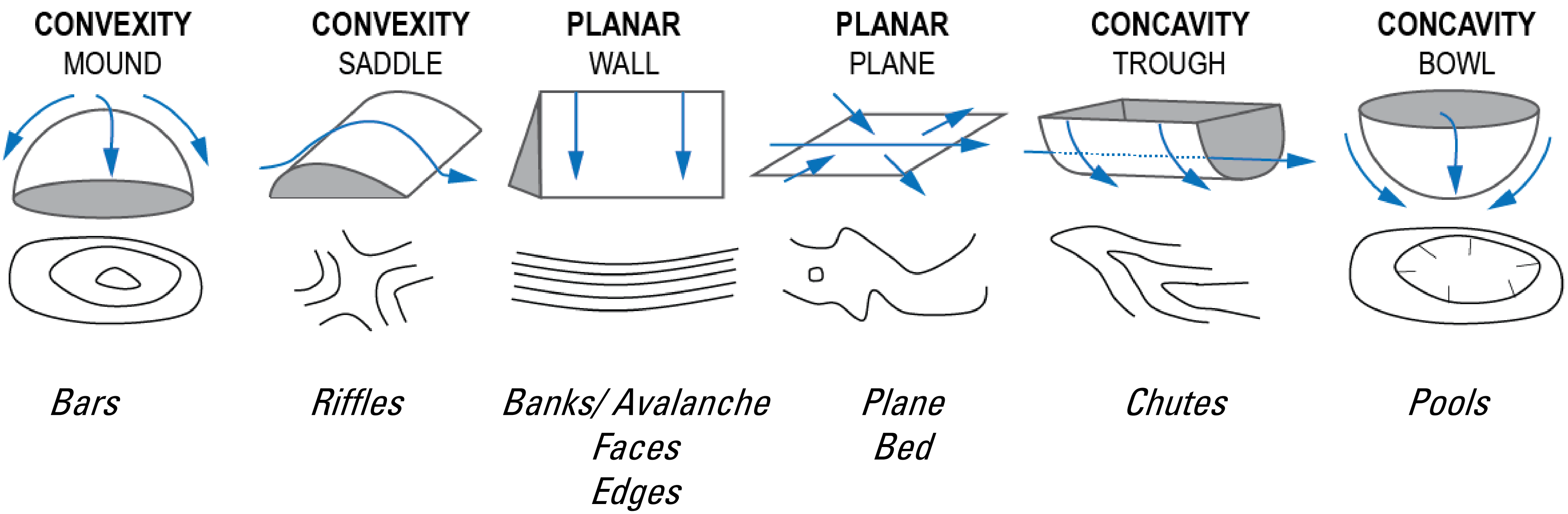
- Just add a verb to tier 1, so it’s a Concave In Channel Unit (i.e. concavity)

Concave Planar Convex



Tier 2 - Form

- Differentiating shape longitudinally (i.e. stream-wise), vs. laterally (i.e. cross sectional)



	Mound	Saddle	Wall	Plane	Trough	Bowl
XS	Convex	Concave	NA	Planar	Concave	Concave
LP	Convex	Convex	NA	Planar	Planar	Concave

Tier 2 – Applied
Shape

GEOMORPHIC UNITS
TIER 2 - Shape / Type

Transition Zones
Channel Margin

Structural Elements

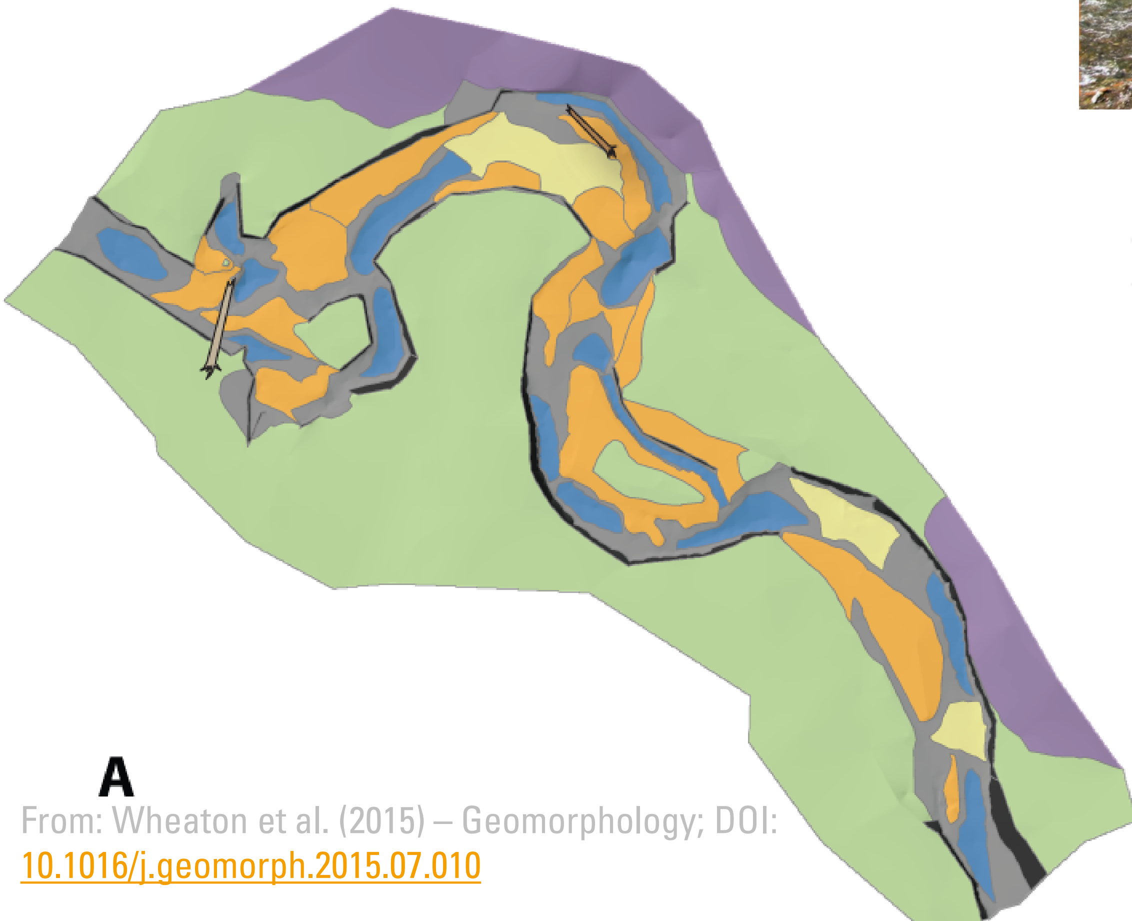
LWD

IN-CHANNEL

Concave In-Channel (i.e. Pools)
Convex In-Channel Features (i.e. Bars)
Planar In-Channel Features

OUT-OF-CHANNEL

Convex Fan
Planar Active Floodplain



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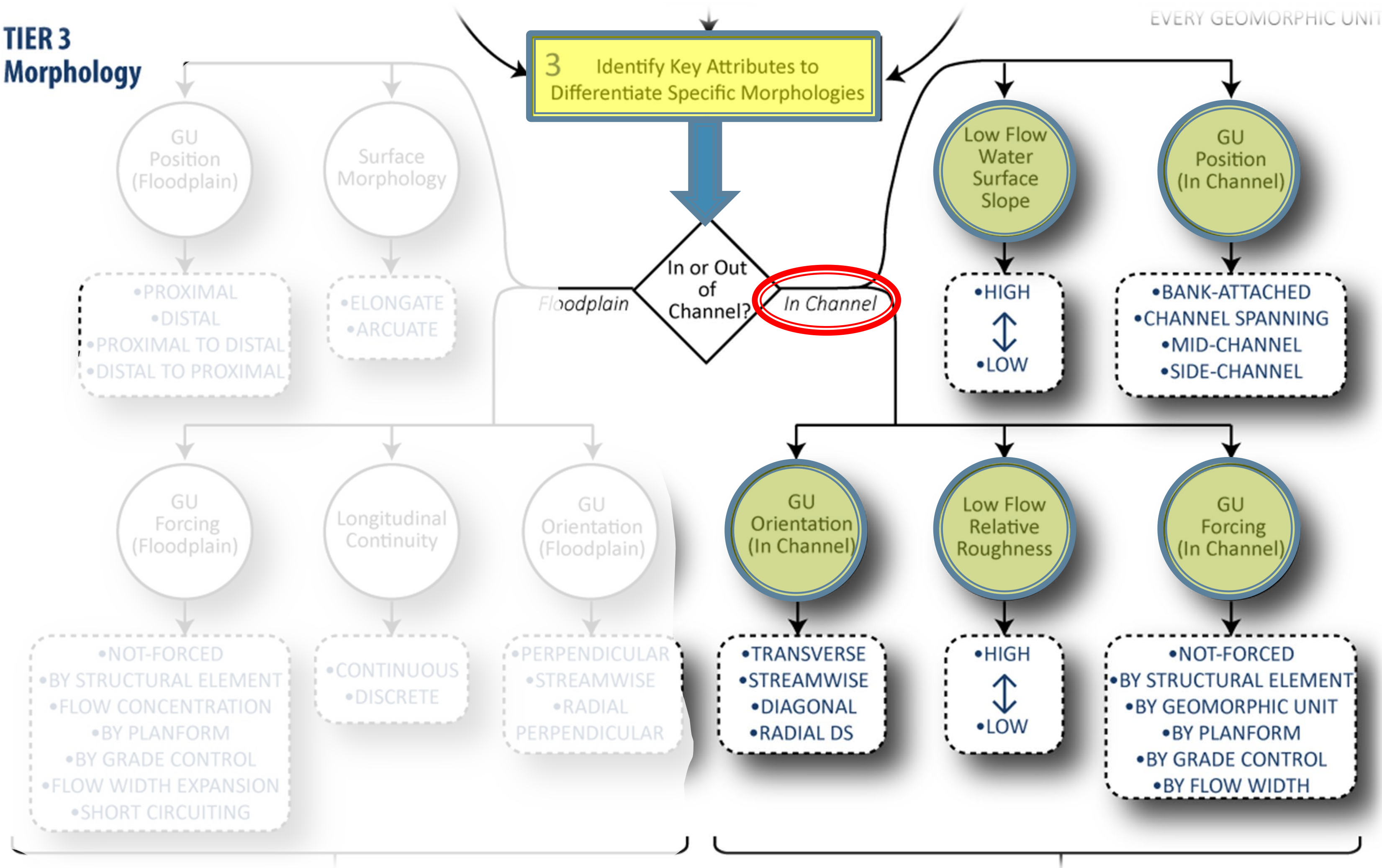
From: Wheaton et al. (2015) – Geomorphology; DOI: 10.1016/j.geomorph.2015.07.010

Tier 3 - Morphology



Key Tier 3 Attributes:	Types	Description
GU Forcing		Occurs when a non-uniform hydraulic flow pattern creates a flow environment conducive to forcing the formation, maintenance or accentuation of a geomorphic unit.
	∟ **Not Forced**	The GU forms on its own (e.g. free bars)
	∟ **By Structural Element**	Forcing can be caused by structural elements (e.g. large woody debris causing a plunge pool or an eddy bar)
	∟ **By Geomorphic Unit**	Forcing can be caused by another geomorphic unit (e.g. a pool can be forced by a bar)
	∟ **By Planform**	Forcing can be induced by sinuosity (e.g. flow separation on inside bends leading to point bars)
	∟ **By Flow Width**	Forcing is often associated with flow width expansion for depositional units and flow with constriction for erosional units
GU Orientation		The orientation is defined by the longest axis of the geomorphic unit and relative to dominant flow direction.
	∟ **Transverse**	Transverse units are oriented perpendicular to the flow (e.g. *riffles)*
	∟ **Streamwise**	Streamwise units are oriented parallel to the flow (e.g. *forced pools* are elongated in a streamwise fashion associated with the convergent flow jet)
	∟ **Diagonal**	Diagonal units intersect the channel at an angle and flow is shunted diagonally over them at high flows.
	∟ **Radial DS**	Some units have lobate shapes (e.g. *lobate bars*) which
GU Position		Defines the position of the GU within the low-flow channel
	∟ **Bank-Attached**	Many units are appended to the channel margins (e.g. *point bars*); Note 'bank-attached' is common termionology in the fluvial literature even though the entire length of all channels are bound by true banks. Channel margins is a more generic term, but less common.
	∟ **Channel Spanning**	Some units are bank-attached on both sides and span the entire low flow channel (e.g. *riffles*)
	∟ **Mid-Channel**	Some units are not attached to a channel margin and occur in the center of a channel (e.g. *longitudinal bar*)
	∟ **Side-Channel**	For some mapping purposes, it is helpful to differentiate units that only occur in side and/or secondary channels
Low Flow Water Surface Slope		Especially for in-channel, planar units, low flow water surface slope is a helpful way of differentiating across the spectrum from low-slope glides, through intermediate slope runs and riffles, through high slope rapids, up to very high slope cascades.
	∟ **Flat**	Water surface slope = 0
	∟ **Shallow**	Water surface slope < 0.005
	∟ **Moderate**	Water surface slope > 0.005 & < 0.03
	∟ **Steep**	Water surface slope > 0.03
Low Flow Relative Roughness		Relative roughness is defined as the ratio of roughness height to flow depth (z_0/h).
	∟ **Low**	Relative roughness < 0.5 (i.e. majority of flow depth not obstructed by substrate)
	∟ **Moderate**	Relative roughness between 0.5 and 1 (i.e. majority of flow depth obstructed by substrate, but substrate not protruding from water surface)
	∟ **High**	Relative roughness > 1 (i.e. particles protruding from water surface)
	∟ **Very High**	Relative roughness >> 1 (i.e. flow depth is negligible relative to massive boulders protruding from water surface)

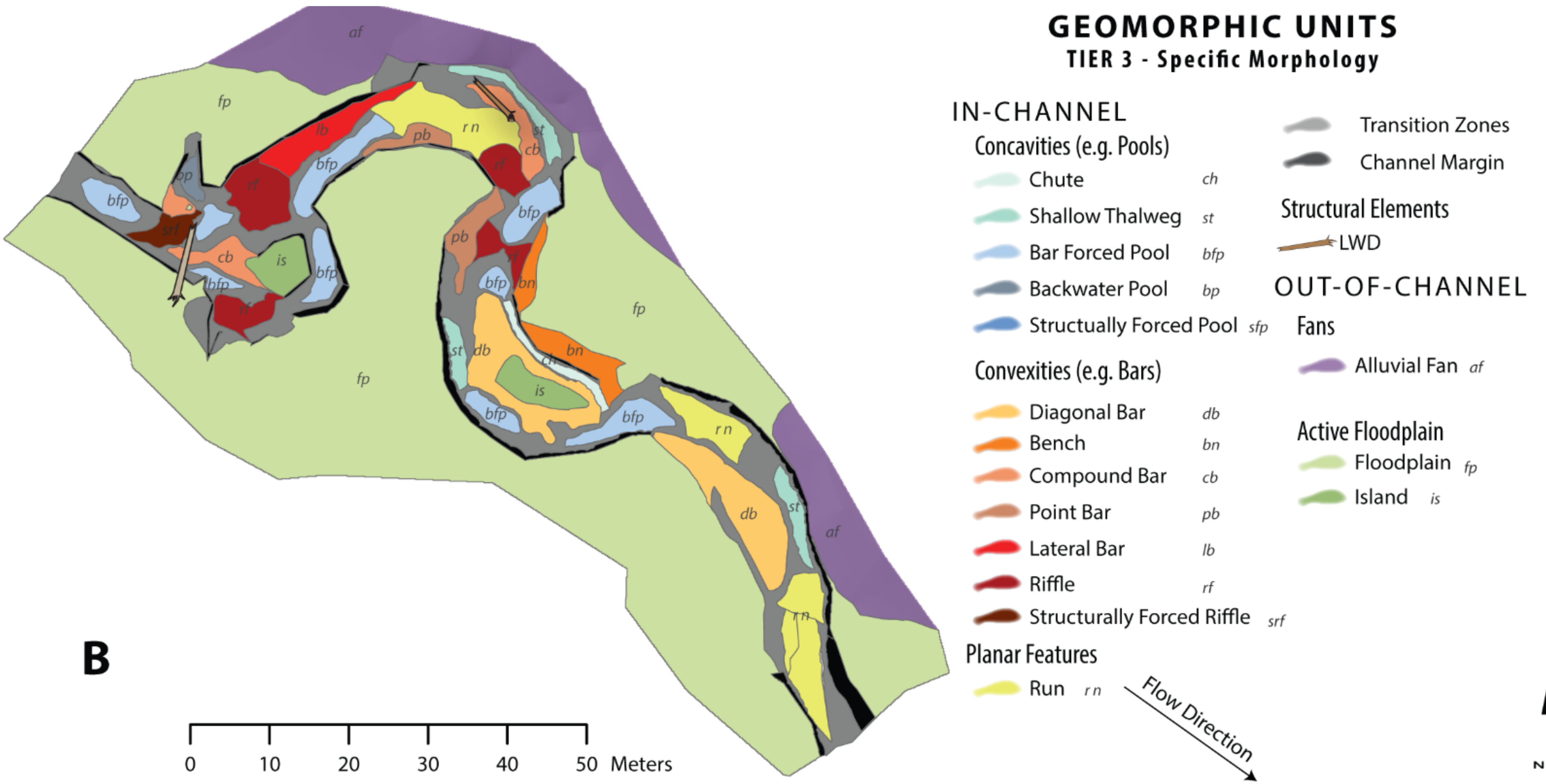
Tier 1	Tier 2	Tier 3							
Stage Height	Shape/Type	Specific Morphology	Key Attributes to Differentiate Specific Morphologies						
			GU Forcing	Low Flow Relative Roughness	GU Orientation	GU Position	Low Flow Water Surface Slope	Also Known As	Similar to or Confused With
∟	Planar								
		∟ Bench	Not Forced	Varies	Streamwise	Bank-Attached	Varies	Inset Floodplain	Ledge, but depositional feature; Terrace, but within active bankfull channel
		∟ Ledge	Not Forced	Varies	Streamwise	Bank-Attached	Varies	Inset Floodplain	Bench, but erosional feature; Terrace, but within active bankfull channel
		∟ Glide	Not Forced	Low (< 0.5)	Streamwise	Varies	Shallow	NA	Run, but much lower gradient water surface and low relative roughness
		∟ Run	Not Forced	Moderate (< 1)	Streamwise	Varies	Shallow to Moderate	NA	Sometimes confused with riffles or glides
		∟ Rapid	Varies	High (> 1)	Streamwise	Varies	Moderate to Steep	NA	Cascade, but less relative roughness and lacking vertical drops
		∟ Cascade	Varies	Very High (>>1)	Streamwise	Varies	Steep	NA	Rapid, but more relative roughness, steeper water surface, and vertical drops; Sometimes confused with step-pools
∟	Concavity (e.g. Pool)								
		∟ Backwater	Grade Control	Low (< 0.5)	Varies	Side Channel	Flat	Slackwater	Similar to other pools but found in disconnected side channels or secondary channels
		∟ Bar-Forced Pool	By Bar	Low (< 0.5)	Streamwise	Bank-Attached	Shallow	NA	Structurally forced pool, but forced by bar shunting flow against resistant boundary
		∟ Beaver Pond	Grade Control from Beaver Dam SE	Low (< 0.5)	Streamwise	Channel Spanning	Flat	Beaver Pool	A specific example of a dammed pool
		∟ Chute	Planform	Varies	Streamwise	Bank-Attached or Mid-Channel	Moderate	NA	Shallow thalweg, but generally steeper and dissecting bar; Also confused with flood channels, but these are in-channel short-circuiting forms
		∟ Confluence Pool	Planform	Low (< 0.5)	Streamwise	Varies	Shallow	Scour Pool	
		∟ Dammed Pool	DS Grade Control from SE	Low (< 0.5)	Streamwise	Channel Spanning	Shallow	NA	Beaver pond, but forcing SE can be any channel spanning obstruction. Also confused with the upstream pool in a step pool
		∟ Plunge Pool	US Grade Control from SE	Low (< 0.5)	Transverse	Varies	Flat	Scour Pool	
		∟ Ramp	Planform	Varies			Varies	NA	
		∟ Return Channel	Forced by Eddy Bar	Varies	Streamwise	Bank-Attached	Varies	NA	Chute, but flow is upstream in association with eddy
		∟ Shallow Thalweg	Forced by planar GU or occasionally bars	Varies	Streamwise	Bank-Attached	Varies, but Typically Moderate	NA	Chute, but does not dissect a bar surface
		∟ Secondary Channel	Planform	Varies	Streamwise	Mid-Bankfull Channel	Varies	NA	Anabranch or Secondary Channel, except that area separating secondary and primary channel is < bankfull
		∟ Structurally-Forced Pool	Flow Width Constriction Forced by SE	Low (< 0.5)	Streamwise	Bank-Attached or Mid-Channel	Varies	NA	Sometimes called 'scour pool'

FILTERING THROUGH TAXONOMY

Tier 1:	In-Channel	Active Floodplain	Terrace	Fan	Hillslope		Total:
Tier 1 Count	1	1	1	1	1		5
Tier 2 Count	3	3	3	3	3		15
Tier 3:							
∟ Concavities	12	12	1	1	1		27
∟ Convexities	18	5	0	3	1		27
∟ Planar	6	5	2	0	1		14
Tier 3 Subtotal:	36	22	3	4	3		68

- Prior to Tiers… could be one of 68
- @ Tier 1, knowing I'm in channel, one of 36
- @ Tier 2, knowing I'm a concavity, one of 12
- @ Tier 3, knowing I'm forced, one of

Tier 3 Applied



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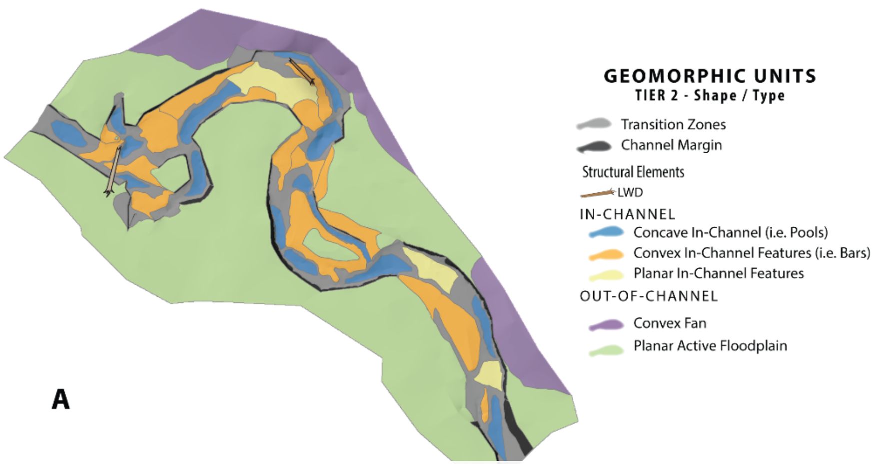
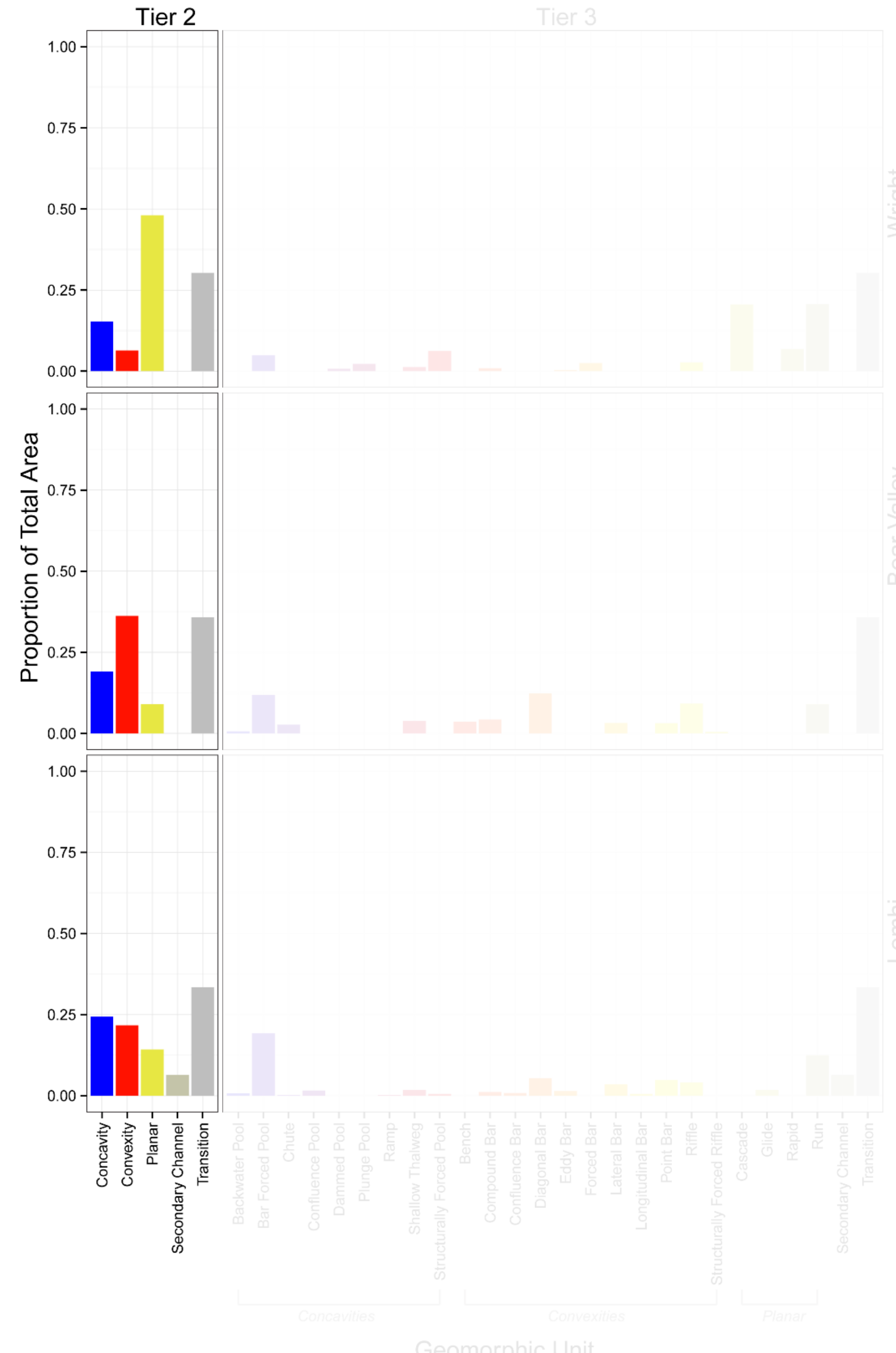
Assemblages

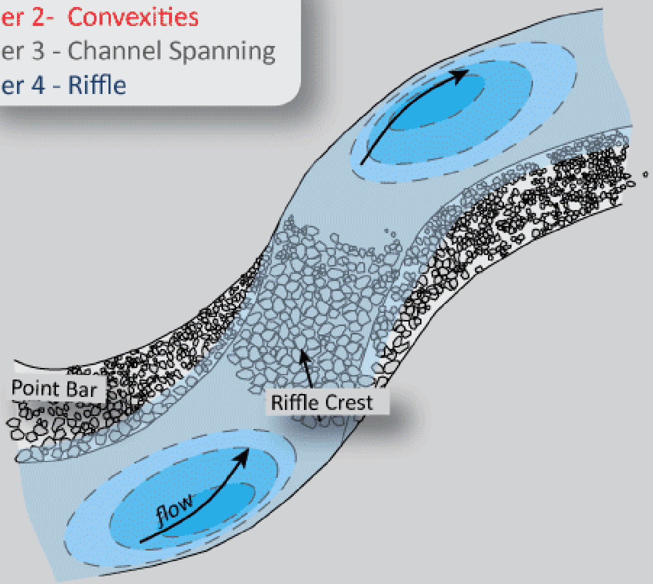


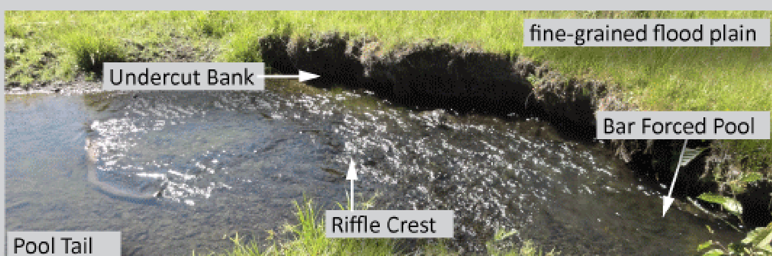


If I Land on a Riffle, But Don't Know It

RIFFLE

Tier 1 - (< or > bankful)
Tier 2- Convexities
Tier 3 - Channel Spanning
Tier 4 - Riffle





Jungle Creek, Middle Fork John Day Watershed, OR

GEOMORPHIC FORM

Riffles form as topographic highs along an uneven longitudinal profile, between bends in sinuous alluvial channels. Alluvial riffles are shallow, step-like, channel-spanning features.

Middle Fork John Day River, OR

PROCESS INTERPRETATION

Riffles are zones of sediment accumulation that increase channel roughness during high flow stages, and are maintained or built at various flow stages by the consequent increased turbulence and reduced velocity over the steepened surface. Riffles are often dissected at low flow stages, and reworked or removed altogether at stages higher than bankful.

TYPICAL *ADJACENT* GEOMORPHIC UNITS

Riffles are commonly associated geomoprhic units that help to force it as a channel spanning bar: the *riffle crest* and steepened planar surface separates the upstream and downstream *Bar-Forced Pools, Bank-attached bars (i.e., Point Bars),* and undercut banks.

TYPICAL SALMONID FISH HABITAT ASSOCIATIONS

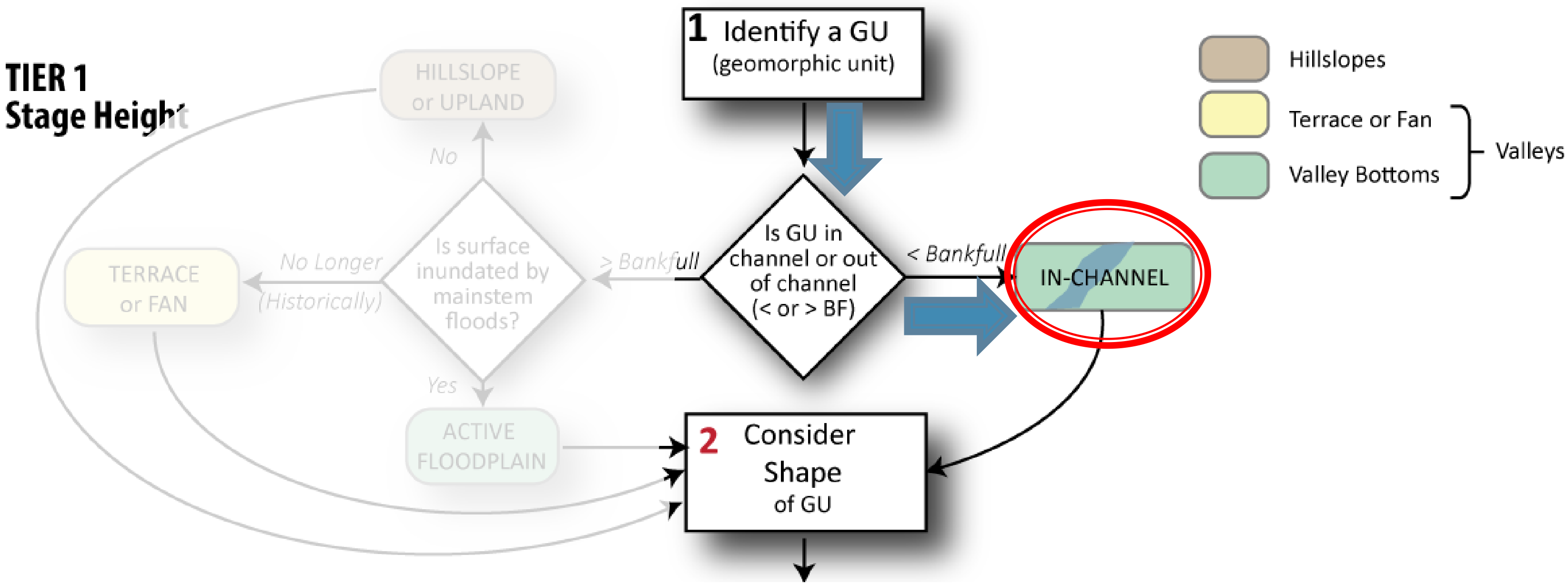
Typical fish habitat is focused at pool tails at the tops of riffles where holding occurs, and pool heads at their bases, where fish can forage on food items being washed down from the steepened ramp above.

Anadromous life stages	Fry	Parr (Juvinile)	Smolt	Adult
Foraging				
Energy Refugia	O	O	O	O
Predation Refugia	✓	✓	✓	✓
Thermal Refugia	X	X	X	X

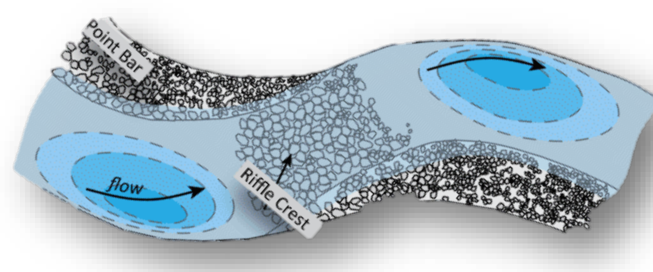
na- Not Applicable ; X - Not Typically Important ; O - Occasionally Provided ; ✓ Critical

Tier 1 Stage Height	Tier 2 Shape/Type	Tier 3 Specific Morphology	Key Attributes to Differentiate Specific Morphologies GU Forcing	Low Flow Relative Roughness	GU Orientation	GU Position	Low Flow Water Surface Slope	Also Known As	Similar to or Confused With
In-Channel									
∟	**Convexity (e.g. bar)**								
	∟	Backwater Bar	Grade Control	Varies	Varies	Side Channel	Varies	Slackwater deposit	Similar to other bars but found in disconnected side channels or secondary channels
	∟	Boulder Bar	Flow Width	Varies	Streamwise	Bank-Attached or Mid-Channel	Varies	Boulder Berm	Similar to other bars, but in much higher gradient systems.
	∟	Compound Bar	Varies	Varies	Varies	Varies	Varies	Bar complex	An amalgamation of multiple unit bars and other bar types (complex history)
	∟	Confluence Bar	Grade Control	Varies	Radial DS & Streamwise	Bank-Attached	Varies	NA	Expansion bar, except in response to gradient drop from tributary to mainstem.
	∟	Diagonal Bar	Planform & Flow Width Expansion	Varies	Diagonal	Mid-Channel	Varies	Mid-Channel Bar	Point bar, but no longer bank-attached (separated by chute)
	∟	Eddy Bar	Planform, SE, and/or Flow Width Constriction	Varies	Streamwise	Bank-Attached or Mid-Channel	Varies	Separation Bar	
	∟	Expansion Bar	Flow Width	Varies	Transverse	Mid-Channel	Varies	NA	Transverse bar, but in response to slope lowering, and does not span channel
	∟	Forced Bar	Varies	Varies	Streamwise	Bank-Attached or Mid-Channel	Varies	NA	Eddy Bar
	∟	Forced Riffle	Channel Spanning SE	Moderate (< 1)	Transverse	Channel Spanning	Shallow	NA	Riffle, but forced by channel spanning structural element buried in bed
	∟	Lateral Bar	By Planform or By Flow Width	Varies	Streamwise	Bank-Attached	Varies	Alternate Bar	Point bars, but can be in bends with lower curvature or channels with lower sinuosity or straight
	∟	Lobate Bar	Grade Control	Varies	Radial DS	Mid-Channel	Varies	Mid-Channel Bar	Similar to other mid-channel bars but distinctive in DS tear-dropped shape and avalanche faces
	∟	Longitudinal Bar	Flow Width	Varies	Moderate (< 1)	Mid-Channel	Varies	Mid-Channel Bar	Similar to other mid-channel bars but distinctive in elongated streamwise orientation and upstream convexity at bar head
	∟	Point Bar	Planform forced	Varies	Streamwise	Bank-Attached	Varies	Bank-Attached Bar	Alternate bars, but in bends with higher curvature
	∟	Reattachment Bar	Varies	Varies	Streamwise	Bank-Attached	Varies	NA	Eddy Bar, but occurs DS of both flow separation and reattachment point
	∟	Ridge	Forced by SE and Flow Separation	Varies	Streamwise	Bank-Attached	Varies	NA	Scroll bar or levee; generally straighter, more linear feature
	∟	Riffle	Flow Width Expansion	Moderate (< 1)	Transverse	Channel Spanning	Moderate	Transverse Bar	Sometimes confused with runs
	∟	Scroll Bar	Planform & Flow Width Expansion	Varies	Streamwise	Bank-Attached	Varies	NA	Ridge, but positioned on point bar and generally curved
	∟	Unit Bar	Flow Width Expansion	Varies	Varies	Varies	Varies	NA	The fundamental building block of all bars

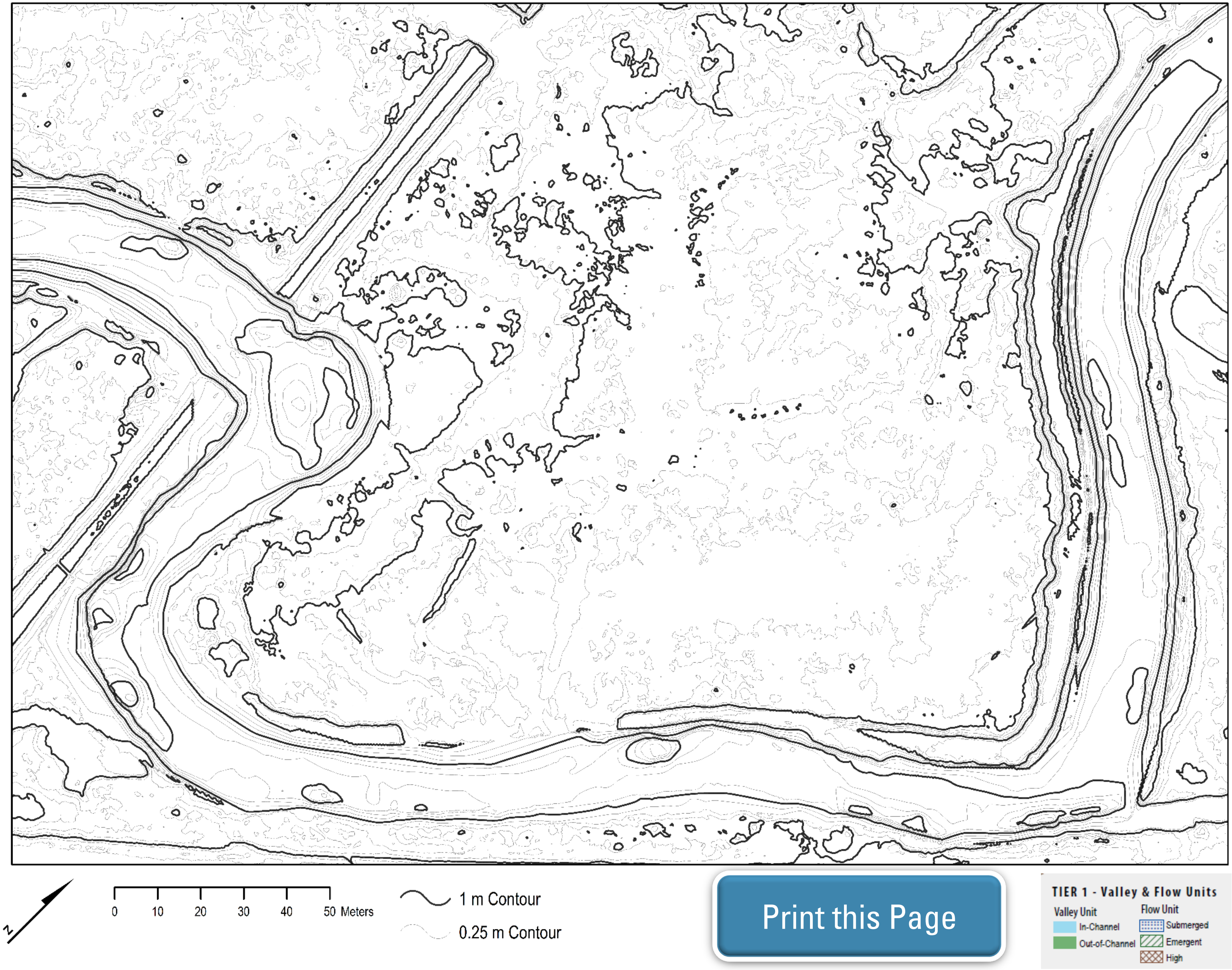
Tier 1 – On that Riffle



- Not so bad…

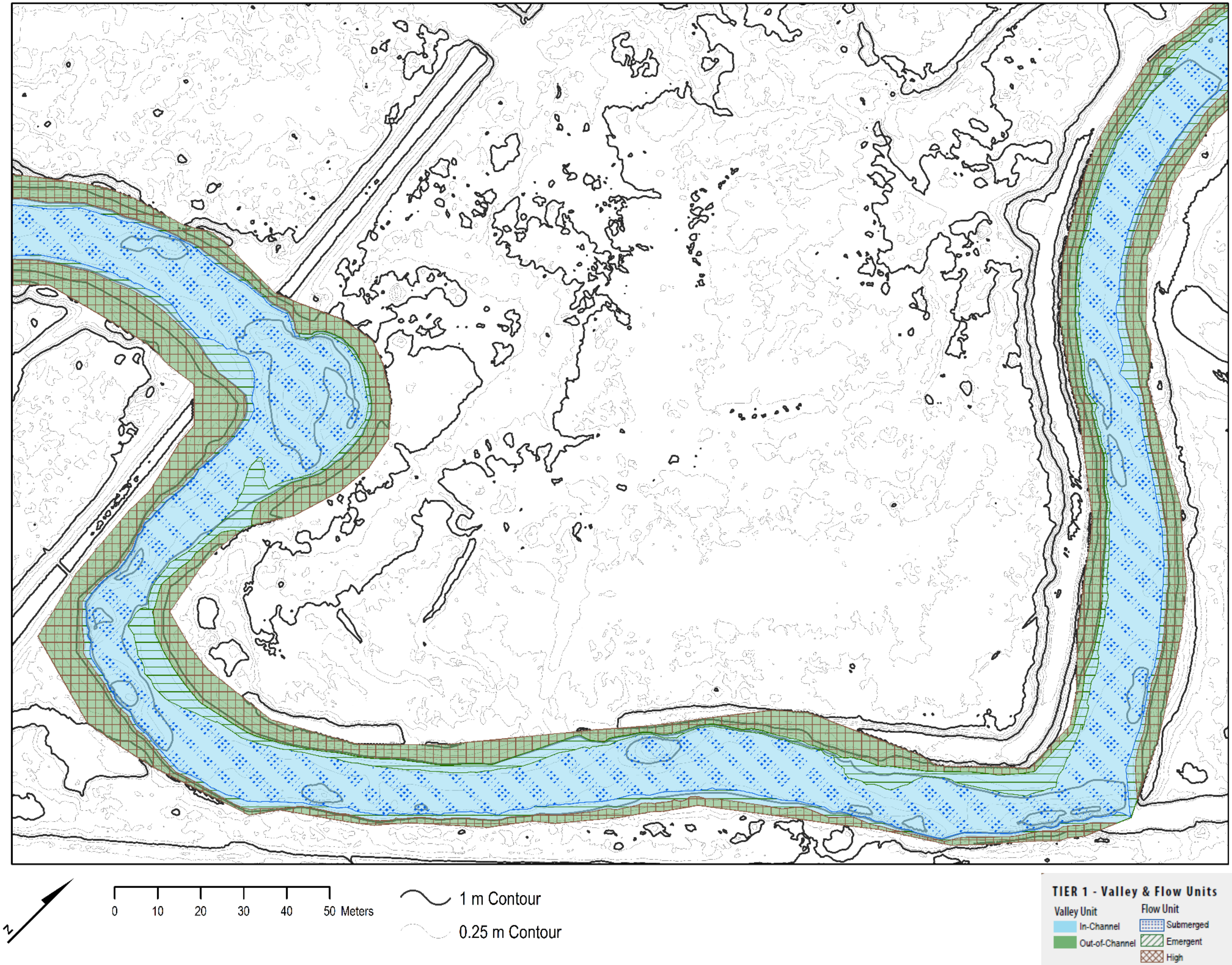


EXERCISE : MAP IN CHANNEL & OUT OF CHANNEL

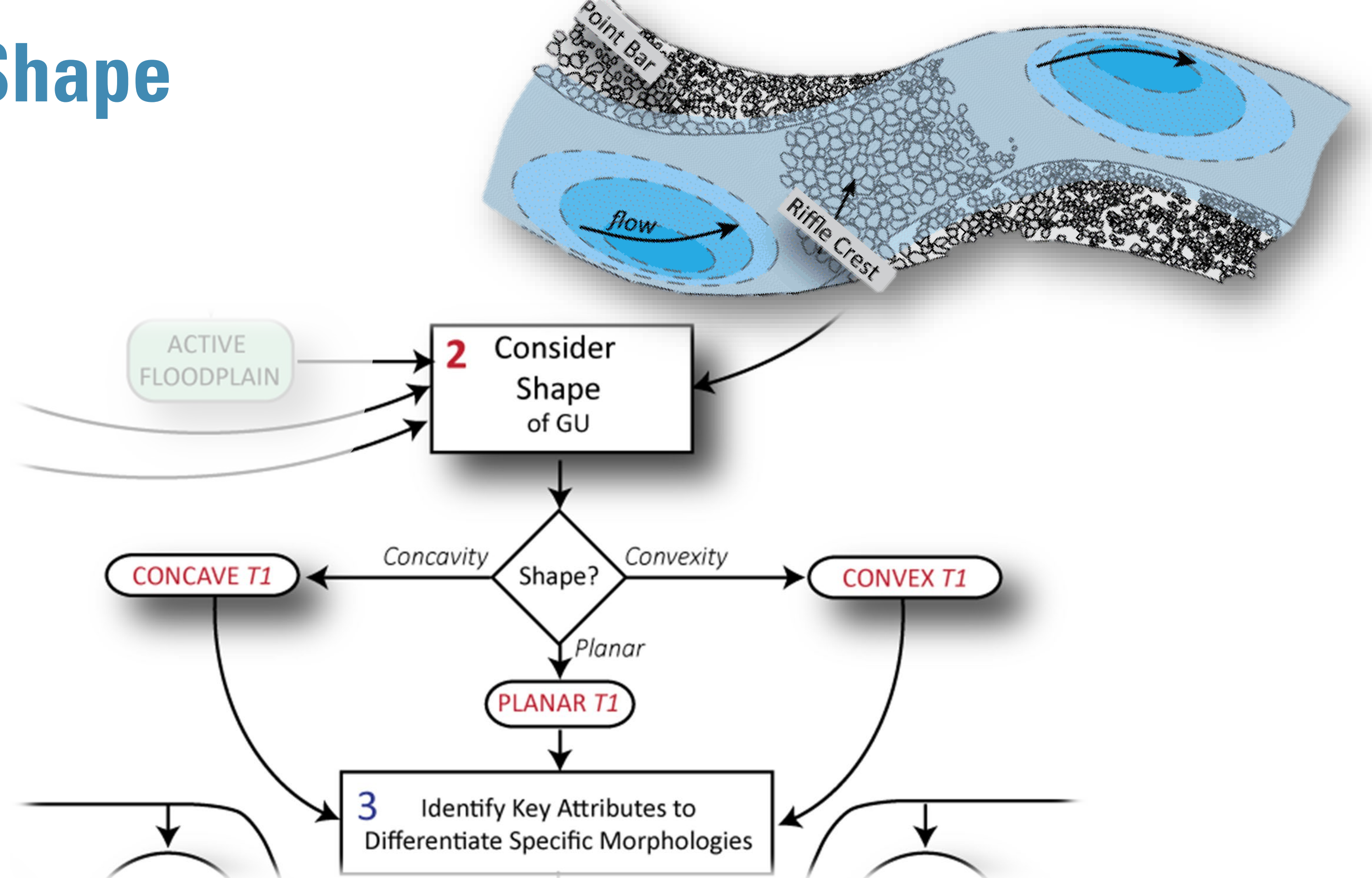


Print this Page

EXERCISE : MAP IN CHANNEL & OUT OF CHANNEL



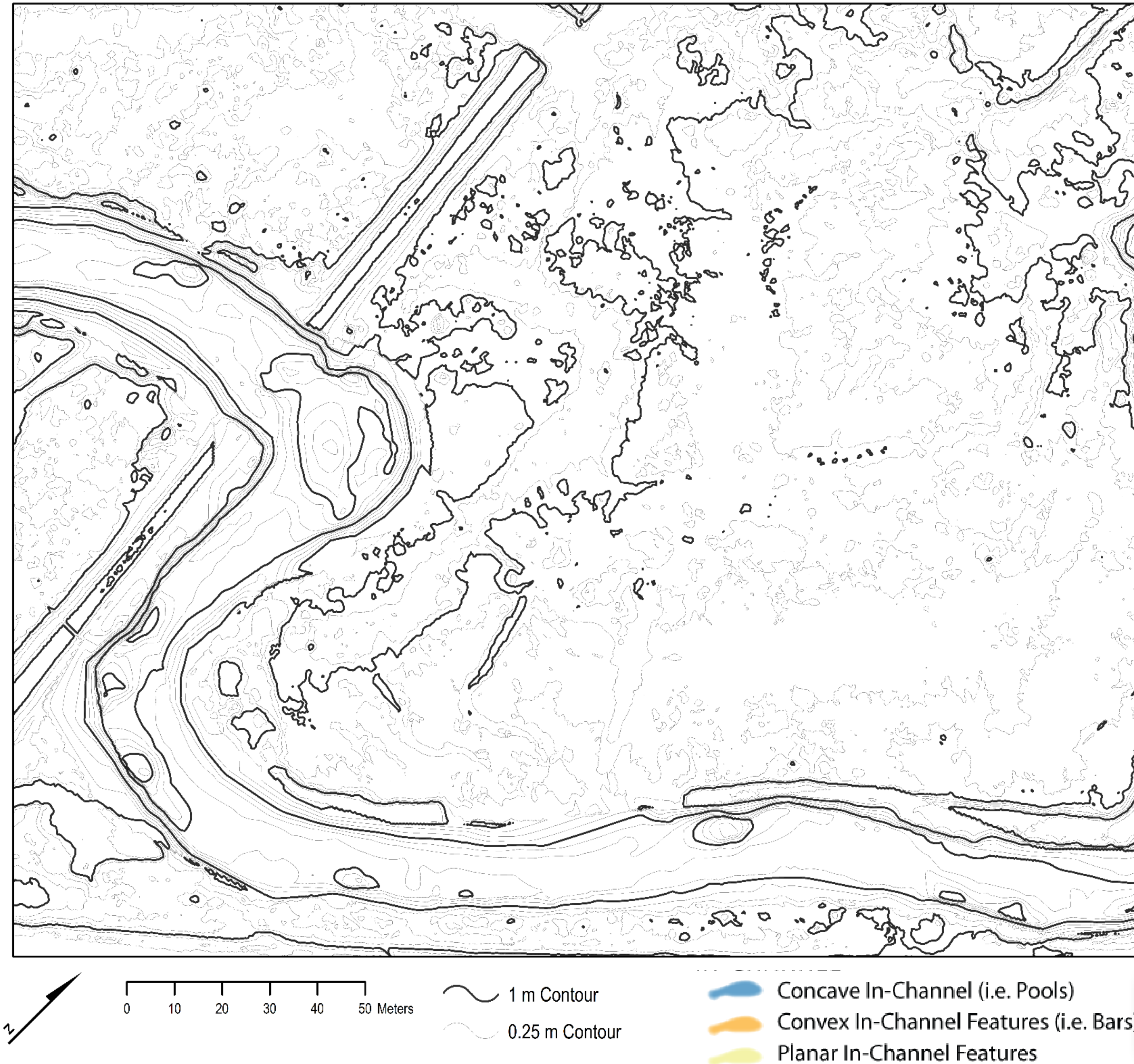
Tier 2 - Shape



- Just add a verb to tier 1, so it's a Concave In Channel Unit (i.e. concavity)

Concave Planar Convex

EXERCISE 4: MAP IN CHANNEL SHAPES (CONCAVITIES 1st, CONVEXITIES 2nd, PLANAR 3rd, TRANSITIONS)



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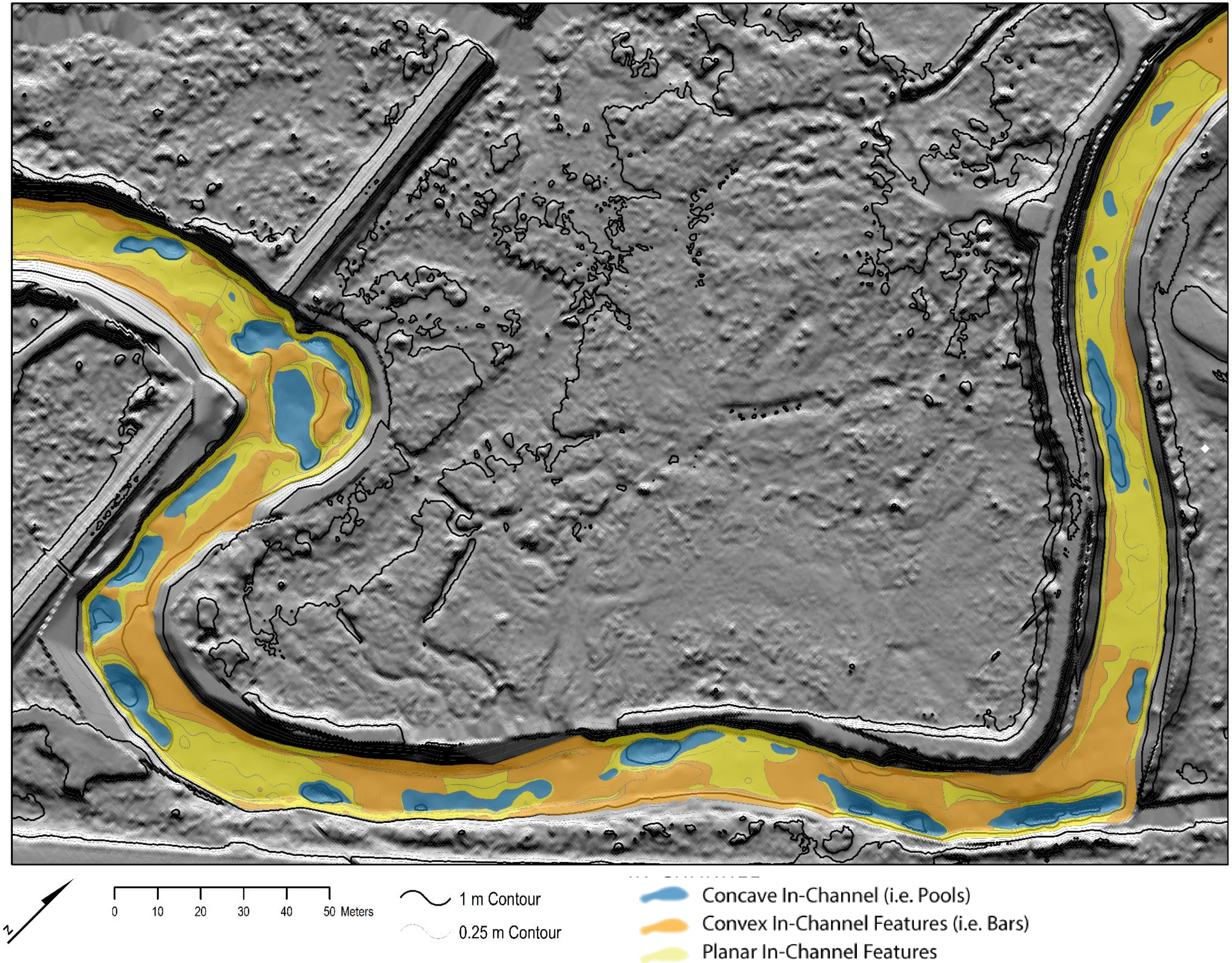
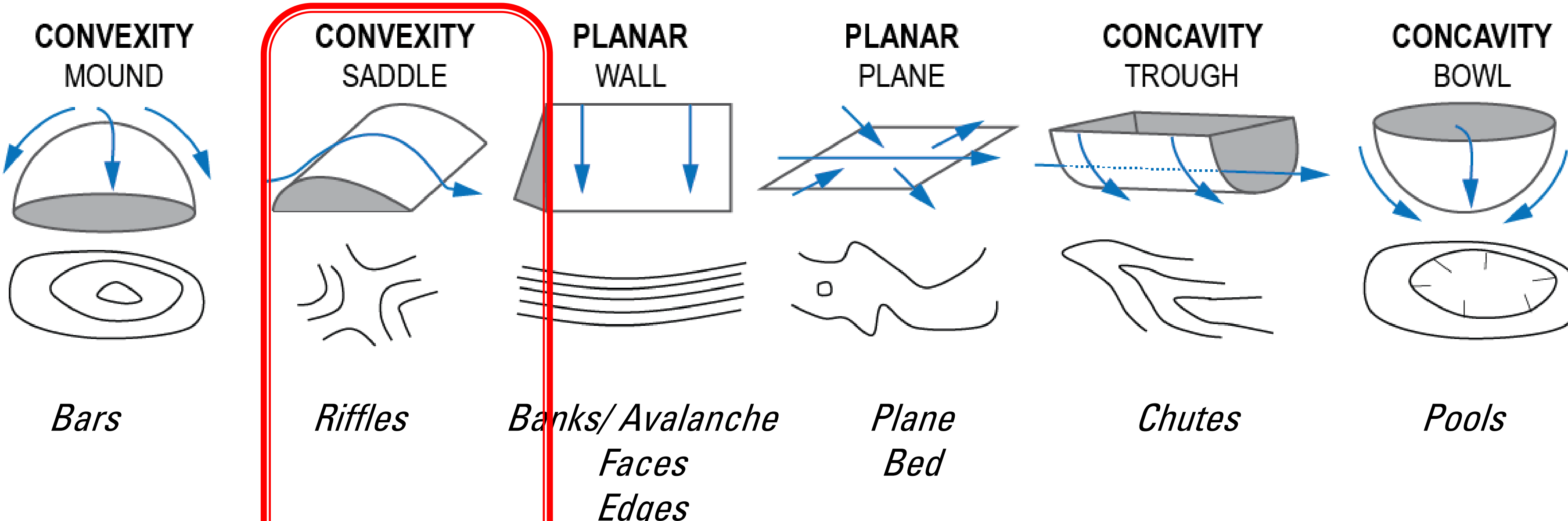
EXERCISE 4: MAP IN CHANNEL SHAPES (CONCAVITIES 1st, CONVEXITIES 2nd, PLANAR 3rd, TRANSITIONS)



Tier 2 - Form

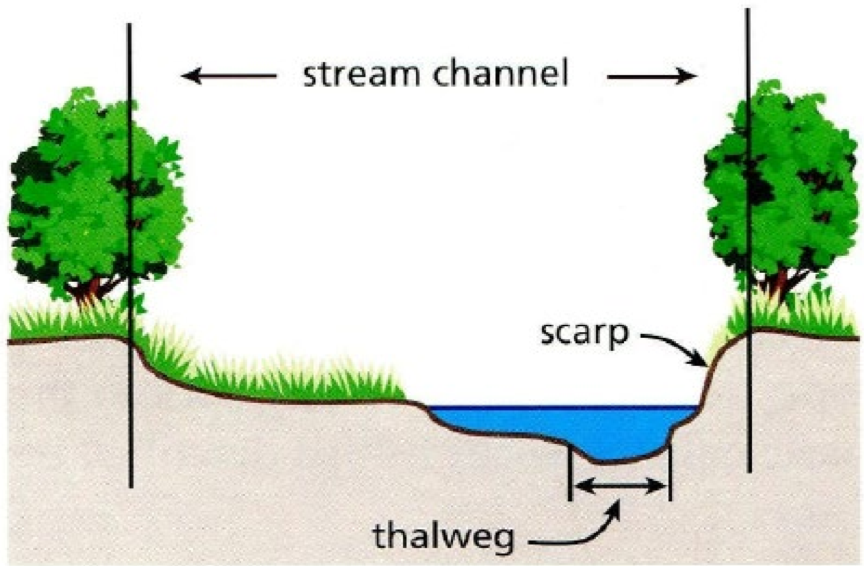
- Key for the riffle… is the thalweg…
- Flow goes up and over (convex), through the thalweg (concave)

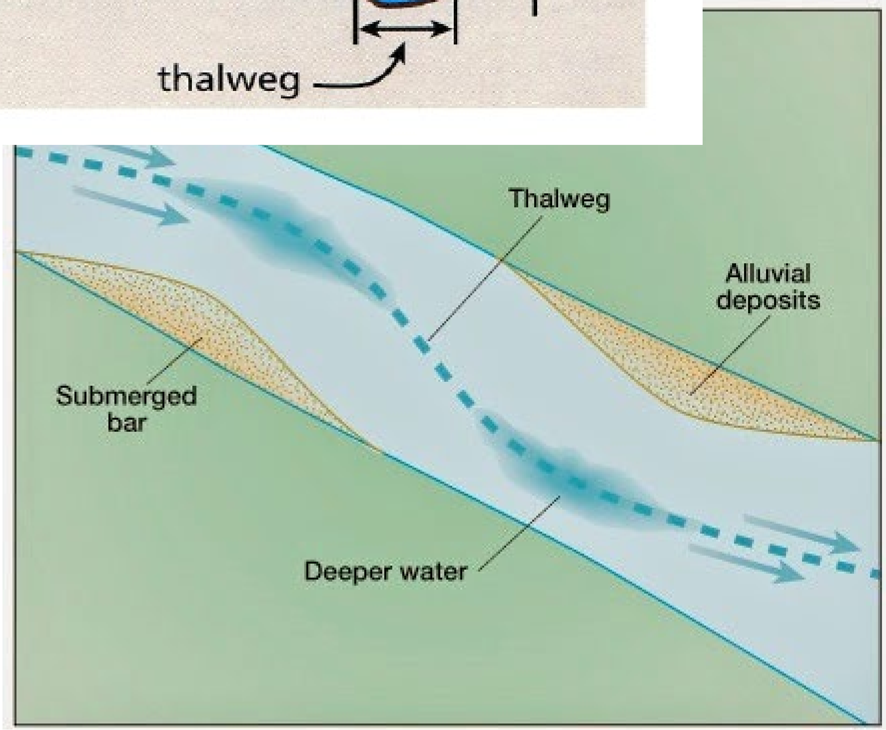


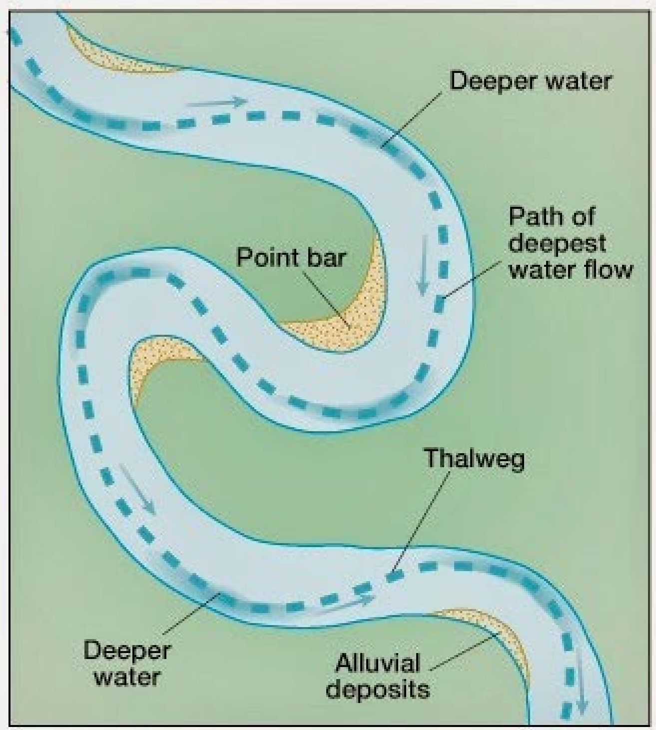
	Mound	Saddle	Wall	Plane	Trough	Bowl
XS	Convex	Concave	NA	Planar	Concave	Concave
LP	Convex	Convex	NA	Planar	Planar	Concave

What is a Thalweg?

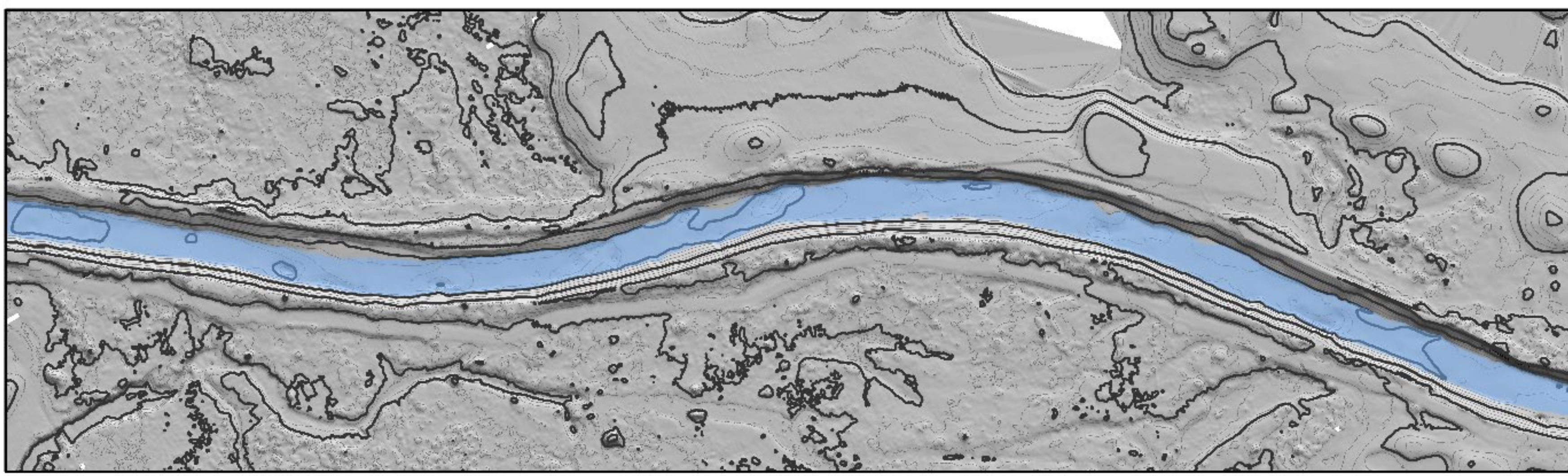
- The deepest part of the channel.





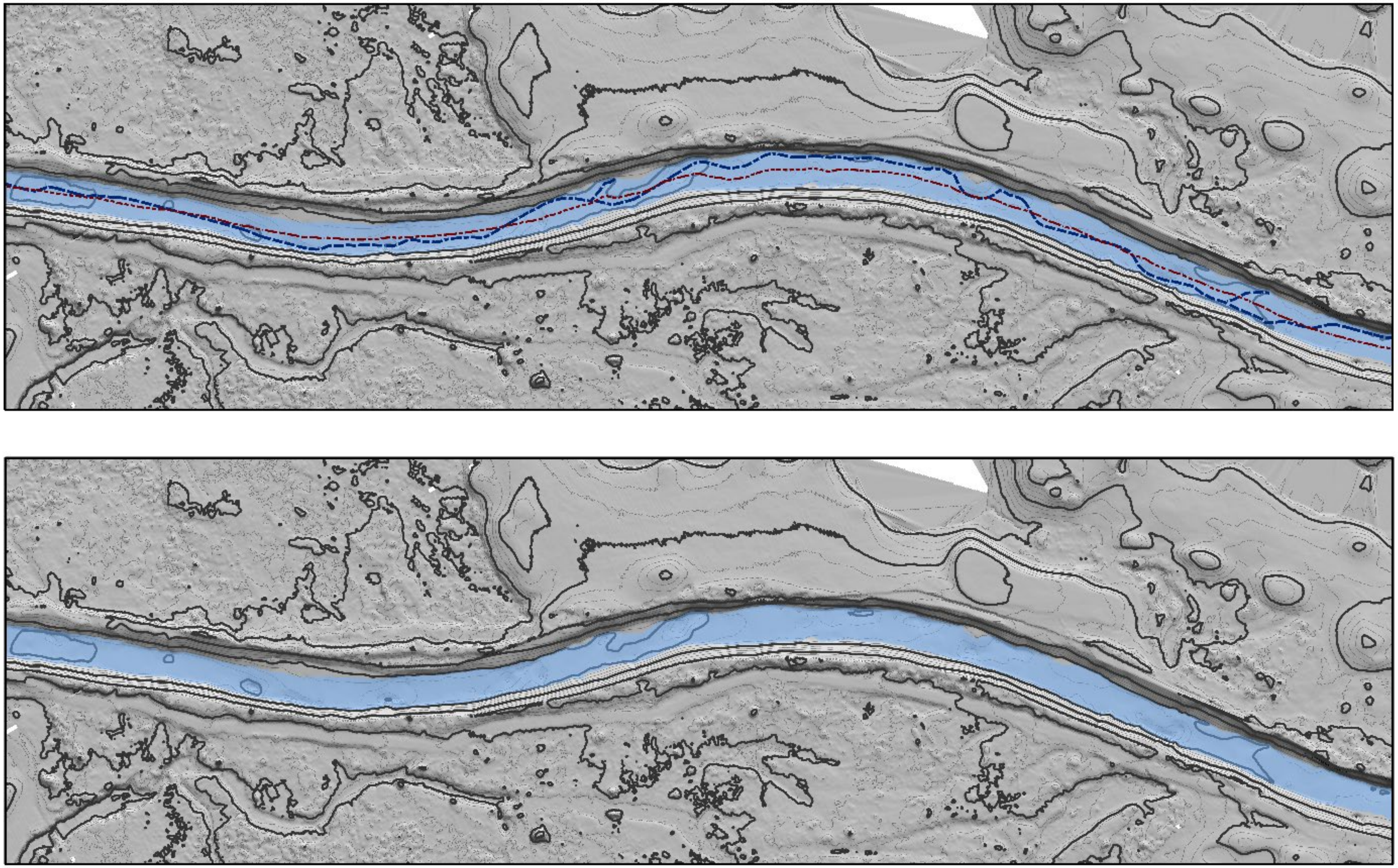


EXERCISE 5 – MAP THALWEG



25 cm Contour Interval
Flow is right to left

Lets Look at Some Thalwegs

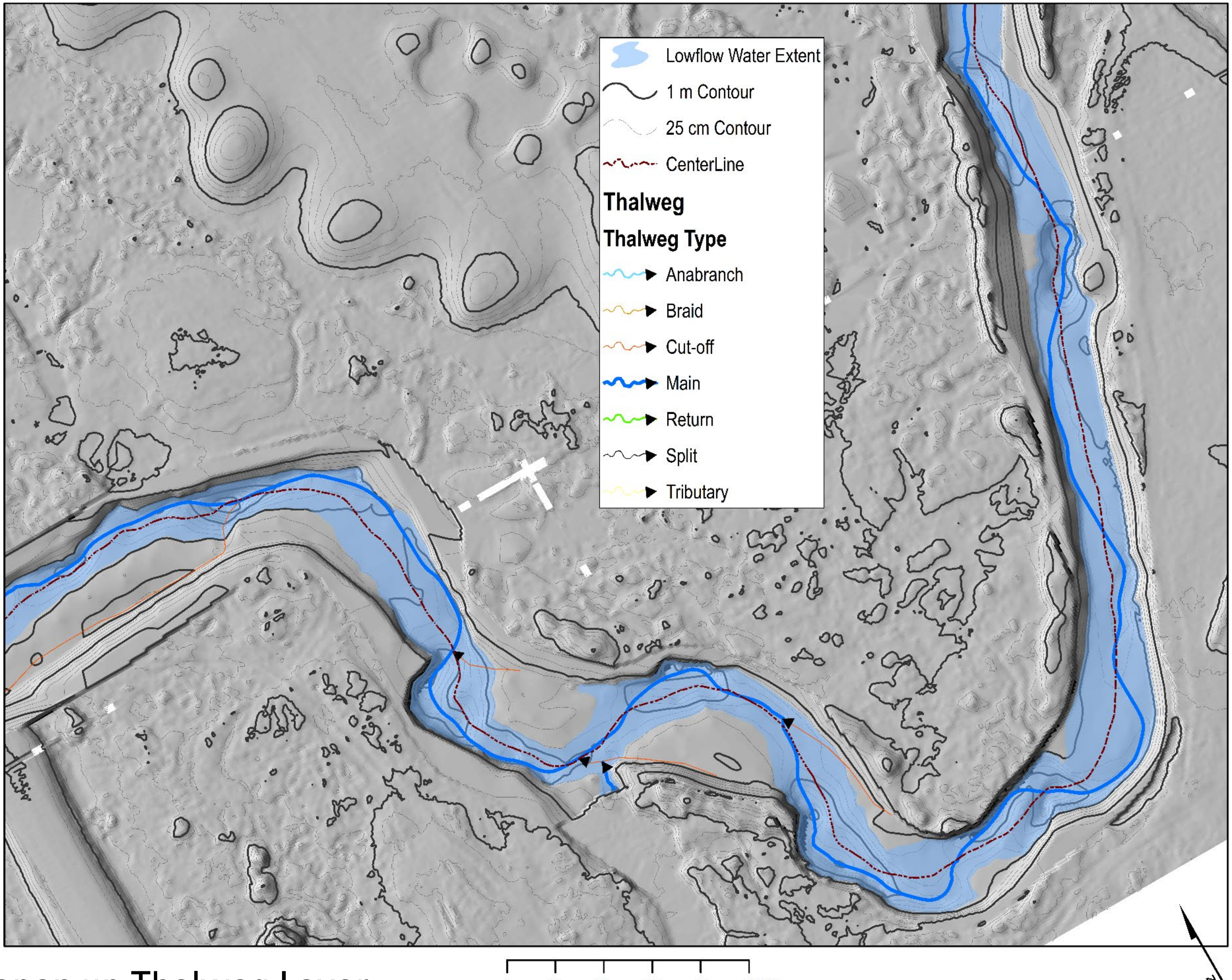


25 cm Contour Interval
Flow is right to left

Thalweg
WaterExtent
Centerline

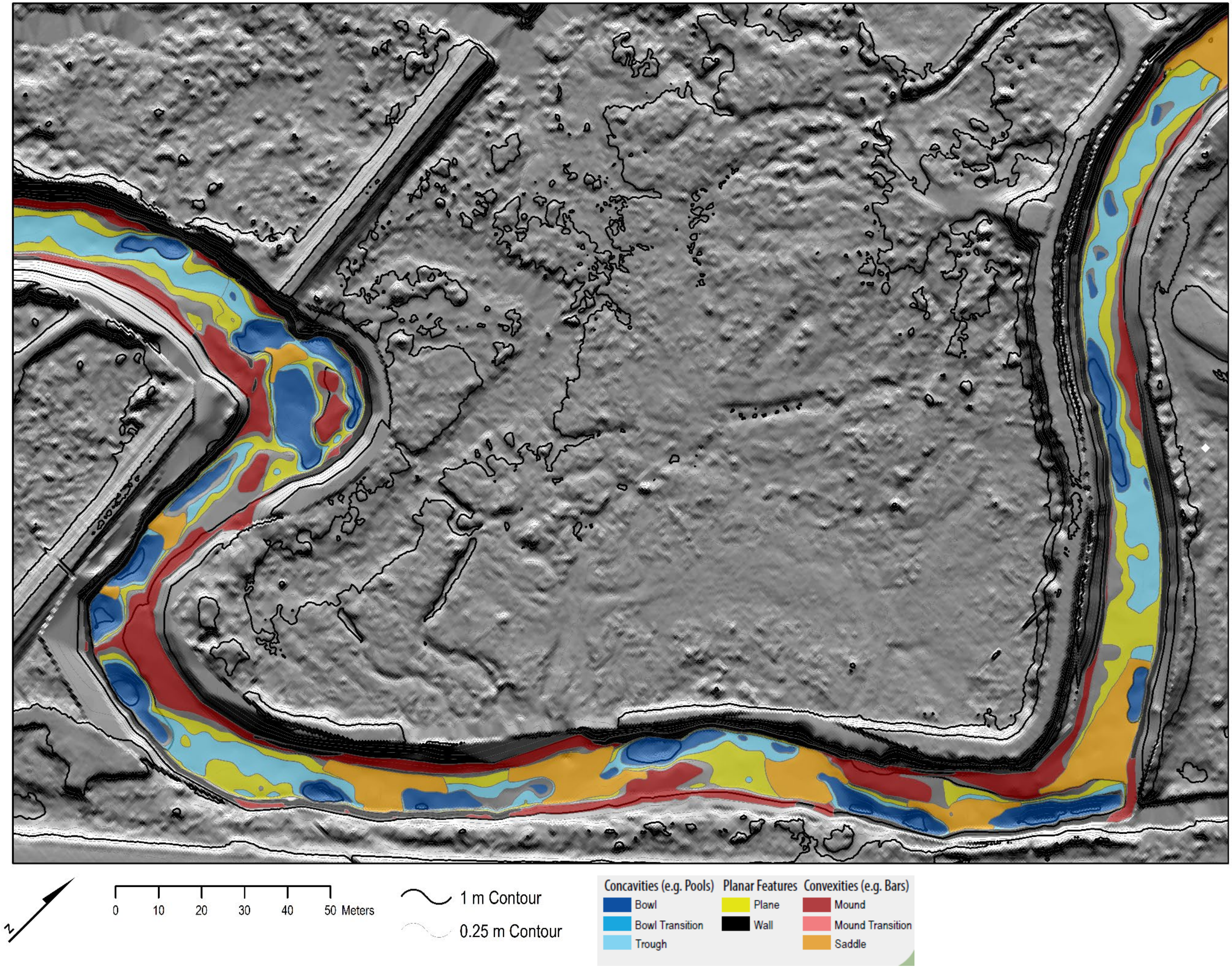
0 25 50 75 100 125 Meters

N

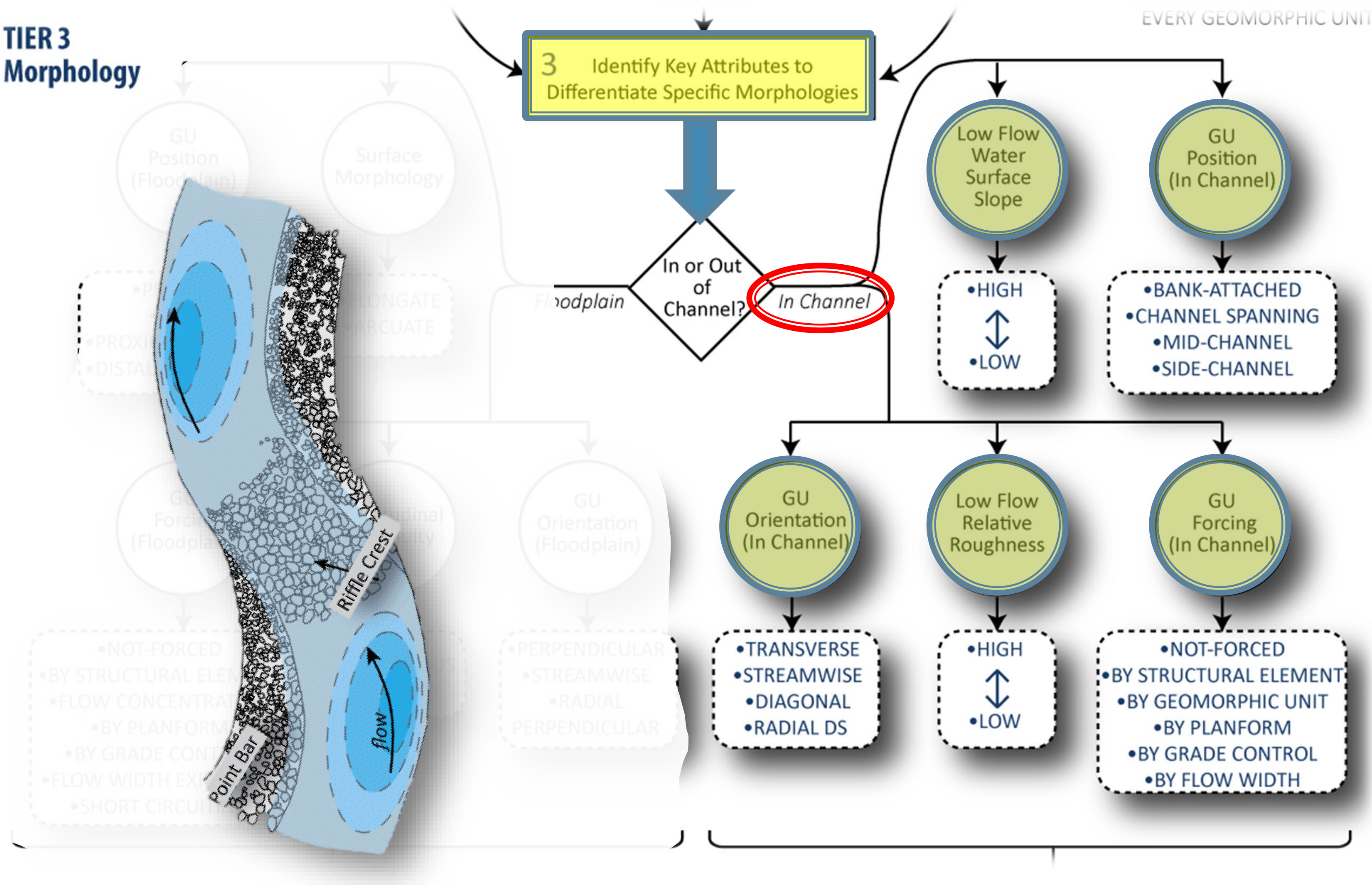


Lets open up Thalweg Layer

CHANNEL FORM



TIER 3 - MORPHOLOGY



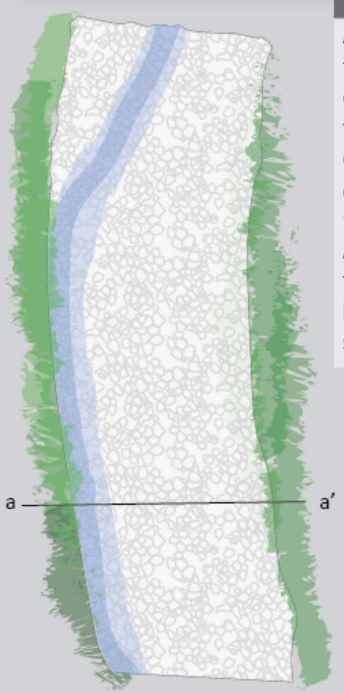
Key Tier 3 Attributes:	Types	Description
GU Forcing		Occurs when a non-uniform hydraulic flow pattern creates a flow environment conducive to forcing the formation, maintenance or accentuation of a geomorphic unit.
	∟ Not Forced	The GU forms on its own (e.g. free bars)
	∟ By Structural Element	Forcing can be caused by structural elements (e.g. large woody debris causing a plunge pool or an eddy bar)
	∟ By Geomorphic Unit	Forcing can be caused by another geomorphic unit (e.g. a pool can be forced by a bar)
	∟ By Planform	Forcing can be induced by sinuosity (e.g. flow separation on inside bends leading to point bars)
	∟ By Flow Width	Forcing is often associated with flow width expansion for depositional units and flow with constriction for erosional units
GU Orientation		The orientation is defined by the longest axis of the geomorphic unit and relative to dominant flow direction.
	∟ Transverse	Transverse units are oriented perpendicular to the flow (e.g. *riffles)*
	∟ Streamwise	Streamwise units are oriented parallel to the flow (e.g. *forced pools* are elongated in a streamwise fashion associated with the convergent flow jet)
	∟ Diagonal	Diagonal units intersect the channel at an angle and flow is shunted diagonally over them at high flows.
	∟ Radial DS	Some units have lobate shapes (e.g. *lobate bars*) which
GU Position		Defines the position of the GU within the low-flow channel
	∟ Bank-Attached	Many units are appended to the channel margins (e.g. *point bars*); Note 'bank-attached' is common termionology in the fluvial literature even though the entire length of all channels are bound by true banks. Channel margins is a more generic term, but less common.
	∟ Channel Spanning	Some units are bank-attached on both sides and span the entire low flow channel (e.g. *riffles*)
	∟ Mid-Channel	Some units are not attached to a channel margin and occur in the center of a channel (e.g. *longitudinal bar*)
	∟ Side-Channel	For some mapping purposes, it is helpful to differentiate units that only occur in side and/or secondary channels
Low Flow Water Surface Slope		Especially for in-channel, planar units, low flow water surface slope is a helpful way of differentiating across the spectrum from low-slope glides, through intermediate slope runs and riffles, through high slope rapids, up to very high slope cascades.
	∟ Flat	Water surface slope = 0
VARIES	**∟ Shallow**	Water surface slope < 0.005
	∟ Moderate	Water surface slope > 0.005 & < 0.03
	∟ Steep	Water surface slope > 0.03
Low Flow Relative Roughness		Relative roughness is defined as the ratio of roughness height to flow depth (z_0/h).
	∟ Low	Relative roughness < 0.5 (i.e. majority of flow depth not obstructed by substrate)
VARIES	**∟ Moderate**	Relative roughness between 0.5 and 1 (i.e. majority of flow depth obstructed by substrate, but substrate not protruding from water surface)
	∟ High	Relative roughness > 1 (i.e. particles protruding from water surface)
	∟ Very High	Relative roughness >> 1 (i.e. flow depth is negligible relative to massive boulders protruding from water surface)

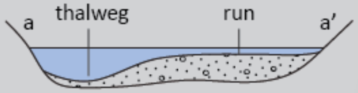
Tier 1	Tier 2	Tier 3	Key Attributes to Differentiate Specific Morphologies						
Stage Height	Shape/Type	Specific Morphology	GU Forcing	Low Flow Relative Roughness	GU Orientation	GU Position	Low Flow Water Surface Slope	Also Known As	Similar to or Confused With
In-Channel									
∟	**Convexity (e.g. bar)**								
	∟	Backwater Bar	Grade Control	Varies	Varies	Side Channel	Varies	Slackwater deposit	Similar to other bars but found in disconnected side channels or secondary channels
	∟	Boulder Bar	Flow Width	Varies	Streamwise	Bank-Attached or Mid-Channel	Varies	Boulder Berm	Similar to other bars, but in much higher gradient systems.
	∟	Compound Bar	Varies	Varies	Varies	Varies	Varies	Bar complex	An amalgamation of multiple unit bars and other bar types (complex history)
	∟	Confluence Bar	Grade Control	Varies	Radial DS & Streamwise	Bank-Attached	Varies	NA	Expansion bar, except in response to gradient drop from tributary to mainstem.
	∟	Diagonal Bar	Planform & Flow Width Expansion	Varies	Diagonal	Mid-Channel	Varies	Mid-Channel Bar	Point bar, but no longer bank-attached (separated by chute)
	∟	Eddy Bar	Planform, SE, and/or Flow Width Constriction	Varies	Streamwise	Bank-Attached or Mid-Channel	Varies	Separation Bar	
	∟	Expansion Bar	Flow Width	Varies	Transverse	Mid-Channel	Varies	NA	Transverse bar, but in response to slope lowering, and does not span channel
	∟	Forced Bar	Varies	Varies	Streamwise	Bank-Attached or Mid-Channel	Varies	NA	Eddy Bar
	∟	Forced Riffle	Channel Spanning SE	Moderate (< 1)	Transverse	Channel Spanning	Shallow	NA	Riffle, but forced by channel spanning structural element buried in bed
	∟	Lateral Bar	By Planform or By Flow Width	Varies	Streamwise	Bank-Attached	Varies	Alternate Bar	Point bars, but can be in bends with lower curvature or channels with lower sinuosity or straight
	∟	Lobate Bar	Grade Control	Varies	Radial DS	Mid-Channel	Varies	Mid-Channel Bar	Similar to other mid-channel bars but distinctive in DS tear-dropped shape and avalanche faces
	∟	Longitudinal Bar	Flow Width	Varies	Moderate (< 1)	Mid-Channel	Varies	Mid-Channel Bar	Similar to other mid-channel bars but distinctive in elongated streamwise orientation and upstream convexity at bar head
	∟	Point Bar	Planform forced	Varies	Streamwise	Bank-Attached	Varies	Bank-Attached Bar	Alternate bars, but in bends with higher curvature
	∟	Reattachment Bar	Varies	Varies	Streamwise	Bank-Attached	Varies	NA	Eddy Bar, but occurs DS of both flow separation and reattachment point
	∟	Ridge	Forced by SE and Flow Separation	Varies	Streamwise	Bank-Attached	Varies	NA	Scroll bar or levee; generally straighter, more linear feature
	∟	Riffle	Flow Width Expansion	Moderate (< 1)	Transverse	Channel Spanning	Moderate	Transverse Bar	Sometimes confused with runs
	∟	Scroll Bar	Planform & Flow Width Expansion	Varies	Streamwise	Bank-Attached	Varies	NA	Ridge, but positioned on point bar and generally curved
	∟	Unit Bar	Flow Width Expansion	Varies	Varies	Varies	Varies	NA	The fundamental building block of all bars

SHALLOW THALWEG

Tier 1 - in-channel
∟Tier 2 - Concavity (in channel cross section)

Key Attributes to Differentiate Specific Morphologies				
GU Forcing	Low Flow Relative Roughness	GU Orientation	GU Position	Low Flow Water Surface Slope
Forced by planar GU or occasionally bars	Varies	Streamwise	Bank- Attached	Varies, but typically moderate





channel cross-section

GEOMORPHIC FORM

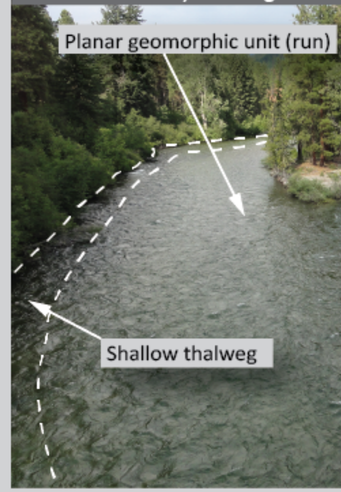
A shallow thalweg is an in-channel concavity, found on the outside bend of a channel that is distinctive because although it shows a concave form in cross section, longitudinally it lacks a concavity or residual pool. *A thalweg is simply the deepest part of the cross section of the channel, which can be traced as a line along any channel.* A shallow thalweg is a concave geomorphic unit that surrounds this line and is distinctive for its bank-attached position and its elongate and streamwise orientation along the thalweg.

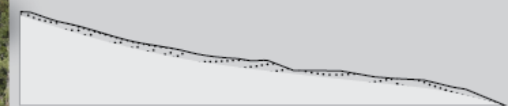
Asotin River, Washington

TYPICAL CONFIGURATIONS

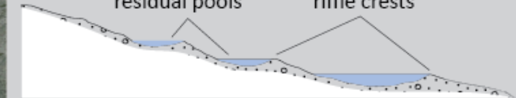
Shallow thalwegs are typically found along the banks of the outside bends of channels, where the main channel is dominated by planar geomorphic units (e.g. runs, glides, rapids), or occasionally poorly defined, broad-faced bars. Their position is one in which you often expect to find a pool, but this concavity lacks a residual pool of qualifying size.

Wenatchee River, Washington





The long profile of a channel associated with a shallow thalweg, lacking pools or residual pool features. The shallow thalweg would not have a puddle left over if the river were drained.



A long profile with riffles and pools and residual pool features shown

PROCESS INTERPRETATION

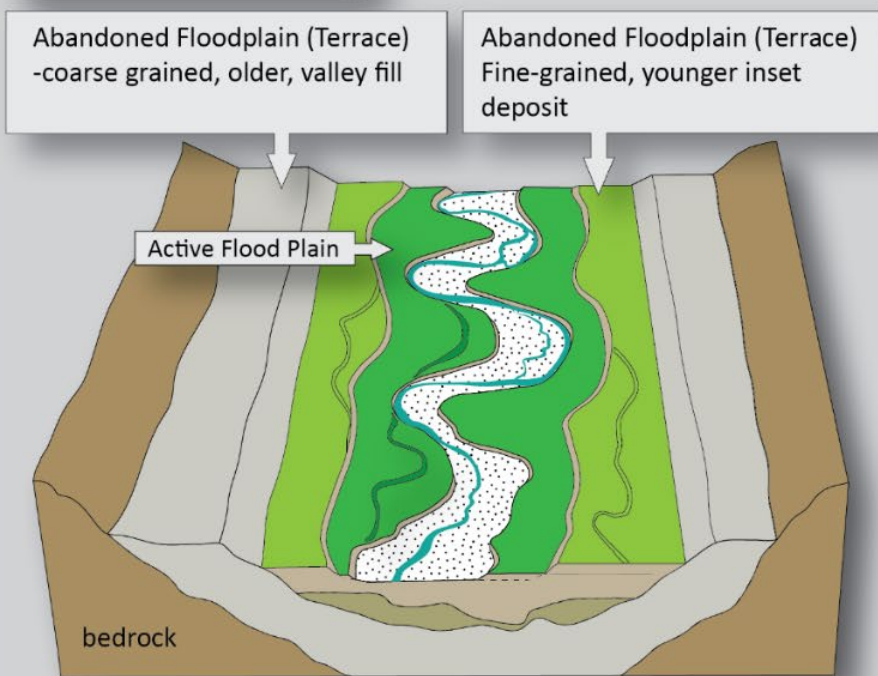
Shallow thalwegs are typically stable geomorphic units characterized by modest erosion in an outside bend (usually of low curvature), that is inadequate to excavate or maintain a pool. They form adjacent to planar geomorphic units or broad bars that steer the flow towards the edge of the channel so they winnow out a thalweg where those flows are concentrated. Shallow thalwegs are maintained most often in stable channels that are transport limited (e.g. plane-bed). They also form in non-transport limited situations where active bars or planar units force lateral migration and bank erosion where the rate of retreat is overwhelmed by deposition from the bar, which prevents a pool from fully forming (for pools to form in this situation would require a more resistant bank to concentrate the flow energy).

SIMILAR TO OR MISTAKEN WITH

Shallow thalwegs are similar to elongated bar-forced pools on outside bends and could be confused with them if the pool is weakly formed. They could also be confused with a chute, which tends to short-circuit flows across bar or floodplain surfaces and not be located on an outside bend.

ABANDONED FLOOD PLAIN (TERRACE)

Tier 1 - (< or > bankful)
Tier 2- Active Flood plain
Tier 3 - Bank Attached
Tier 4 - Floodplain

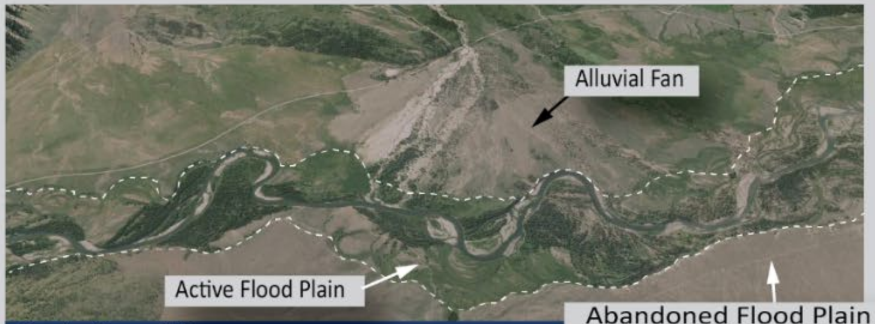


GEOMORPHIC FORM

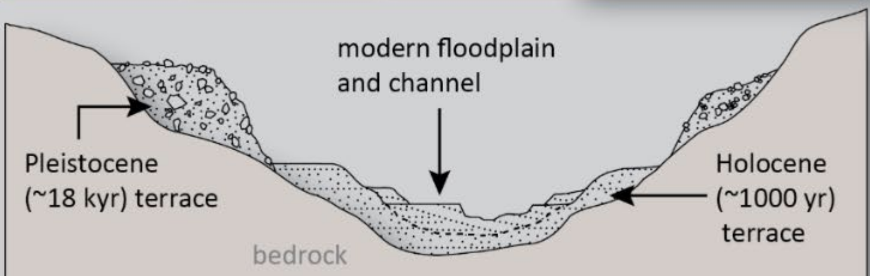
An abandoned Flood Plain (Terrace) is a valley bottom, planar accumulation of stream-deposited alluvium that is no longer directly associated with the active channel. Terraces comprise a ***tread***, the planar upper surface representing the relict floodplain surface; and a ***riser***, the erosional slope or flank of the terrace landform. Terrace sequences can be inset within other terrace deposits forming "flights" of step-like features surrounding the active channel (see above and right).

PROCESS INTERPRETATION

Terraces form as valley-fill floodplain sediments are later eroded (incised) and remnant surfaces are left abandoned along the channel margins. Terraces can form as ***cut*** features, by subsequent incision of valley fill alluvium; as ***fill*** features that are subsequently eroded into terrace forms; or as purely erosional ***strath*** surfaces, etched into resistant deposits, or even bedrock of the confining canyon walls.



Snake River, WY

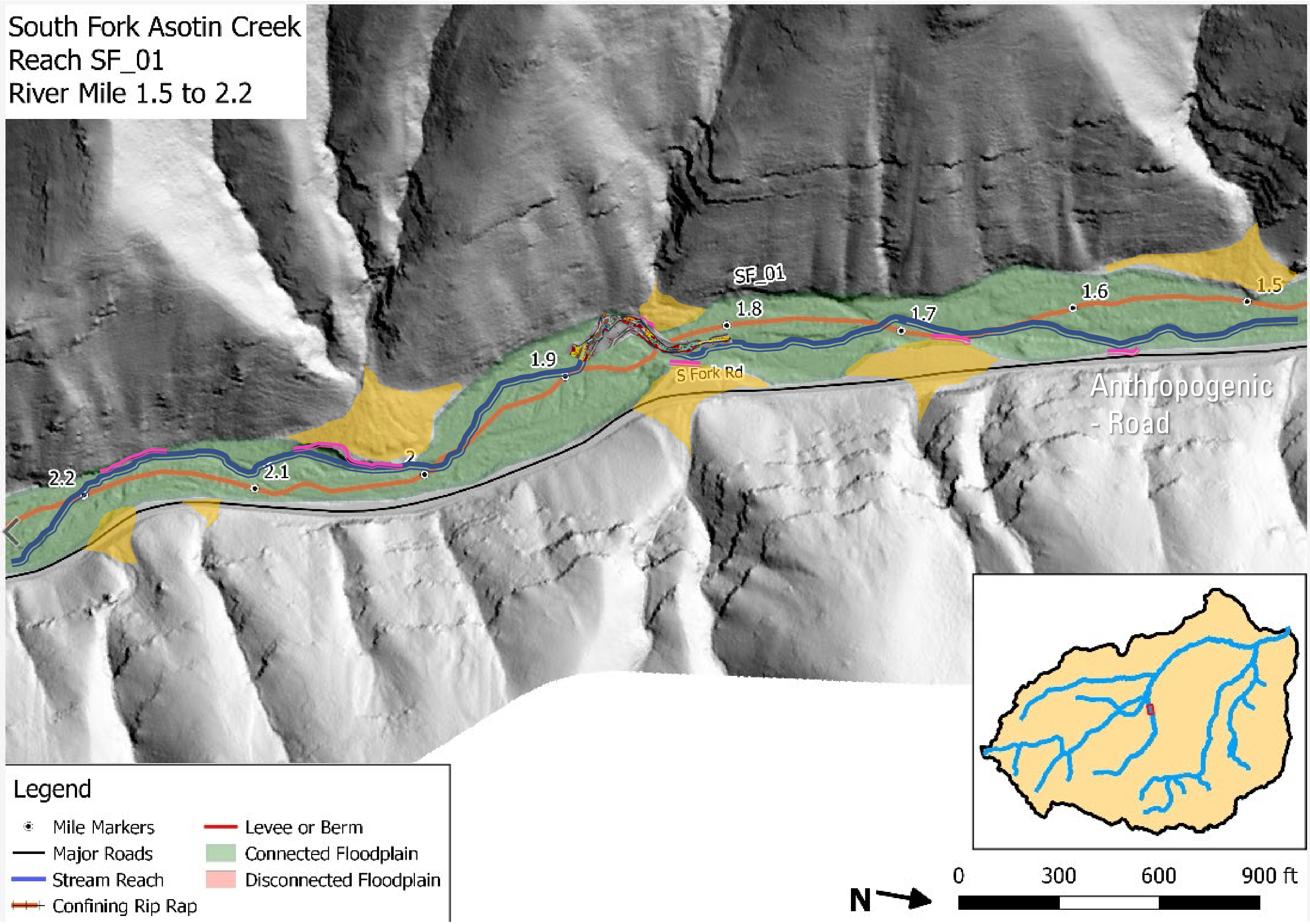


Cross Section of river channel showing inset and remnant terraces

ASSOCIATED GEOMORPHIC UNITS AND STRUCTURAL ELEMENTS

Abandoned floodplains-terraces-are closely associated with both floodplain and hillslope geomorphic units. Older, coarse terrace remnants directly overlie bedrock (above); younger, fine-grained and inset terraces underlie the contemporary floodplain and include paleochannels, channel cutoffs and banks (at left). Terraces are generally not in contact with instream geomorphic units, except where the abandoned floodplain acts as the confining boundary--in this case, the terrace riser would exhibit cutbank forms, and would supply sediment to the active channel.

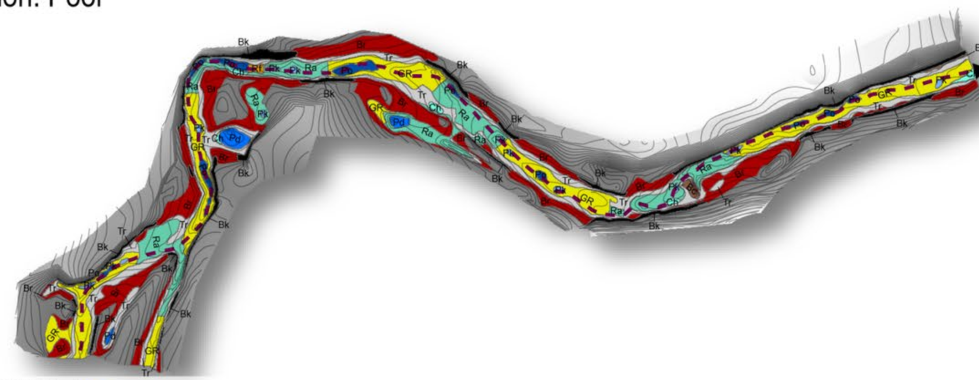
Here's a map of the valley setting for a detailed reach

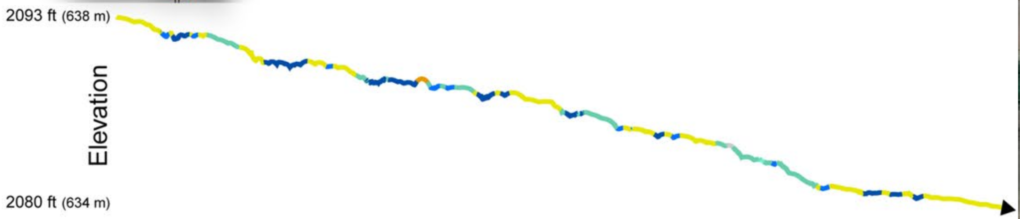


South Fork Asotin Creek: Planformed Controlled with Discontinuous Floodplain

Latitude: 46.2486
Longitude: -117.2

Condition: Poor





Geomorphic Units - Tier 3

IN-CHANNEL

Concavities (e.g. Pools)
- Chute (Ch)
- Pocket Pool (Pk)
- Pond (Pd)
- Pool (Po)

Convexities (e.g. Bars)
- Margin Attached Bar (Br)
- Mid-Channel Bar (Bc)
- Riffle (Rf)

Planar Features
- Cascade (Ca)
- Rapid (Ra)
- Run (GR)
- Transition Zones (Tr)
- Bank (Bk)

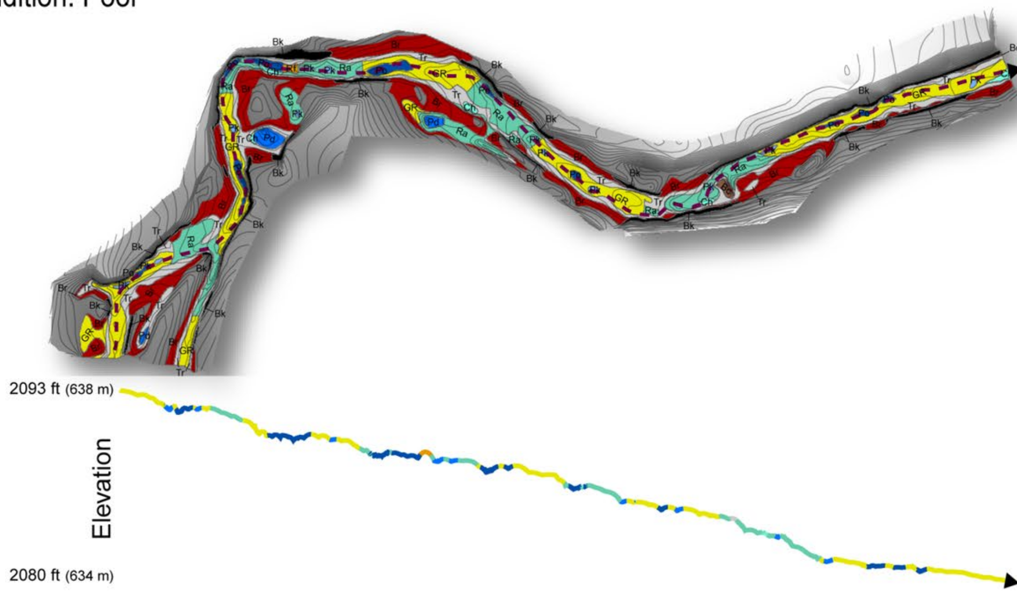
Channel Features
- Thalweg
- Old Thalweg

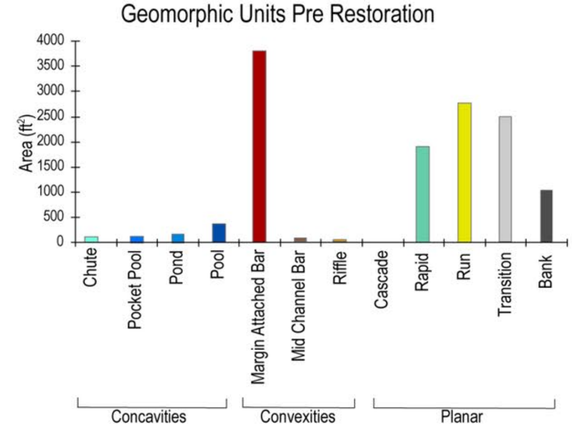
Structural Elements
- LWD

South Fork Asotin Creek: Planformed Controlled with Discontinuous Floodplain

Latitude: 46.24869088939191
Longitude: -117.2892015084726

Condition: Poor





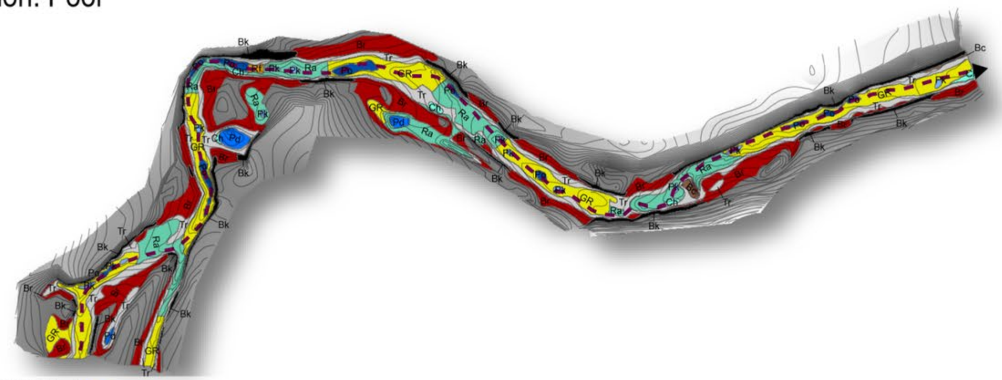
- Plane bed dominated (rapids & runs)
- Starved of wood..
- Limited interaction with floodplain

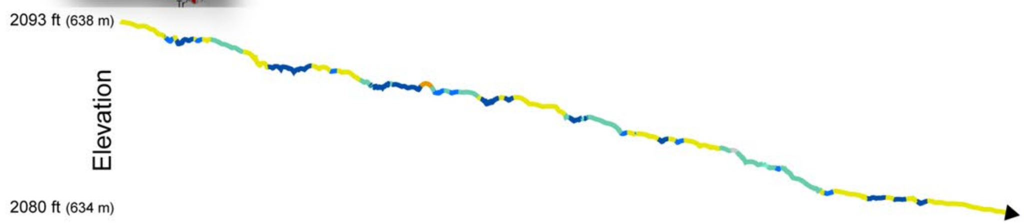
Adding P.A.L.S. (Wood)

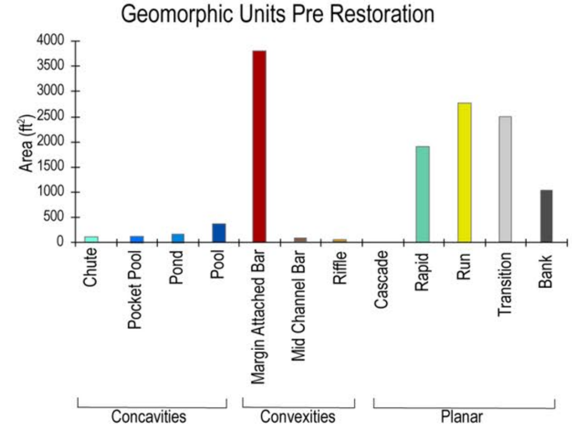
South Fork Asotin Creek: Planformed Controlled with Discontinuous Floodplain

Latitude: 46.24869088939191
Longitude: -117.2892015084726

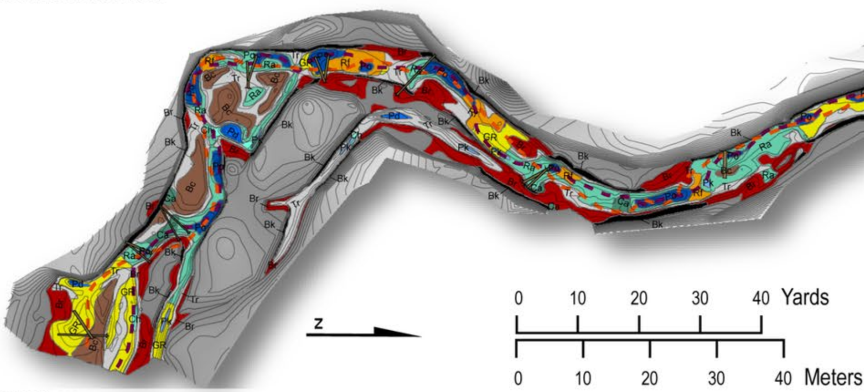
Condition: Poor

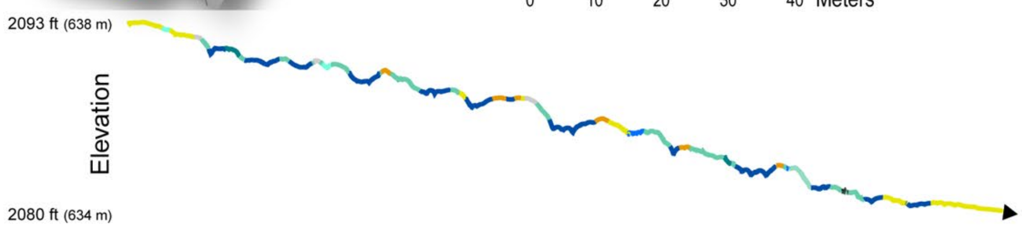


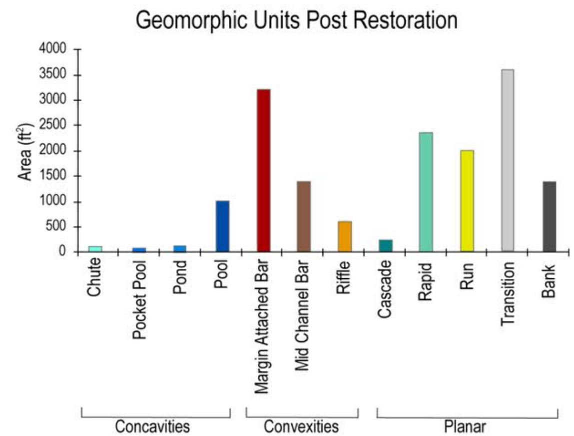


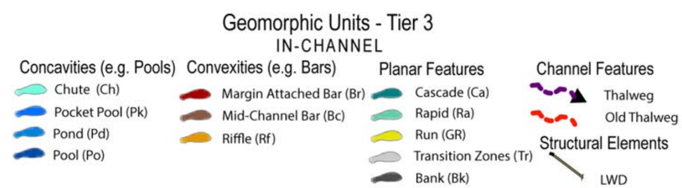


Condition: Moderate









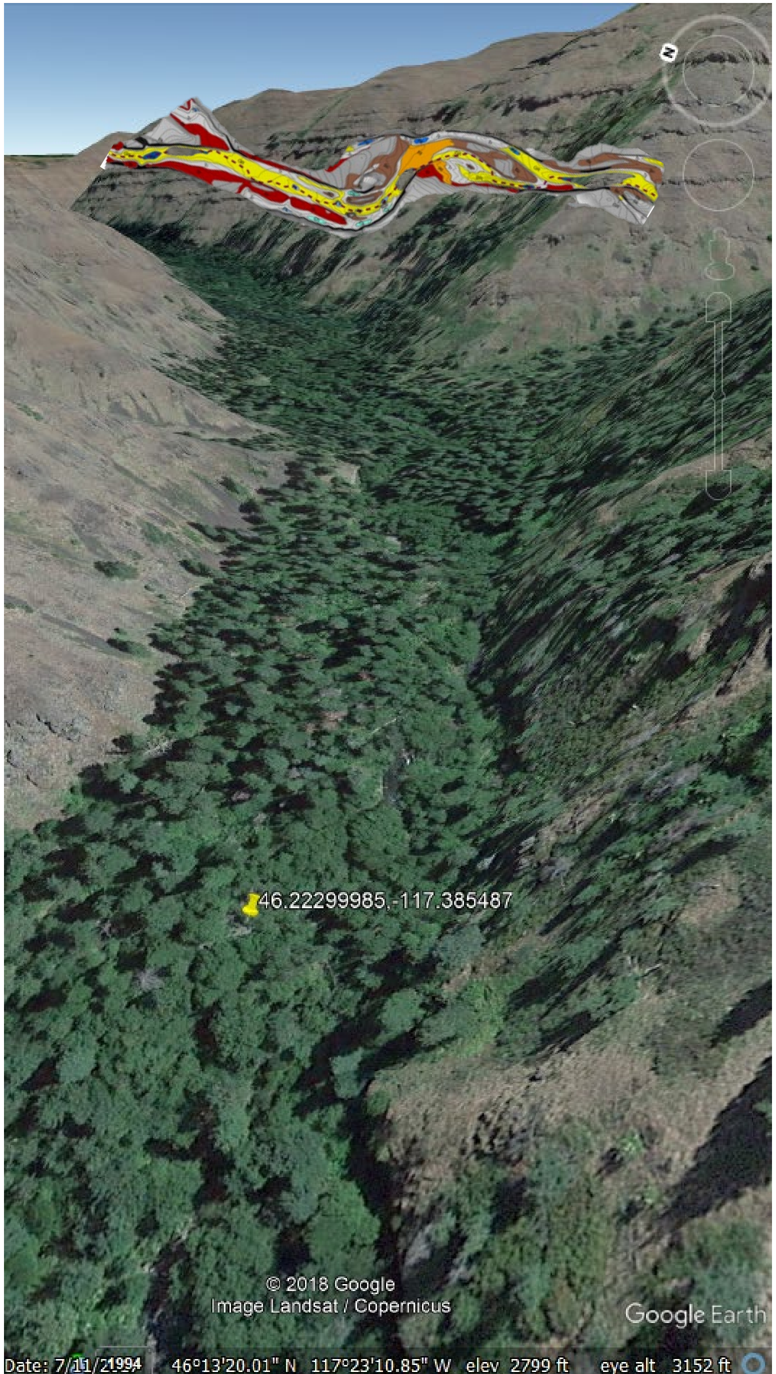

46.22299985,-117.385487
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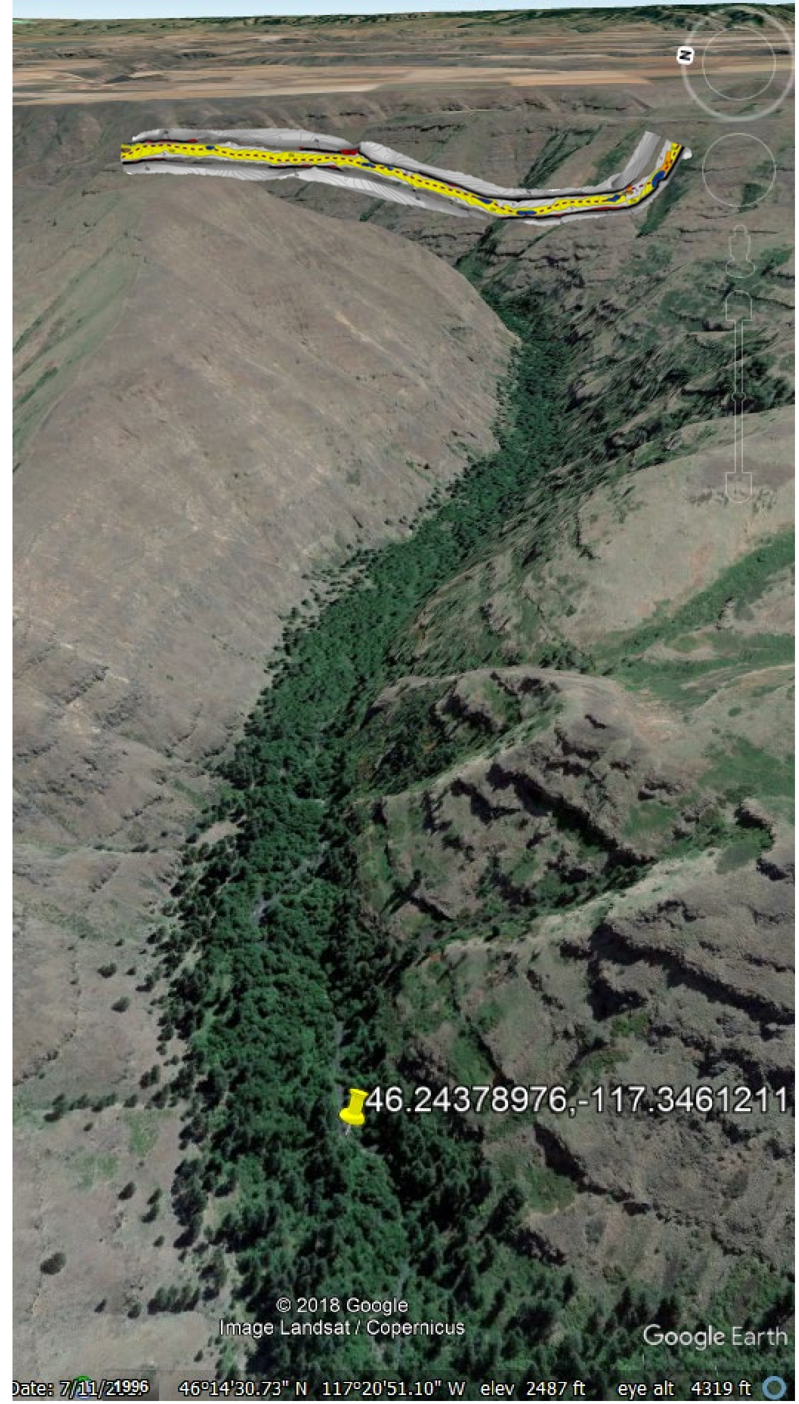
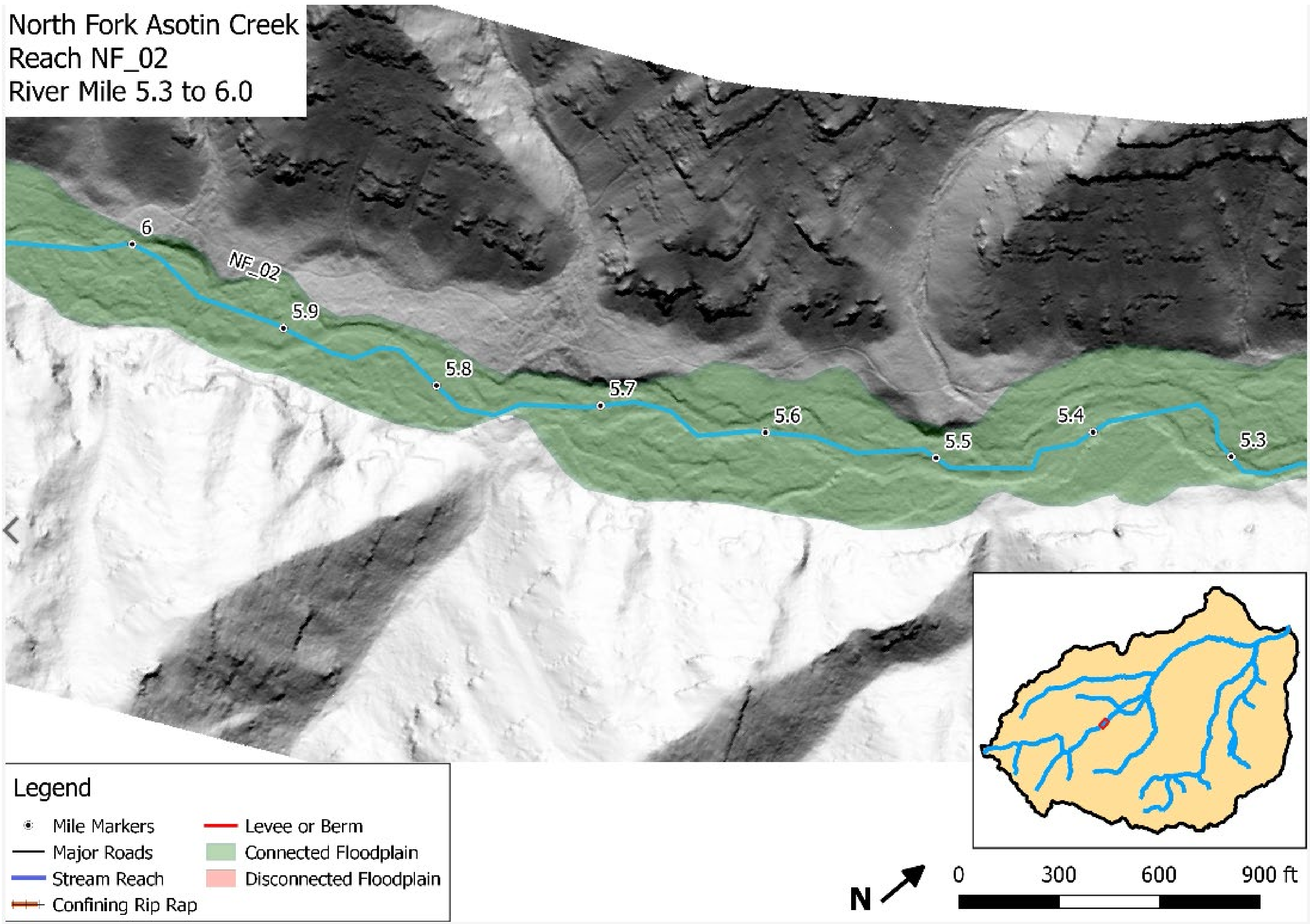
Image Landsat / Copernicus
Google Earth
46°13'20.01" N 117°23'10.85" W elev 2799 ft eye alt 3152 ft


46.24378976,-117.3461211
© 2018 Google
Image Landsat / Copernicus
Google Earth
46°14'30.73" N 117°20'51.10" W elev 2487 ft eye alt 4319 ft

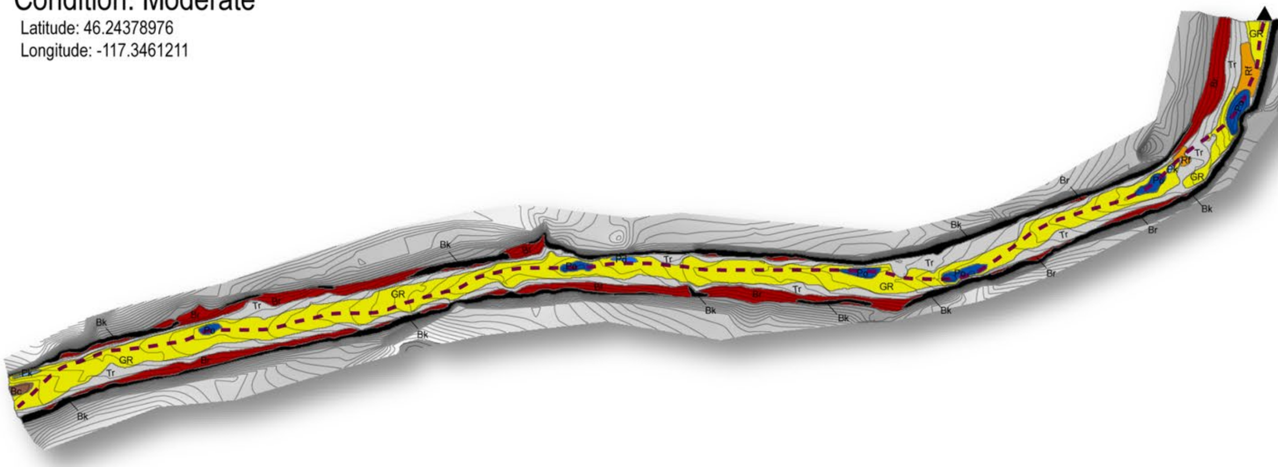


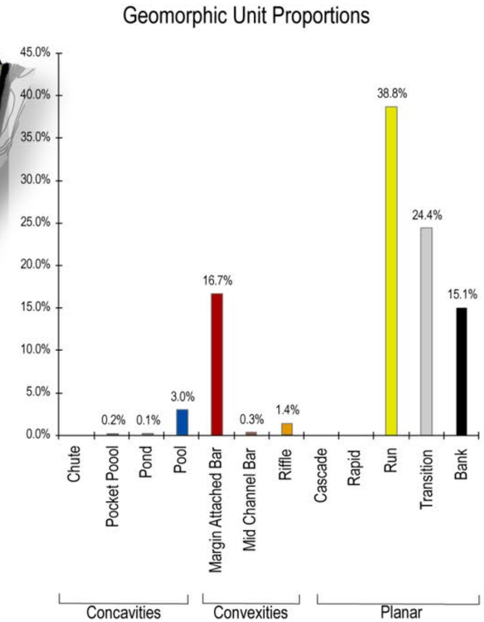
North Fork Asotin Creek
Reach NF_02
River Mile 5.3 to 6.0
6
NF_02
5.9
5.8
5.7
5.6
5.5
5.4
5.3
Legend
Mile Markers
Major Roads
Stream Reach
Confining Rip Rap
Levee or Berm
Connected Floodplain
Disconnected Floodplain
N
0
300
600
900 ft

North Fork Asotin Creek: Wandering Gravel Bed with Discontinuous Floodplain

Condition: Moderate

Latitude: 46.24378976
Longitude: -117.3461211

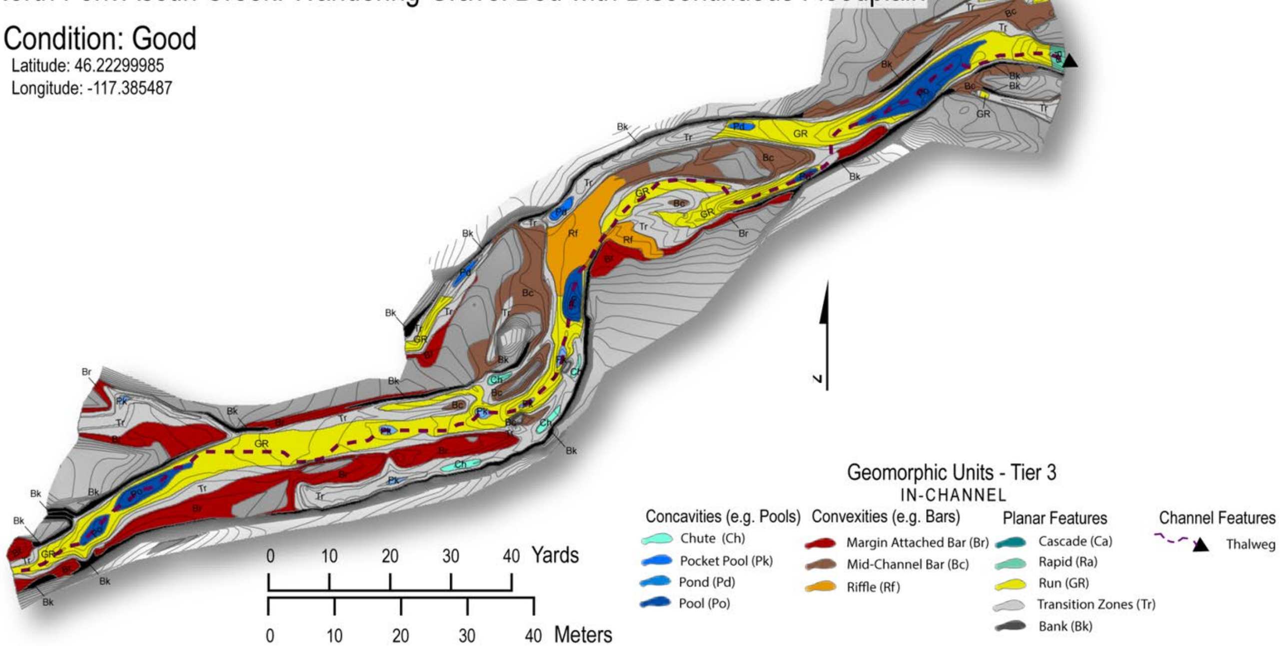


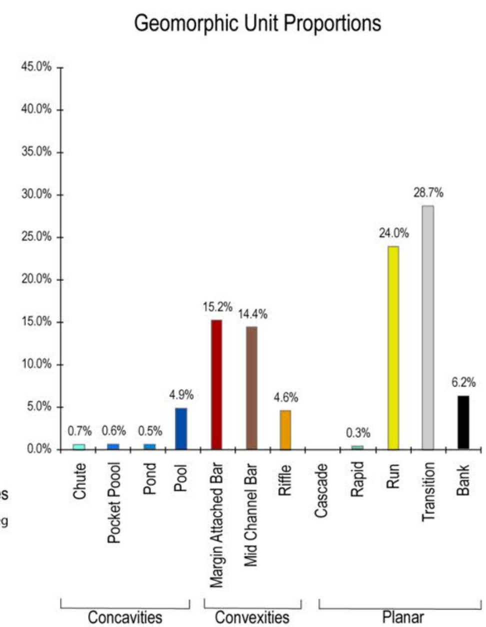


North Fork Asotin Creek: Wandering Gravel Bed with Discontinuous Floodplain

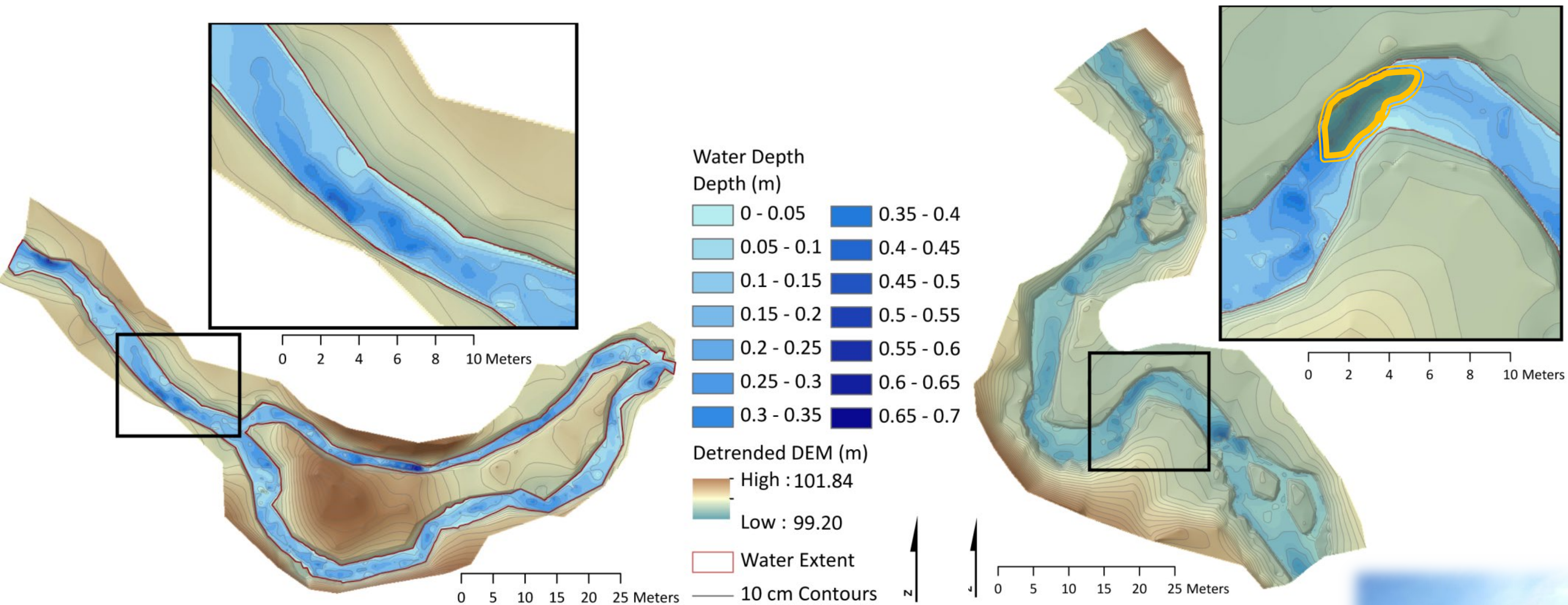
Condition: Good

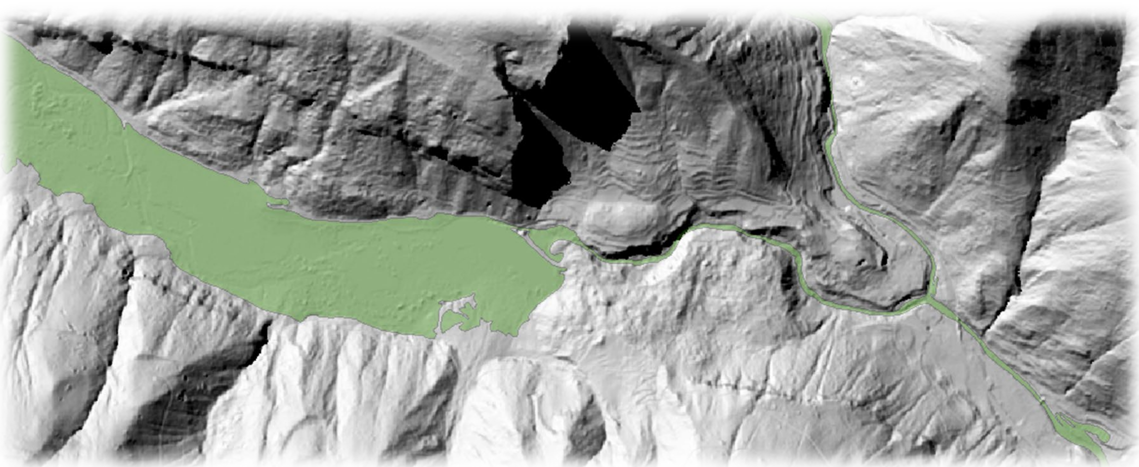
Latitude: 46.22299985
Longitude: -117.385487





How do we map GU's across valley & reach scales?





GUT – Geomorphic Unit Toolkit

Inputs:

- DEM (raster)
- Thalwegs (polyline)
- Centerlines (bankfull & low flow channel) polyline
- Waters Edge (low flow) polygon
- Bankfull polygon

Output:

Tier 1, Tier 2, Tier 3 Geomorphic Units

https://riverscapes.github.io/pyGUT/

TIER 1: Valley & Flow Units

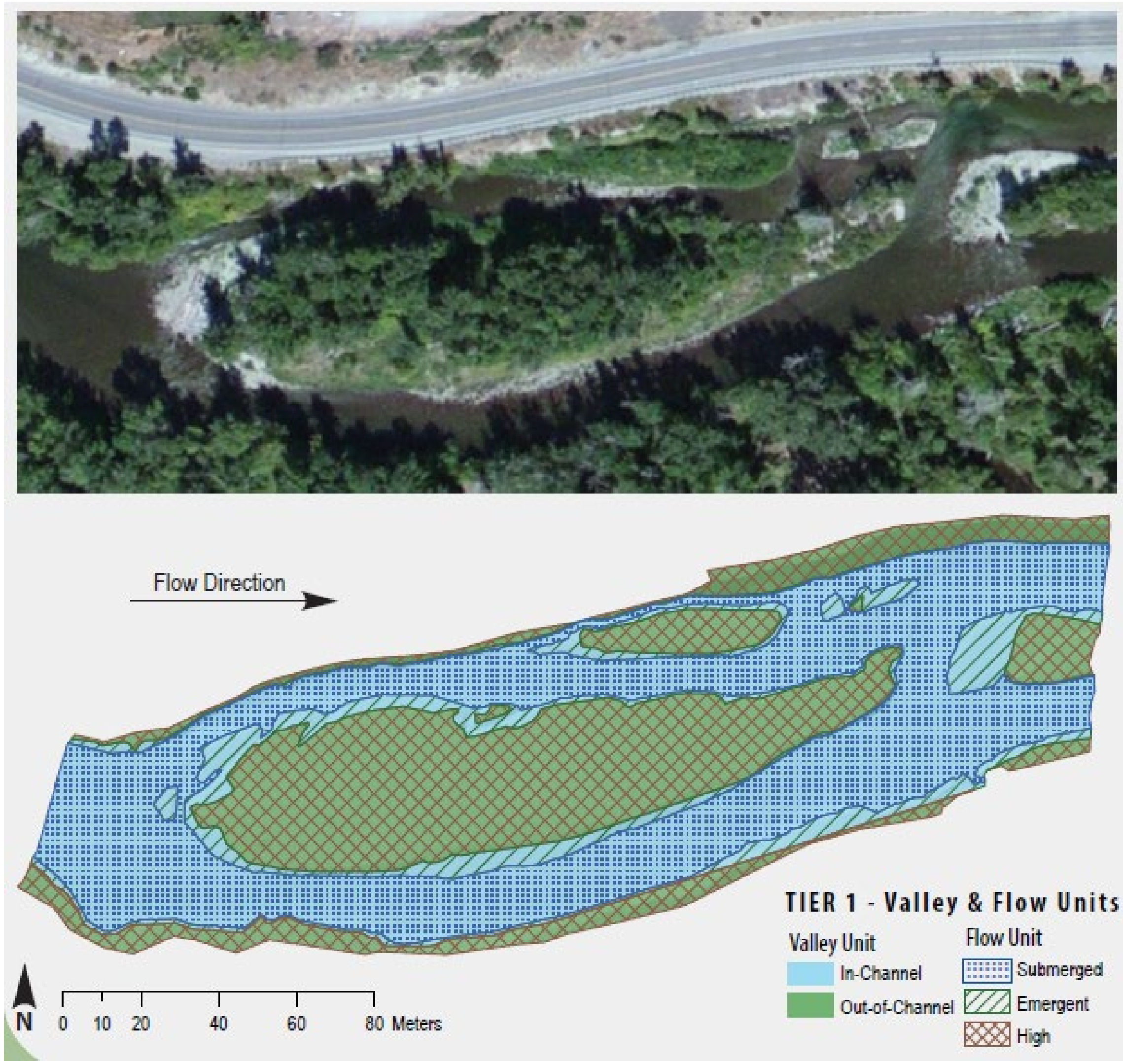


Figure 3: GUT Tier 1 output for CHaMP reach (ENT00001-1BC1) on the Entiat River (WA). This site is a low gradient (0.5%), partly con-fined, multi-threaded reach with an average bankfull width of 18 m. Data was collected in 2014 using total st-ations

Evidence Layers: bankfull polygon, water extent polygon

Valley Units (Wheaton et al 2015)

- In-Channel *(within bankfull extent)*
- Out-of-Channel *(outside bankfull extent)*

Flow Units (Rinaldi et al 2015)

- Submerged *(within wetted extent)*
- Emergent *(within bankfull extent but not wetted)*
- High *(outside bankfull extent)*

Bangen et al. (2017): DOI: 10.13140/RG.2.2.31118.66884
Bangen et al. (2017): DOI: 10.13140/RG.2.2.31118.66884

Tier 2: Unit Shape & Form: Evidence

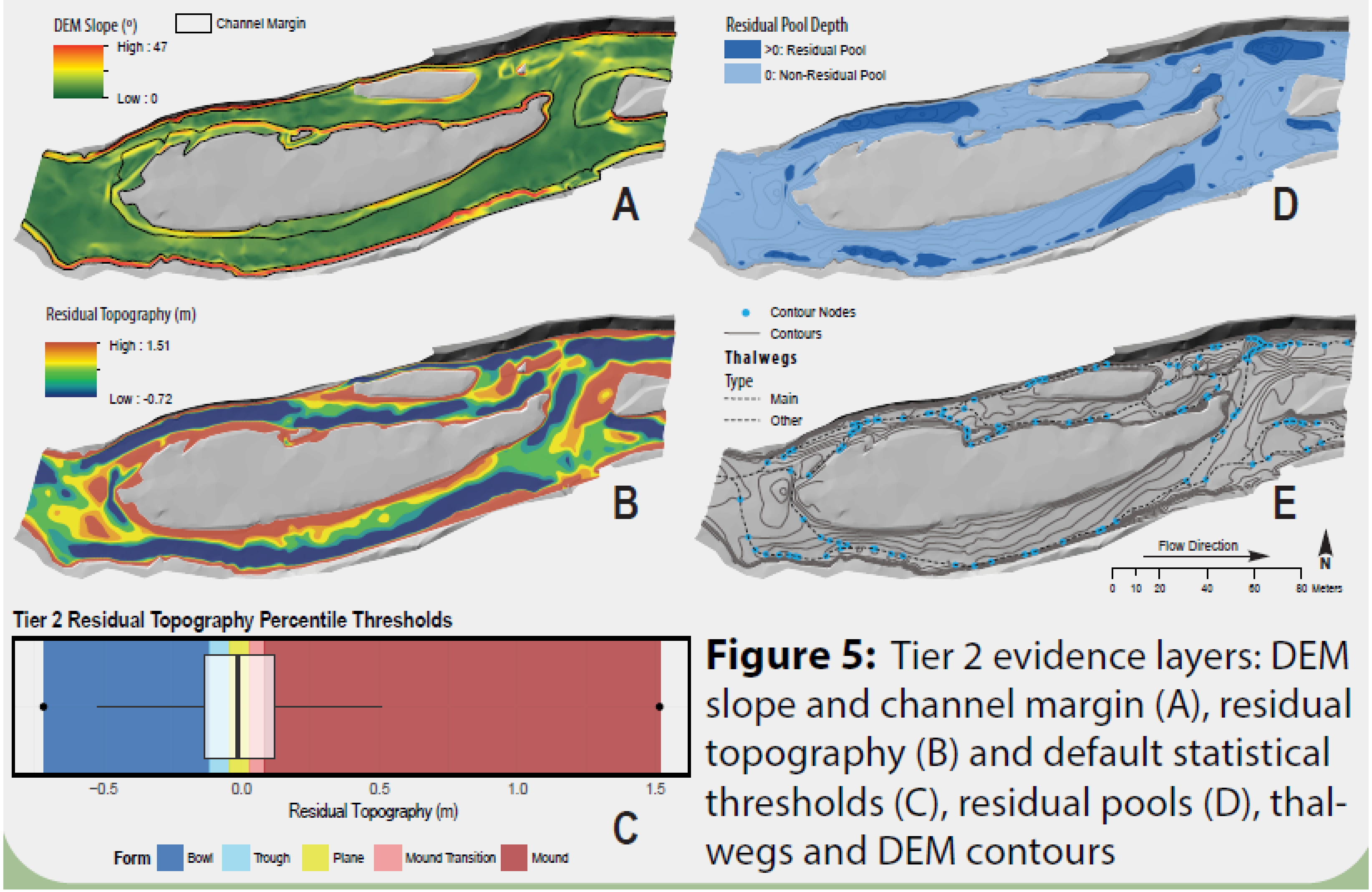


Figure 5: Tier 2 evidence layers: DEM slope and channel margin (A), residual topography (B) and default statistical thresholds (C), residual pools (D), thalwegs and DEM contours

Bangen et al. (2017): DOI: 10.13140/RG.2.2.31118.66884

ow

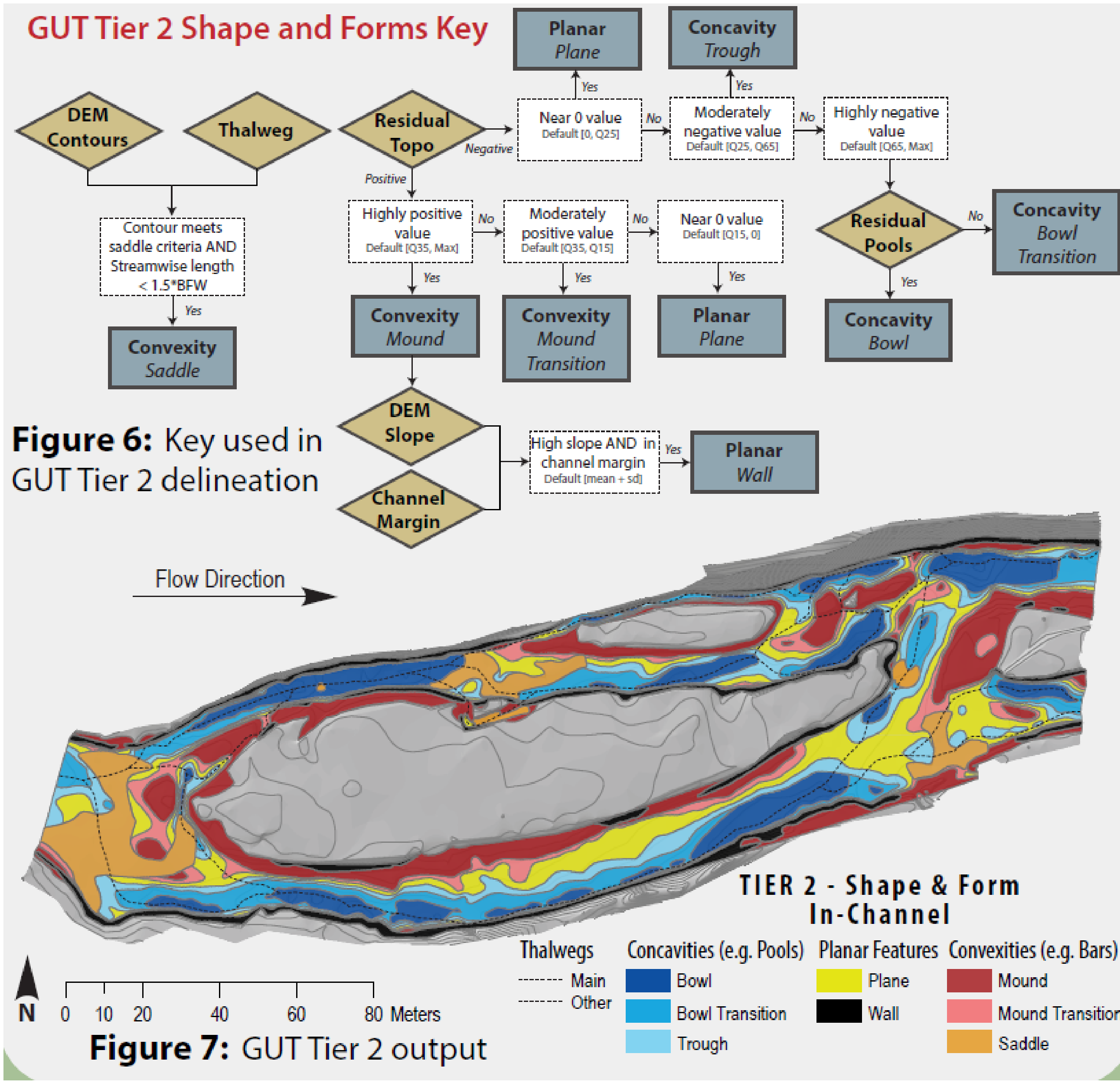


Figure 6: Key used in GUT Tier 2 delineation

Figure 7: GUT Tier 2 output

Bangen et al. (2017): DOI: 10.13140/RG.2.2.31118.66884

TIER 3: GU's & SUB-GU's

Workflow:

- Attribute each Tier 2 Form unit with Tier 3 GU key attributes. Classify Tier 3 GU using keys.
- Attribute each Tier 3 GU with Tier 3 Sub-GU key attributes. Classify Tier 3 Sub-GU using keys.

Tier 3 GU Key Attributes*:

- Position *(margin attached, mid-channel, channel spanning)*
- Orientation *(longitudinal, diagonal, transverse)*
- Bankfull Water Surface Slope
- Bankfull Width Ratio *(unit width / bfw)*
- Channel Type *(e.g., main, cut-off, return)*
- Elongation Ratio *(2·√(area/π)/length)*

Tier 3 Sub-GU Key Attributes*:

- Thalweg Count *(# of thalwegs intersecting unit)*
- Meander Bend *(inside, straight, outside)*
- Bed Slope *(mean DEM slope)*
- Relief *(DEM Z_{max} - Z_{min})*
- Forcing Element *(e.g., plunge, grade control**)*

*Examples (i.e., not a list of all attributes calculated by GUT)
**User defined (i.e., not automated in GUT)

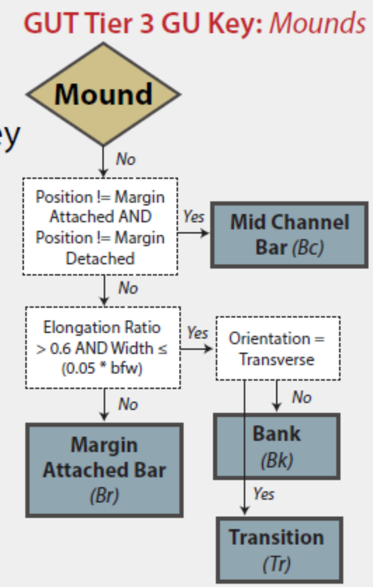


Figure 8: Key used in GUT Tier 3 delineation for Tier 2 Mound units

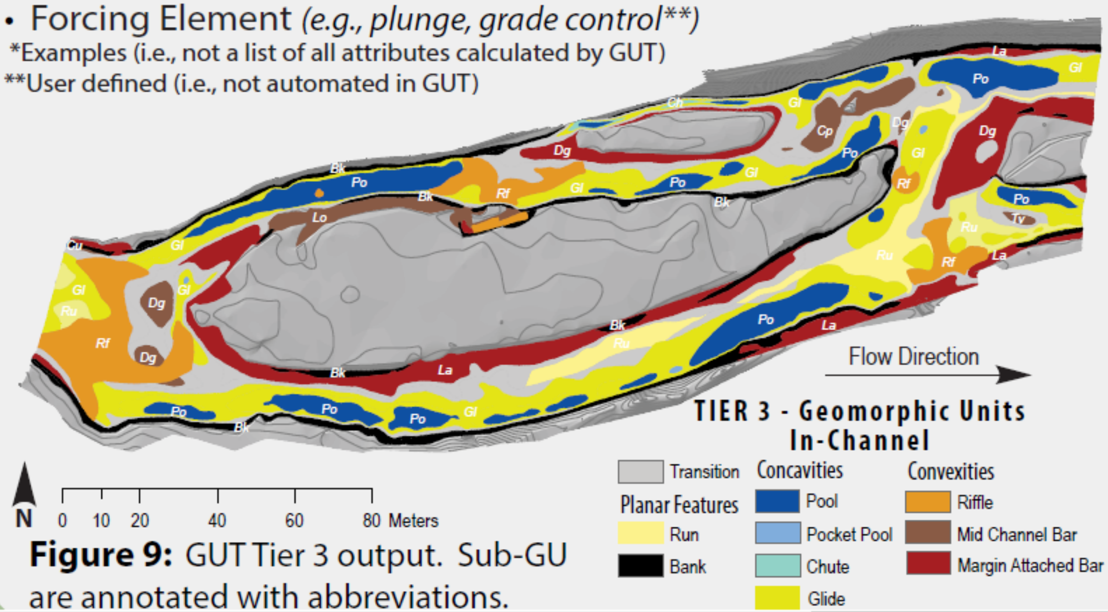
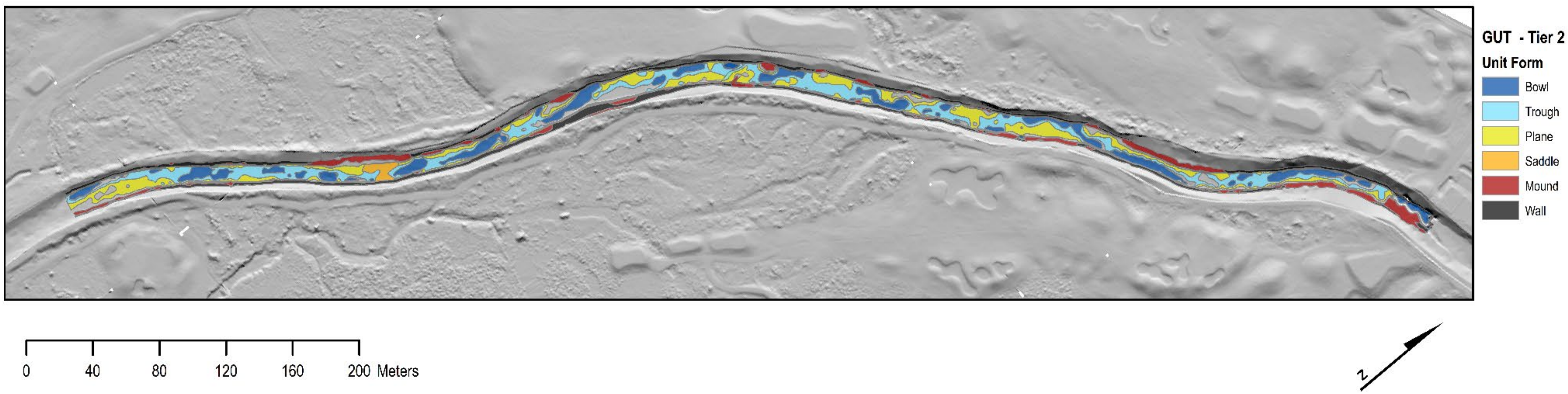
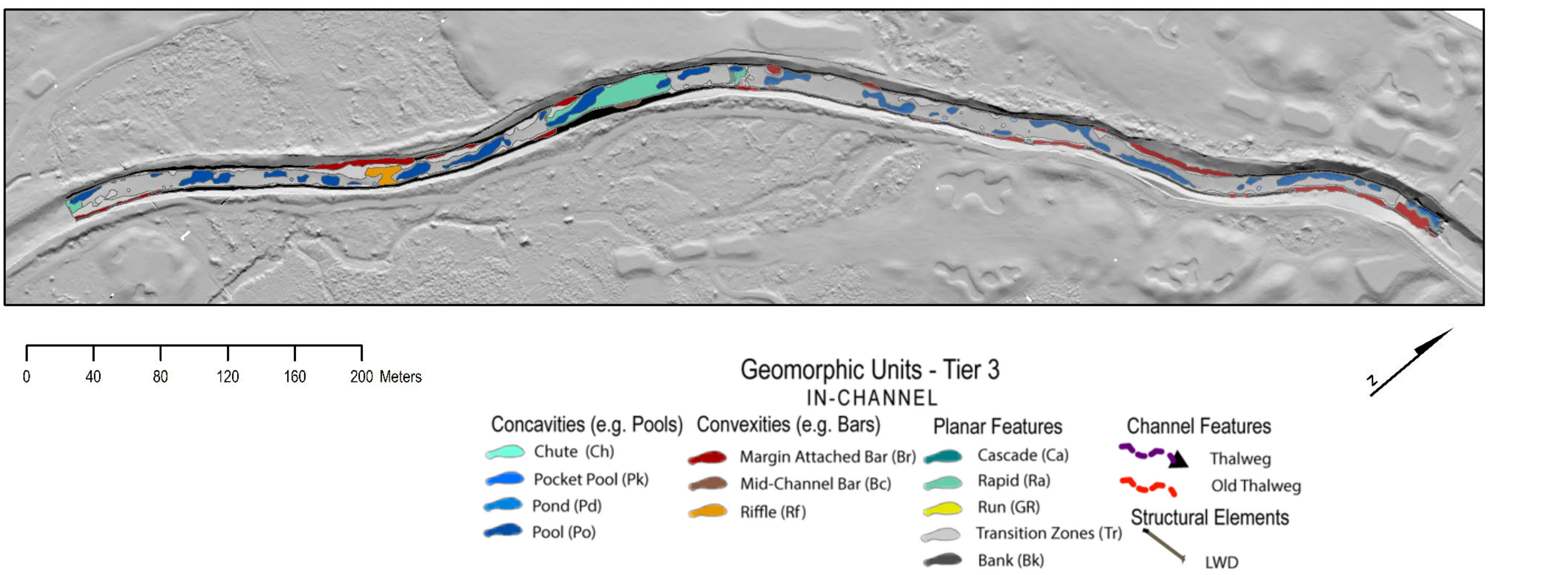


Figure 9: GUT Tier 3 output. Sub-GU are annotated with abbreviations.

Bangen et al. (2017): DOI: 10.13140/RG.2.2.31118.66884


GUT - Tier 2
Unit Form
Bowl
Trough
Plane
Saddle
Mound
Wall
0
40
80
120
160
200 Meters
N


0
40
80
120
160
200 Meters
N
Geomorphic Units - Tier 3
IN-CHANNEL
Concavities (e.g. Pools)
Chute (Ch)
Pocket Pool (Pk)
Pond (Pd)
Pool (Po)
Convexities (e.g. Bars)
Margin Attached Bar (Br)
Mid-Channel Bar (Bc)
Riffle (Rf)
Planar Features
Cascade (Ca)
Rapid (Ra)
Run (GR)
Transition Zones (Tr)
Bank (Bk)
Channel Features
Thalweg
Old Thalweg
Structural Elements
LWD

Geomorphology & Habitat

I. Reach Types

II. Building Blocks

  I. Margins (entry into Valley Setting)

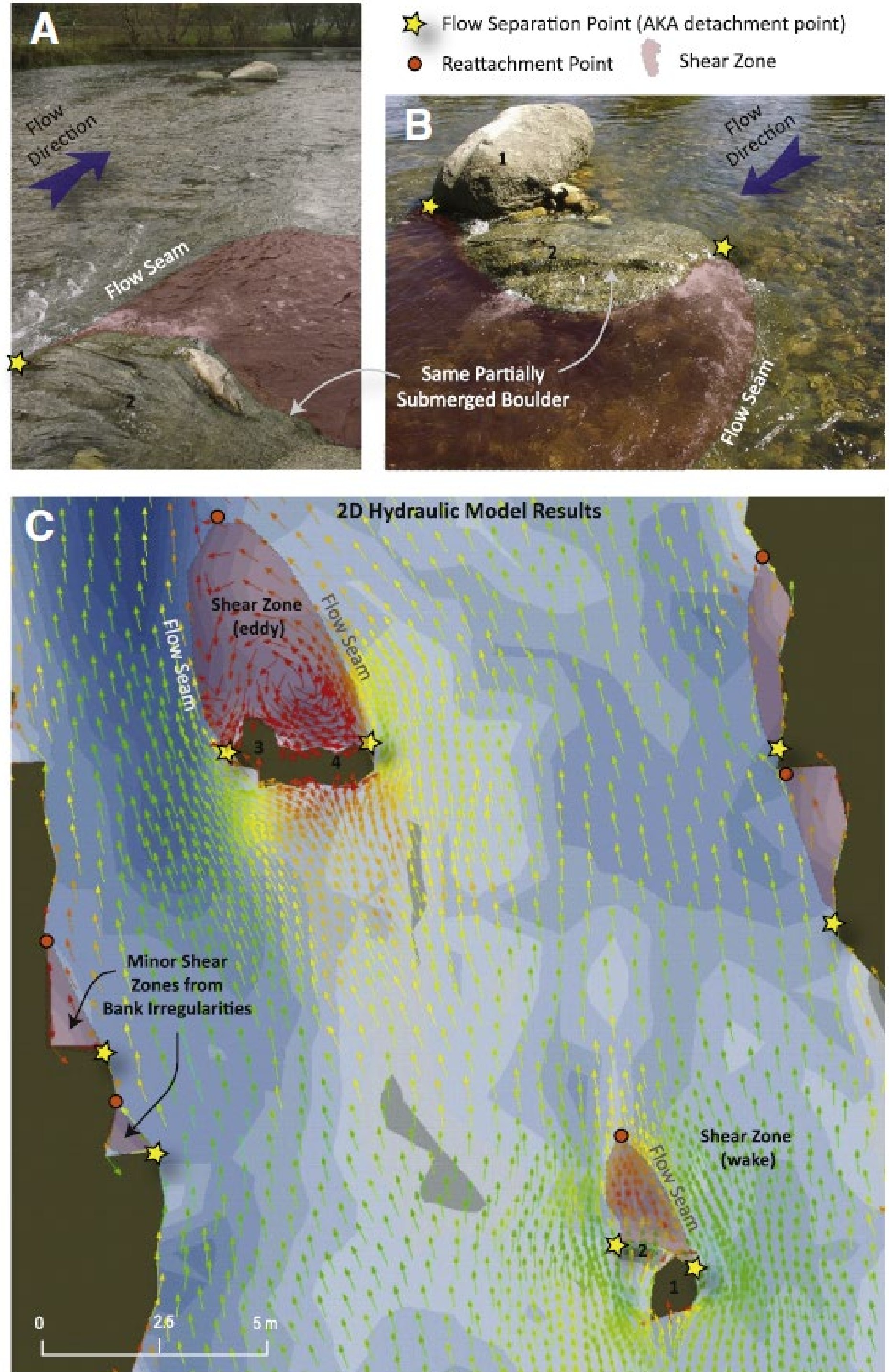
  II. Geomorphic Units

  III. Structural Elements

III. Habitat

Structural Element Definition

- A structural element is a discrete object that directly influences hydraulics
- Structural elements produce:
  - Flow separation points
  - Flow seams
  - Shear zones
  - Reattachment point or zone
- Help predict zones of erosion, deposition, margins and ‘forced’ geomorphic units

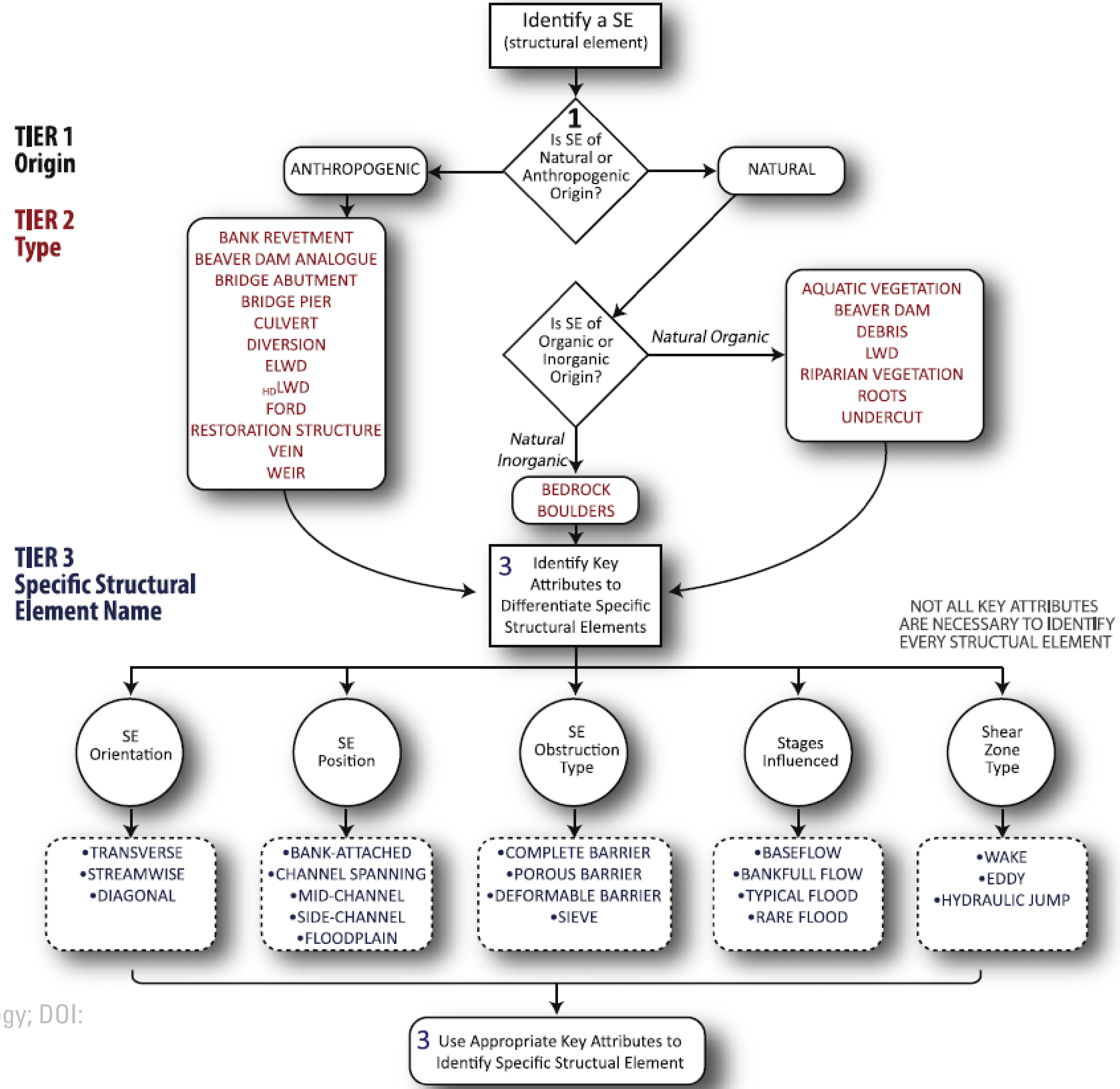


From: Wheaton et al. (2015) – Geomorphology;
DOI: 10.1016/j.geomorph.2015.07.010

Differentiating Structural Elements

- Helps predict its:
  - Hydraulic influence
  - geomorphic influence

From: Wheaton et al. (2015) – Geomorphology; DOI: 10.1016/j.geomorph.2015.07.010



Key Attributes of Structural Elements

Table 1
Key attributes that help differentiate tier 3 structural elements; abbreviations: SE (structural element).

Key Tier 3 attributes:	Types	Description
SE orientation		The orientation refers to the relative alignment of the structural element's long axis with respect to the dominant streamwise flow direction
	∟Transverse	Transverse SEs are oriented perpendicular to the flow (e.g. *beaver dam)*
	∟Streamwise	Streamwise SEs are oriented parallel to the flow (e.g. *a piece of LWD aligned with the flow*)
	∟Diagonal	Diagonal SEs intersect the flow at an angle
SE Position		The position of the SE with respect to the channel(s); Note use consistency whether the 'channel' refers to the low flow channel or bankfull channel.
	∟Bank Attached	Attached or connected to one side of the channel margin
	∟Channel Spanning	Spanning across the entire channel from channel margin to channel margin
	∟Mid Channel	Not attached or connected to either side of the channel margin
	∟Side-Channel	Located in a side or secondary channel
	∟Floodplain	Located on the floodplain
SE obstruction type		Refers to the type and nature of flow obstruction the SE object creates
	∟Complete Barrier	When all flow is forced around or over top of the SE
	∟Porous Barrier	When most flow is forced around or over top of the SE, but some flow can flow through the SE itself (e.g. a debris jam)
	∟Deformable Barrier	When SE is non-rigid such that when subjected to flows it deforms in a streamwise fashion (e.g. grasses)
	∟Sieve	When most flow is forced through various pathways through SE, but some can flow over or around
	∟Funnel	When flow is funneled through the SE (e.g. a culvert)
	∟Roughness	When flow is not obstructed by SE, but instead SE simply exerts more drag on the flow at the boundary then the typical boundary
Stages influenced		Refers to the flow/flood stage at which the SE exerts an influence on the flow
	∟Baseflow	The mean low flow stage (note, this may be zero for intermittent and ephemeral channels)
	∟Bankfull Flow	The discharge just before flow spreads out on to a floodplain (not present in all channels)
	∟Typical Flood	The discharge associated with floods that occur regularly (e.g. 1 to 5 year recurrence intervals)
	∟Rare Flood	The maximum probable or historically recorded flood
Shear zone type		Refers to the type of hydraulic impact induced by the downstream typically just downstream or on the lee side of the SE; the shear zone type is very stage dependent, but closely related to the obstruction type
	∟Wake	A wake is a zone of slower moving water in the lee of an obstruction to the flow but that is still generally flowing in a streamwise direction
	∟Eddy	An eddy is a flow recirculation cell downstream of a flow separation (often, but not always induced by SE) in which the flow direction varies (including flowing upstream) but generally makes a circular vortice
	∟Hydraulic Jump	Represents a transition from subcritical to supercritical (typically over the SE) and back to subcritical flow; such hydraulic features can take various forms (e.g. wave trains, standing wave, submerged jump (i.e. drop))

Many Flavors of Structural Elements…

Table 2
Structural elements (SE) at tier 3 and their key attributes: note, any key attribute listed as 'varies' or 'NA' (not applicable) is not useful in differentiating that SE from other SEs; this list is complete at tiers 1 and potentially tier 2, but other specific SEs exist at tier 3.

Tier 1	Tier 2	Tier 3	Key attributes to differentiate specific structural elements				
Origin	Type	Specific structural element name	Geometry		Nature of flow impact		
			SE orientation	SE position	SE obstruction type	Stages influenced	Shear zone type
Anthropogenic							
∟	Bank revetment	Bioengineered, Gabions, detroit rip rap, boulder rip rap, erosion control blanket	Streamwise	Bank-attached	Roughness	Varies	DS eddy
	Beaver dam analogue	Primary dam, secondary dam, reinforced existing dam		Channel-spanning	Porous barrier	All	US backwater
∟	Bridge abutments	NA		Bank-Attached	Complete barrier	Varies	DS eddy
∟	Bridge pier	NA		Mid-channel	Complete barrier	All	DS eddy
∟	Culvert	Box, arch, pipe	Streamwise	Channel-spanning	Funnel	All	US backwater
∟	Diversion	Irrigation, canal, pump point of diversion	Transverse	Bank-attached or channel- spanning	Complete barrier	Varies	US backwater
∟	ELWD	Debris jam, bank deflectors	Varies	Varies	Porous barrier	Varies	Varies
∟	$_{HD}$LWD	Post-assisted log structure, constriction structure, mid-channel structure	Varies	Varies	Porous barrier	Varies	US & DS eddies
∟	Ford	Concrete, native bed material	Transverse	Channel-spanning	Complete barrier	All	US backwater
∟	Restoration structure	Many types	Varies	Varies	Varies	Varies	Varies
∟	Rock vein	NA	Diagonal	Bank-attached	Porous barrier	All	DS & US eddy
∟	Vortex weir	NA	Transverse	Channel-spanning	Porous barrier	All	Varies
Natural inorganic							
∟	Bedrock						
	∟	Bedrock ledge	Varies	Varies	Complete barrier	Varies	DS eddy
	∟	Bedrock outcrop	Varies	Varies	Complete barrier	Varies	DS eddy
∟	Boulder						
	∟	Boulder cluster	Varies	Mid-channel	Complete barrier	All	DS eddy
	∟	Boulder dam	Transverse or diagonal	Channel-spanning	Porous barrier	All	US backwater
	∟	Boulder ribs	Transverse or diagonal	Mid-channel	Porous barrier	Varies	DS eddy
Natural organic							
∟	Aquatic vegetation	Many types	Varies	Varies	Porous barrier	All	DS Wake (occ. DS eddy)
Beaver dam							
	∟	Intact Dam	Transverse	Channel-Spanning	Porous Barrier	All	US Backwater & DS Wake
	∟	Breached dam	Transverse	Channel-spanning	Porous barrier	All	US backwater and DS eddies
	∟	Blown-out dam	Transverse	Channel-spanning or bank-attached	Porous barrier	All	DS & US eddy
LWD							
	∟	Individual root wad	Varies	Varies	Porous barrier	Varies	DS Eddy or wake
	∟	Debris jam	Transverse	Channel-spanning	Porous barrier	All	US backwater & DS wake
	∟	Channel spanning log Raft jams	Transverse or diagonal	Channel-spanning	Varies	Varies	Varies
	∟	Log	Varies	Varies	Varies	Varies	Varies
	Riparian vegetation	Many types	Varies	Varies	Porous barrier	> Flood stage	Varies

Fluvial Taxonomy Take Aways

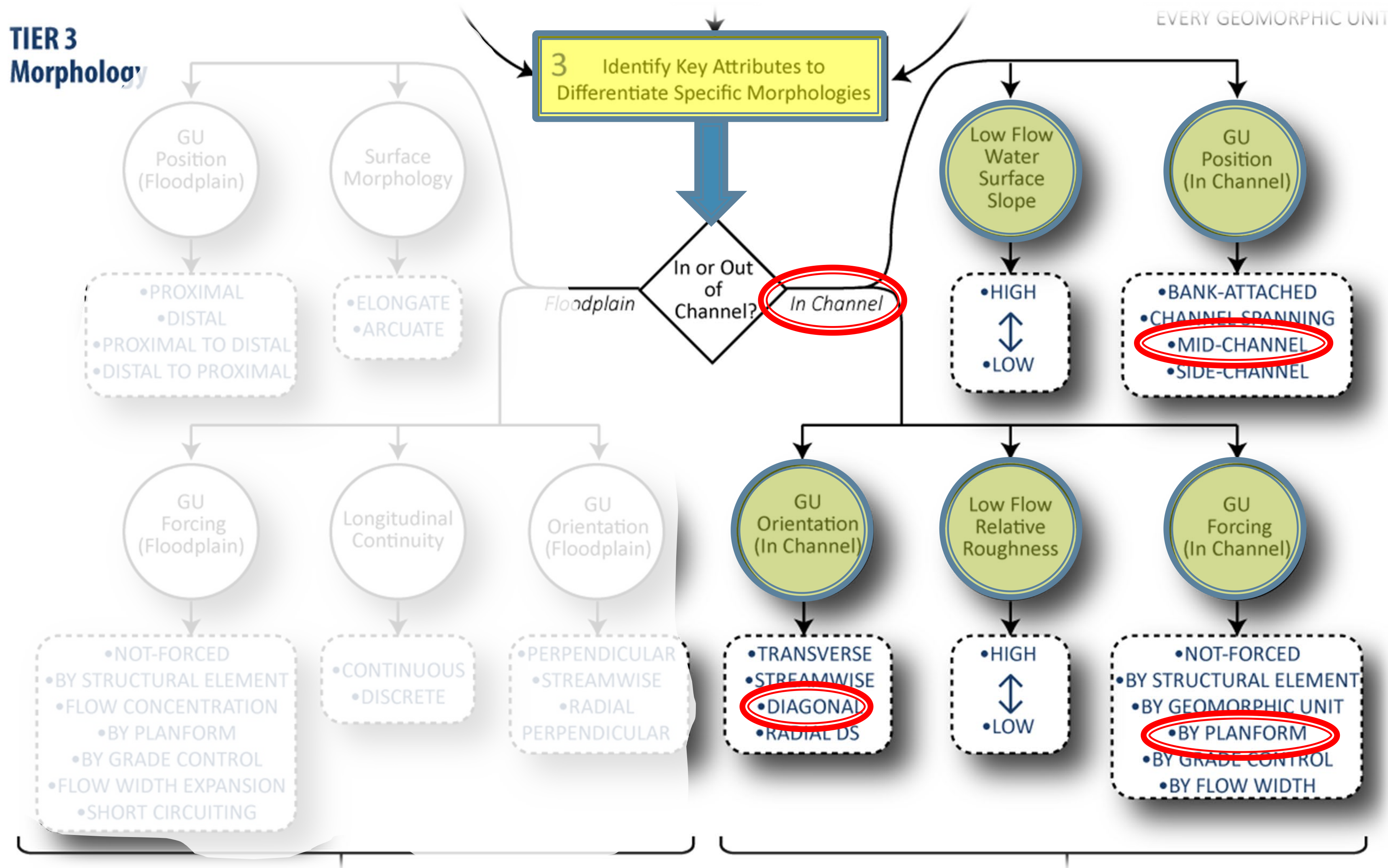
- Fluvial taxonomy framework does provide some clarification and promote consistency
- Provides basis for the legends of geomorphic maps:
  - Margins – *controls planform, lateral adjustment potential and steering of flow*
  - Structural Elements – *direct impact on hydraulics*
  - Geomorphic Units – *building blocks of riverscape*
- Clearer definitions give rise to:
  - Stronger basis for predicting process from form
  - Better chance of developing algorithms and tools for deriving from topographic data – i.e. GUT
  - More coherent theory about how rivers work
- Stay tuned for more geomorph trivia at a bar near you

DIAGONAL BAR Tangent

- Diagonal bars are a mid-channel bar that starts out as a bank-attached point bar, but then becomes mid-channel via the process of chute cutoff…

- Their name describes flow across them (@ higher stages), which flows diagonally from a higher anabranch to a lower anabranch

Tier 3 – Morphology of Diagonal Bars



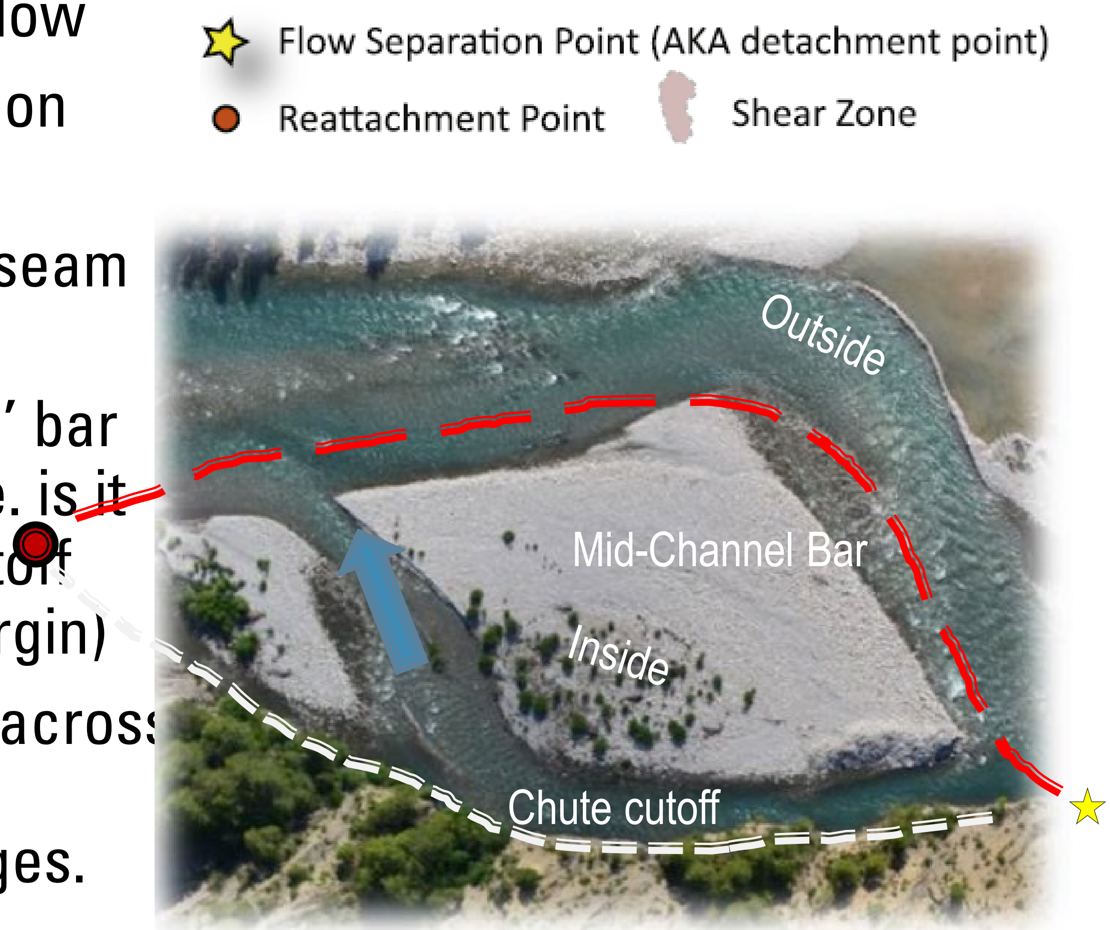
How do these differ from other mid channel bars?

- Flow in anabranches on both sides is not symmetrical
- Occur over much more diverse range of valley settings, confinement and reach types
- Start their life as bank-attached deposits

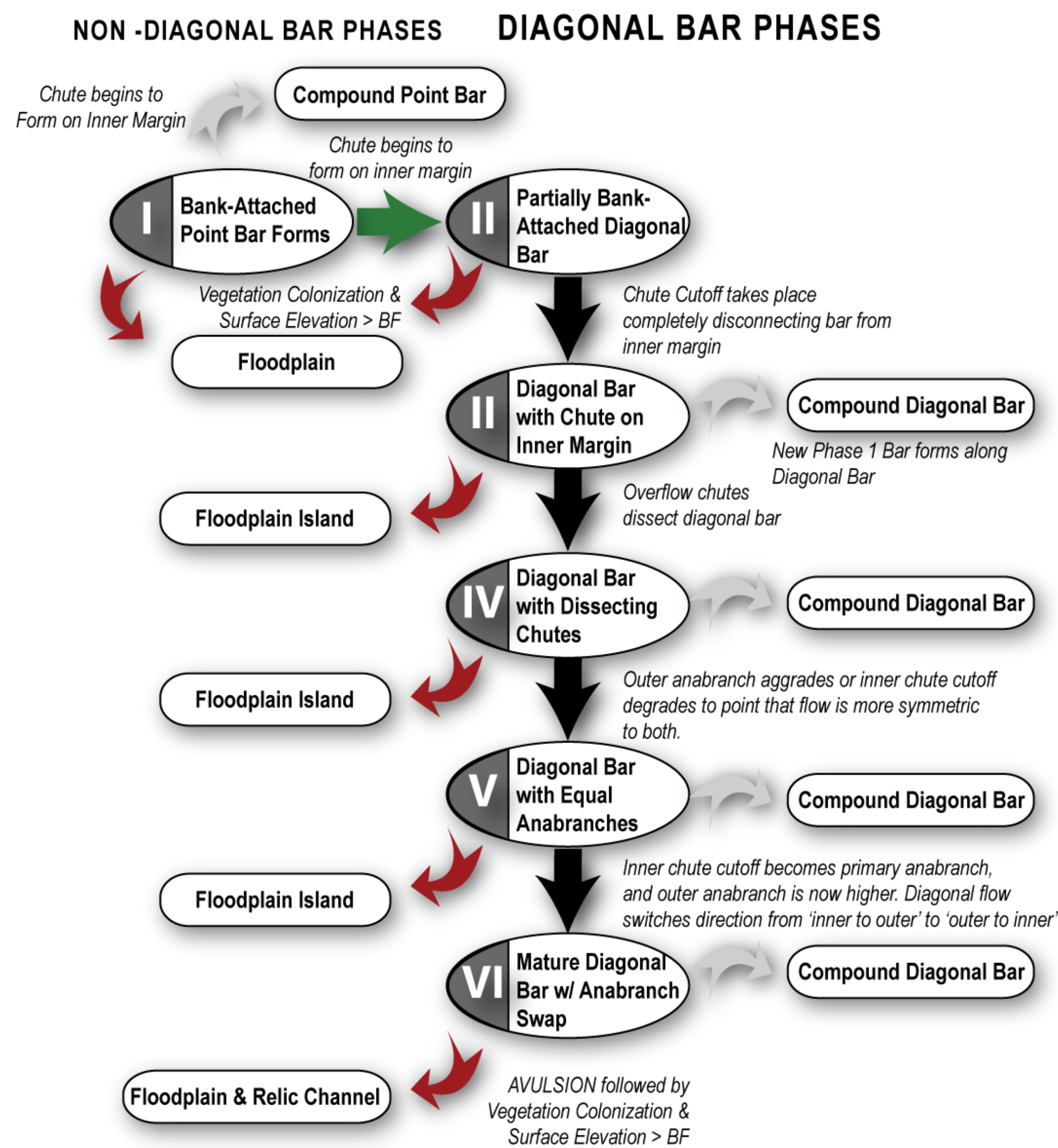
Tier 1	Tier 2	Tier 3	Key attributes to differentiate specific morphologies						
Stage height	Shape/type	Specific morphology	GU forcing	Low flow relative roughness	GU orientation	GU position	Low flow water surface slope	Also known as	Similar to or confused with
In–channel									
L	Convexity (e.g. bar)								
	L	Backwater bar	Grade control	Varies	Varies	Side channel	Varies	Slackwater deposit	Similar to other bars but found in disconnected side channels or secondary channels
	L	Boulder bar	Flow width	Varies	Streamwise	Bank–attached or mid–channel	Varies	Boulder berm	Similar to other bars, but in much higher gradient systems.
	L	Compound bar	Varies	Varies	Varies	Varies	Varies	Bar complex	An amalgamation of multiple unit bars and other bar types (complex history)
	L	Confluence bar	Grade control	Varies	Radial DS & streamwise	Bank–attached	Varies	NA	Expansion bar, except in response to gradient drop from tributary to mainstem.
	L	Diagonal bar	Planform & flow width expansion	Varies	Diagonal	Mid–channel	Varies	Mid–channel bar	Point bar, but no longer bank-attached (separated by chute)
	L	Eddy bar	Planform, SE, and/or flow width constriction	Varies	Streamwise	Bank–attached or mid–channel	Varies	Separation bar	
	L	Expansion bar	Flow Width	Varies	Transverse	Mid–channel	Varies	NA	Transverse bar, but in response to slope lowering, and does not span channel
	L	Forced bar	Varies	Varies	Streamwise	Bank–attached or mid–channel	Varies	NA	Eddy Bar
	L	Forced riffle	Channel spanning SE	Moderate (< 1)	Transverse	Channel spanning	Shallow	NA	Riffle, but forced by channel spanning structural element buried in bed
	L	Lateral bar	By planform or by flow width	Varies	Streamwise	Bank–attached	Varies	Alternate bar	Point bars, but can be in bends with lower curvature or channels with lower sinuosity or straight
	L	Lobate bar	Grade Control	Varies	Radial DS	Mid–channel	Varies	Mid–channel bar	Similar to other mid–channel bars but distinctive in DS tear–dropped shape and avalanche faces
	L	Longitudinal bar	Flow Width	Varies	Moderate (< 1)	Mid–channel	Varies	Mid–channel bar	Similar to other mid–channel bars but distinctive in elongated streamwise orientation and upstream convexity at bar head
	L	Point bar	Planform forced	Varies	Streamwise	Bank–attached	Varies	Bank–attached bar	Alternate bars, but in bends with higher curvature
	L	Reattachment bar	Varies	Varies	Streamwise	Bank–attached	Varies	NA	Eddy Bar, but occurs DS of both flow separation and reattachment point
	L	Ridge	Forced by SE and flow separation	Varies	Streamwise	Bank–attached	Varies	NA	Scroll bar or levee; generally straighter, more linear feature
	L	Riffle	Flow width expansion	Moderate (< 1)	Transverse	Channel spanning	Moderate	Transverse bar	Sometimes confused with runs
	L	Scroll bar	Planform & flow width expansion	Varies	Streamwise	Bank–attached	Varies	NA	Ridge, but positioned on point bar and generally curved
	L	Unit bar	Flow width expansion	Varies	Varies	Varies	Varies	NA	The fundamental building block of all bars

Keys To Identifying Diagonal Bars

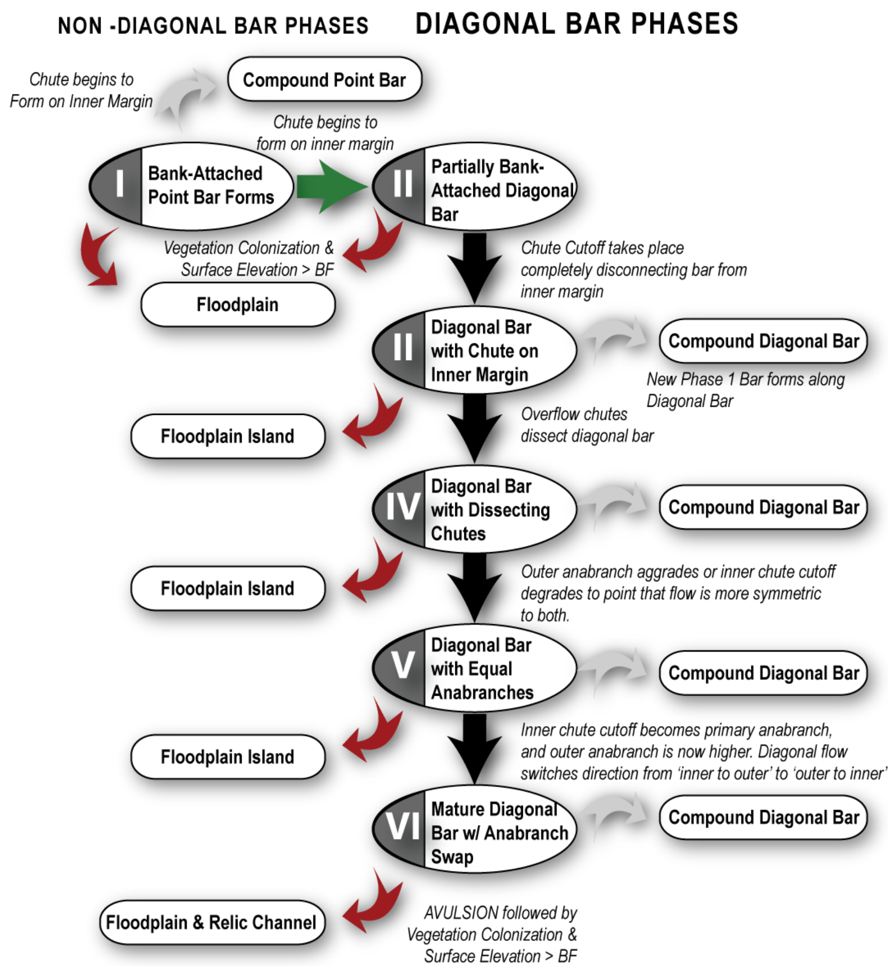
1. Identify ‘inside bend’ of flow
2. Identify the flow separation point.
3. Trace a high-stage flow seam to a reattachment zone
4. Identify the ‘mid-channel’ bar within the shear zone (i.e. is it separated by a chute cutoff along inside channel margin)
5. Confirm flow is diagonal across bar from ‘high’ to ‘low’ anabranch at higher stages.



We propose six potential phases of diagonal bar evolution:



Identify Bar, & Stages



Identify Bar, & Stages