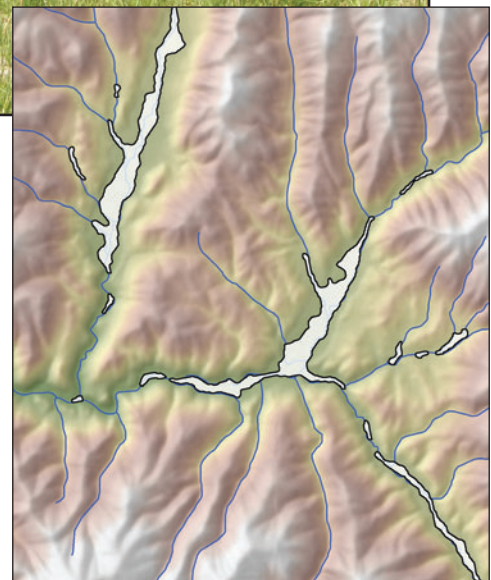
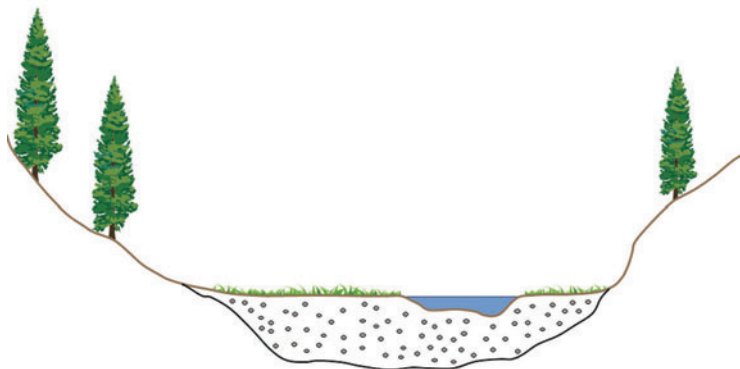


A Landscape Scale Valley Confinement Algorithm: Delineating Unconfined Valley Bottoms for Geomorphic, Aquatic, and Riparian Applications

David E. Nagel, John M. Buffington, Sharon L. Parkes, Seth Wenger, and Jaime R. Goode



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Abstract

Valley confinement is an important landscape characteristic linked to aquatic habitat, riparian diversity, and geomorphic processes. This report describes a GIS program called the Valley Confinement Algorithm (VCA), which identifies unconfined valleys in montane landscapes. The algorithm uses nationally available digital elevation models (DEMs) at 10-30 m resolution to generate results at subbasin scales (8 digit hydrologic unit). User-defined parameters allow results to be tailored to specific applications and landscapes. Field data were sampled to verify geomorphic characteristics of valley types identified by the program, and a detailed accuracy assessment was conducted to quantify the reliability of the algorithm output.

Keywords: valley confinement, valley bottom, stream channel morphology, fish habitat, riparian habitat

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Executive Summary

Valley confinement describes the degree to which bounding topographic features, such as hillslopes, alluvial fans, glacial moraines, and river terraces, limit the lateral extent of the valley floor and the floodplain along a river. Valleys can be broadly classified as confined or unconfined, with corresponding differences in their appearance, vegetation, ground water exchange rates, topographic gradient, and stream characteristics. Unconfined valleys are generally less extensive than confined valleys in montane environments, but host a diverse array of terrestrial and aquatic organisms and provide disproportionately important ecosystem functions. Consequently, identifying the location and abundance of each valley type is increasingly recognized as an important aspect of ecosystem management. In this report, we describe a GIS program called the Valley Confinement Algorithm (VCA) that maps the extent and shape of unconfined valley bottoms using readily available spatial data as input.

The VCA is designed to operate using ESRI ArcGIS software with 1:100,000 scale stream lines from the National Hydrography Dataset (NHDPlusV1) and 10-30 m digital elevation models (DEMs). The algorithm focuses on fluvial applications and therefore only considers channelled valleys. The smallest unconfined valley that can be resolved by the VCA depends on the resolution of the DEM; the VCA is unable to resolve unconfined valleys that are narrower than about two to three times the DEM cell size (i.e., valleys that are 60-90 m in width for a 30 m DEM or

20-30 m for a 10 m DEM). In addition, as bankfull width approaches two times the DEM cell size, the VCA may misinterpret the channel as a narrow unconfined valley. Consequently, care should be exercised in interpreting results in such locations.

We conducted field work in central Idaho to document channel characteristics in confined and unconfined valleys mapped by the algorithm. Results showed that channel confinement measured in the field (ratio of valley width to bankfull width) agreed with valley confinement predicted by the algorithm 79% of the time and that channel characteristics were similar to those documented in other studies of confinement. In particular, confined channels typically exhibited steep-gradient step-pool and plane-bed morphologies composed of coarse-grained bed material, with a median channel confinement of about 2 bankfull widths. In contrast, unconfined channels were primarily low-gradient pool-riffle and plane-bed streams composed of finer substrate, with a median channel confinement of about 10 bankfull widths.

We further assessed the accuracy of the algorithm by generating a stratified random sample of points equally partitioned between confined and unconfined valleys as identified by the VCA. Predicted valley types were compared with those observed from digital photos and quadrangle maps. Results showed that the algorithm could differentiate between the two valley types with 89-91% accuracy.

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Introduction

Looking across a mountainous landscape, an observer will immediately perceive the peaks, ridges, and valleys that comprise the terrain. Our attention is often drawn to the peaks, but it is the valleys that carry surface water, harbor fish, provide riparian habitat, and impart critical resources to the montane ecosystem. The morphology, or shape of the valley, is an important predictor of the types of services that the valley can provide for the ecosystem. One of the most fundamental characteristics of a valley is its degree of lateral confinement by topographic features, such as hillslopes, alluvial fans, glacial moraines, and relict river terraces.

Confined valleys in mountain basins are typically narrow and v-shaped, with little alluvial fill (figure 1). These valleys have relatively steep, erosive gradients, and contain coarse-grained, high-energy streams with little to no floodplain (e.g., Montgomery and Buffington's (1997) transport reaches [cascade and step-pool channels] or Rosgen's (1994, 1996) A, B, and G channel types) (figure 2).

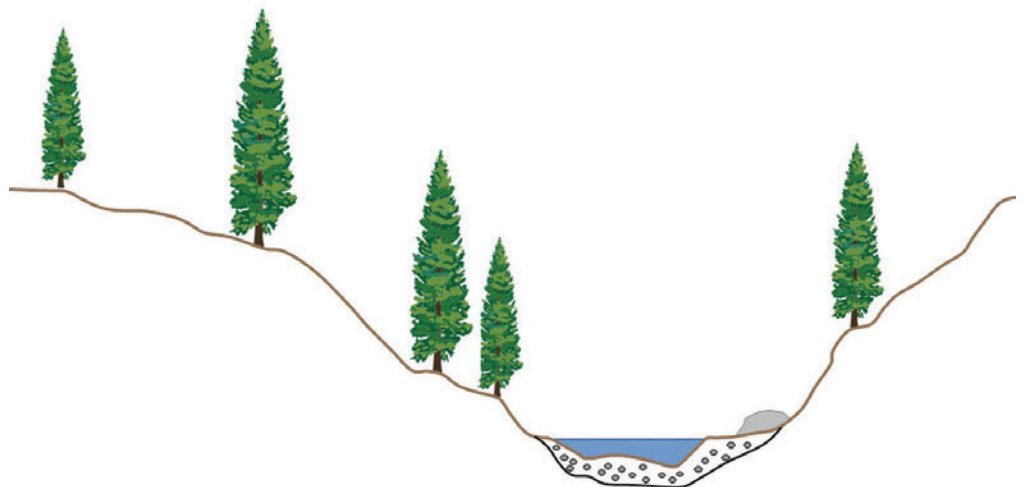


Figure 1—Graphic of a typical confined valley illustrating shallow alluvial deposits.



Figure 2—Typical confined valleys in the project study area, described in Part III.

In contrast, unconfined valleys are wider depositional areas, with extensive alluvial fill and broad floodplains that allow active channel migration and the development of channel sinuosity or braiding (figure 3). Unconfined valleys typically have relatively lower gradients and finer-grained sediment (e.g., Montgomery and Buffington's (1997) response reaches [pool-riffle and dune-ripple channels] or Rosgen's (1994, 1996) C, E, and F channel types) (figure 4), except where coarse-grained braided rivers occur below alpine glaciers.

Both confined and unconfined valleys are associated with different process domains and ecosystems (e.g., Brierley and Fryirs 2005; Buffington and Tonina 2009; Montgomery 1999; Paustian and others 1992; Wohl and others 2013). Knowing the location and abundance of each valley type can be a key component for addressing a variety of management issues related to aquatic species and terrestrial riparian animals.

To help address management and research endeavors in fluvial systems where valley confinement is of interest, a GIS-based software program called the Valley Confinement Algorithm (VCA) was developed that identifies unconfined valleys using readily available, nationwide spatial data. The program uses stream line data from the National Hydrography Dataset (NHDPlusV1) and digital elevation models (DEMs) with 10-30 m resolution as input. Unconfined valley bottom polygons are delineated by the algorithm and output in ArcGIS shapefile format. All areas within these polygons are considered unconfined valleys, while other areas along streams but outside of the polygons are considered confined valleys (figure 5). The output is generated at landscape scales composed of subbasins defined by 8-digit (4th code) hydrologic units (Seaber and others 1987). Valley confinement can be identified along stream reaches as small as 100 m in length. The algorithm optionally produces a second output that computes network distance along the stream channel to the nearest unconfined valley bottom polygon (figure 6), which was developed for fisheries applications (Wenger and others 2011). In addition to the VCA, this report describes an online database of valley confinement data that have been processed for a substantial portion of the western United States.

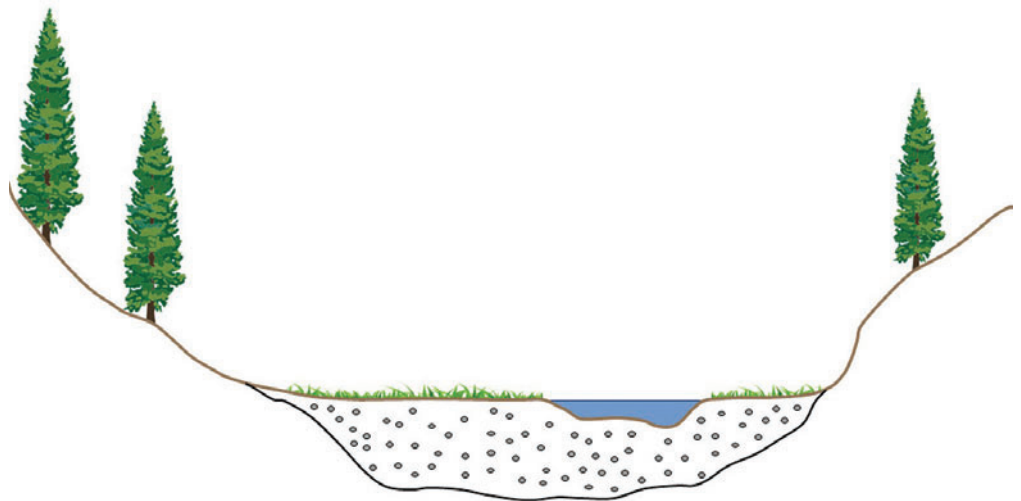


Figure 3—Graphic of a typical unconfined valley illustrating relatively deep alluvial deposits.



Figure 4—Typical unconfined valleys in the project study area, described in Part III.

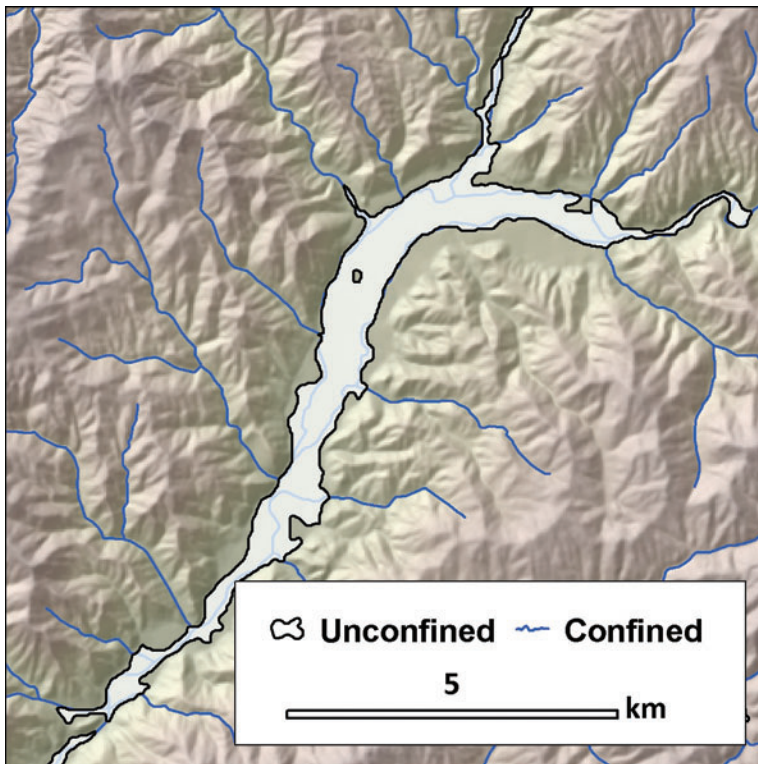


Figure 5—Example output from the VCA, where unconfined valleys are delineated as polygons and all other valleys outside of the polygon and along stream channels are considered confined.

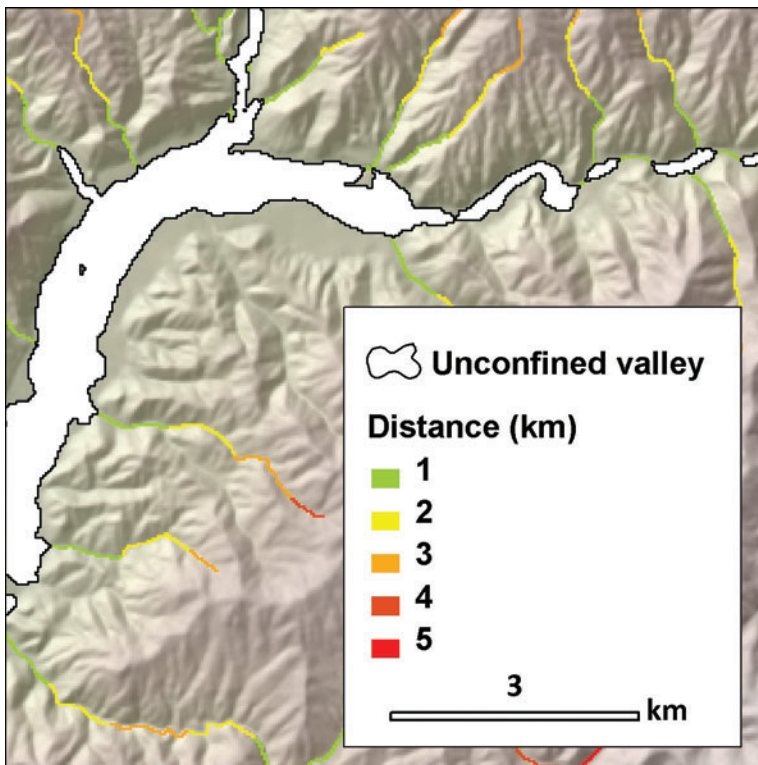


Figure 6—Distance from unconfined valleys as measured along the stream network.

Part I of this document reviews the formation of unconfined valleys, the application and significance of valley confinement, and prior automated routines for identifying unconfined valleys. Part II describes the VCA software and its technical implementation, including details for downloading and preprocessing the input GIS data and an overview of the algorithm methods. Part III presents field data documenting channel characteristics in confined and unconfined valleys mapped by the VCA for central Idaho, and qualitatively assesses the results of the algorithm. Part IV describes a statistical assessment of the VCA output to examine classification accuracy. Part V describes an online database of valley confinement data for the Intermountain Region of the western United States, and Part VI summarizes the report.

The VCA program described herein may be accessed from the Rocky Mountain Research Station valley confinement website:

http://www.fs.fed.us/rm/boise/AWAE/projects/valley_confinement.shtml

Part I—Review

Morphogenesis of Unconfined Valleys

In the broadest sense, an unconfined valley is a landscape feature that is low lying and relatively flat compared to its surroundings (Gallant and Dowling 2003). Unconfined valleys may be formed by a variety of geologic processes in mountainous environments. Some unconfined valleys may be structural features, such as fault-bound grabens, like those of the basin and range physiography of the western United States. Others may be self-formed depositional features that occur where the long-term sediment supply exceeds the channel transport capacity (typically lower-sloped portions of the stream network). In these self-formed cases, floodplain initiation and the development of an unconfined valley may be related to downstream gradients in stream power (Jain and others 2008), while absolute values of stream power affect the type of floodplain environment that occurs (Nanson and Crooke 1992).

In northerly and high elevation systems, Pleistocene alpine glaciers are one of the primary agents that have influenced valley form. Where glaciers have scoured bedrock to form U-shaped valleys, valley width is generally greater than in fluvially formed environments (Amerson and others 2008; Montgomery 2002). In addition, glaciers can have indirect effects on valley form by delivering large sediment supplies to valleys (e.g., Wohl 2000). When glacial sediment cannot be transported because of inadequate stream power or because it is blocked by a downstream obstruction, such as a moraine or bedrock constriction, a wide valley may be formed with deep alluvial deposits.

Valleys may also fill with alluvium from more recent geomorphic activity, such as debris flows and landslides. Again, if a valley obstruction or inadequate stream power reduces sediment transport, a wide valley bottom will often form. Valleys may become wider still if side slopes are composed of low-strength material. These side slopes may become over-steepened by lateral erosion, causing slope failure and facilitating additional sediment input (Lifton and others 2009). Valley width has also been linked to the occurrence of deep-seated landslides that are controlled by lithology and geologic structure and that, in turn, influence habitat availability for salmonids (May and others 2013).

Riverine animals and riparian vegetation can also modulate fluvial processes and affect valley form. For example, beaver dams alter channel slope, transport capacity, and the frequency of overbank flooding, promoting deposition and the development or expansion of unconfined valleys, particularly in smaller channels (e.g., Butler and Malanson 1995; 2005; Pollock and others 2007; Persico and Meyer 2009; Polvi and

Wohl 2012). Similarly, riparian vegetation creates roughness that increases floodplain sedimentation and stability (Allmendinger and others 2005; Smith 2004) that over time may lead to expansion of unconfined valleys.

Application and Significance of Valley Confinement

Valley confinement mapping has been used for a variety of geomorphic, aquatic, and riparian applications. Some applications pertain to physical modeling, such as debris-flow routing, while others are concerned with in-stream biological habitat, botanical predictions, or wildlife management.

Valley confinement in mountain basins is widely used for classifying process domains and stream reach morphology due to the strong effect of confinement and associated valley slope on fluvial processes and hillslope–channel coupling (e.g., Bengueyfield 1999; Brierley and Fryirs 2005; Montgomery 1999; Montgomery and Buffington 1997; Paustian and others 1992; Rosgen 1994; 1996; Schumm 1977). In addition, confinement is recognized as an important factor in debris-flow routing because entrained material is likely to be deposited in unconfined valley segments due to declining gradients and dissipation of energy by overbank flow (Benda and Cundy 1990; Fannin and Wise 2001; Miller and Burnett 2008). This is true for fluvial sediment routing as well, with the occurrence of unconfined valleys along the stream network influencing system-wide sediment routing and residence times (Goode and others 2012).

Unconfined valleys in montane systems are also recognized for their propensity to exchange ground and surface water, creating a unique environment for supporting various life stages of riparian and aquatic species (e.g., Baxter and Hauer 2000; Malard and others 2002; Poole and others 2006; Stanford 2006; Stanford and Ward 1993). The mixing of groundwater with stream flow is known as hyporheic exchange, and the character of this exchange will vary depending on the nature of the stream and underlying alluvium (e.g., Buffington and Tonina 2009; Wondzell and Gooseff 2013). Higher-gradient streams in confined valleys exhibit shallow hyporheic exchange because these reaches lack deep, unconsolidated sediments. In contrast, unconfined valleys with deep alluvial deposits often support pool-riffle channels that promote lateral water movement across bars and between meanders, enhancing sub-reach scale exchange rates (Tonina and Buffington 2007) and providing deep and long hyporheic flow paths through the extensive alluvial deposits that characterize unconfined valleys (Stanford 2006; Stanford and Ward 1993). The broad distribution of flow paths and hyporheic residence times in unconfined valleys influences stream temperature and enhances biochemical reactions which, in turn, affect the character of the surface and subsurface water and their associated habitats (e.g., Buffington and Tonina 2009; Malard and others 2002; Poole and others 2006; 2008; Wondzell 2011).

In addition to affecting hyporheic exchange and water quality, numerous studies document the role of valley confinement in structuring fish populations. For example, juvenile coho salmon (*Oncorhynchus kisutch*) have been noted in greater densities in unconfined stream reaches, while 1-year old steelhead trout (*O. mykiss*) often avoid these same reaches, preferring confined stream segments (Burnett and others 2003; Gresswell and others 2006). Similarly, field studies in central Idaho demonstrate that Chinook salmon (*O. tshawytscha*) preferentially spawn in unconfined valleys (Buffington and others in prep.; Isaak and Thurow 2006; McKean and Tonina, 2013). In general, the current distribution of anadromous salmon populations in the Pacific Northwest, United States, is closely associated with the distribution of unconfined floodplain channels (Hall and others 2007). This result may reflect a variety of factors, including (1) increased habitat diversity in unconfined valleys, such as side channels and pools for juvenile fish (Hall and others 2007); (2) availability of spawning gravels

in pool-riffle and plane-bed channels that commonly occur in unconfined valleys due to lower stream gradients (Buffington and others 2004; Coulombe-Pontbriand and Lapointe 2004; Wilkins and Snyder 2011); (3) favorable hyporheic flows for mitigating adverse summer and winter stream temperatures (Baxter and Hauer 2000; Boxall and others 2008); and (4) potentially greater spawning success due to extensive floodplains that effectively mitigate high flows and reduce the risk of bed mobility and scour during embryo incubation (e.g., Goode and others 2013; Magiligan 1992; McKean and Tonina, 2013). The lower stream gradients and higher sinuosity of channels in unconfined valleys also reduce stream velocity, providing refugia for aquatic organisms during high flow periods (e.g., Wenger and others 2011). Furthermore, field studies in eastern Oregon demonstrate that unconfined channels have approximately 80% more pool area and 40% deeper pools than channels in confined valleys, providing higher quality habitat for salmonids (McDowell 2001).

Unconfined valleys are bounded longitudinally at their upstream and downstream ends by confined valley segments (Baxter and others 1999). Consequent downstream changes in valley width and alluvial volume force large-scale hyporheic circulation and upwelling of groundwater at the downstream ends of unconfined valleys (Poole and others 2008; Stanford 2006; Tonina and Buffington 2009) that has been shown to affect trout distributions. For example, bull trout (*Salvelinus confluentus*) in western Montana preferentially spawn in downstream portions of unconfined valleys, where hyporheic upwelling may warm stream temperatures and enhance overwintering success of bull trout embryos (Baxter and Hauer 2000). Similarly, Lahontan cutthroat trout (*O. clarki henshawi*) in southeastern Oregon show a preference for locations directly downstream from unconfined valleys, where hyporheic upwelling likely modulates stream temperature, providing cooler flow in the summer and warmer flow in the winter, as well as greater flow depths in all seasons (Boxall and others 2008).

Brook trout (*S. fontinalis*) are considered an invasive species in the western United States, and can displace native fish such as cutthroat trout (Dunham and others 2002). To help reduce brook trout populations, researchers have attempted to identify their preferred habitat. Wenger and others (2011) found that brook trout had a positive association with unconfined valleys, and where these fish were present, cutthroat trout demonstrated a negative association with unconfined valleys. These findings indicate that brook trout prefer unconfined channels, possibly because warmer groundwater in winter provides favorable conditions for egg incubation (Curry and others 1995).

Valley confinement also has a strong control on riparian habitats. Riparian zones form a narrow interface between aquatic and terrestrial ecosystems and represent only a small fraction of the terrestrial landscape. However, these areas harbor high levels of species richness (Birken and Cooper 2006; Kovalchick and Chitwood 1990; Ward 1998) and provide disproportionately important ecosystem functions (Wissmar 2004). Such environments are characterized by unique soils (Bohn and Buckhouse 1985), plant species (Dwire and others 2006), and wildlife (Morrison and others 1994). Valley confinement is strongly linked to riparian width in montane systems, with unconfined valleys supporting wider riparian zones (Polvi and others 2011). In the western United States, these riparian areas support some of the most important vegetative communities for providing wildlife habitat at both the site and landscape scales (USFWS 2009; Ward 1998) and are thought to be the most productive type of wildlife habitat on land (Kauffman and Krueger 1984). Confined riparian areas are preferred by some species, such as bats (Hagen and Sabo 2011), but unconfined valleys provide more suitable habitat for fauna, such as beaver (Polvi and Wohl 2012), elk, waterfowl, and bird species like the Willow Flycatcher (Sanders and Flett 1989). Unconfined valleys are associated with the presence of montane riparian meadows (Polvi and Wohl 2012) that are critical for wildlife, but are often targeted by livestock (Kauffman and others 1997). As a result,

many of these areas see decreased diversity, function, and productivity. Because of its relevance to riparian habitat, valley confinement has been used as a baseline factor for classifying and mapping riparian zones (Hemstrom and others 2002; Kovalchik and Chitwood 1990; Manning and Maynard 1994; Verry and others 2004; Winters and others, submitted). As such, identifying unconfined valleys in montane regions may be an important step toward restoring riparian habitat.

Previous Algorithms and Comparison to the VCA Approach

Automated valley confinement and valley width algorithms have been previously developed for a range of aquatic and riparian applications. Strager and others (2000) developed a landscape scale riparian habitat model that used 1:100,000 scale stream lines and 30 m DEMs as input. The algorithm delineated near-stream riparian habitat using a path-distance function. The path-distance method computed the relative “cost” of moving laterally away from the stream channel while subject to a resistance measure, defined as ground slope. The result was a raster with cost increasing as the cumulative product of ground slope and distance from the stream, with values rapidly increasing where slope was greater. Low-cost, relatively flat-lying areas were associated with wetland/riparian habitat.

Williams and others (2000) mapped valley bottoms using an elevation approach, where valley bottom polygons were delineated when cells proximal to the channel fell within a user-defined elevation threshold compared to the elevation of the stream as depicted by the DEM. All cells with elevations less than or equal to the local threshold were included in a valley bottom zone. Valley width was then computed using transects generated across the zone.

Elevation and ground slope were used by Gallant and Dowling (2003) to generate an index of valley bottom flatness from DEM data. The algorithm used basic concepts of flatness and lowness to identify valley bottoms at various scales. Flatness was derived from a standard percent slope measure and lowness was determined by elevation percentile, a ranking of the elevation of a grid cell with respect to the surrounding cells in a circular region.

Vertical change and valley bottom width thresholds were used to map probable riparian areas by Ruefenacht and others (2005). The first threshold restricted the valley bottom based on vertical rise from the DEM modeled channel and the second threshold constrained the valley bottom by a maximum width (Finco and others 2008).

Hall and others (2007) used cross-valley transects and 10-m DEMs to estimate horizontal floodplain extent and to classify stream reaches as confined or unconfined. In their approach, bankfull width and depth were predicted for each stream reach as functions of contributing area and precipitation. The cross-valley transects were placed above the stream at a height of three times the modeled bankfull depth. Where transects intersected the valley side-slopes, the edge of the floodplain was demarcated. The channel confinement ratio was next computed as a function of floodplain width divided by bankfull width. Channels were classified as confined if the ratio was ≤ 3.8 and unconfined if the ratio was > 3.8 , an empirical threshold based on the observed potential for lateral channel migration.

Walterman and others (2008) used a three-step approach to delineating valley bottom extent, with each step subsequently refining the likelihood of identifying riparian habitat. First a stream buffer distance, scaled by stream order, was computed for the study area. This layer was refined by thresholding a change in height above the stream elevation, which was further refined using a ground slope threshold.

Benda and others (2007, 2009, 2011) developed a tool called NetMap that generates numerous watershed attributes and indices, including a channel confinement

classification. Channel confinement is calculated as floodplain width divided by channel width. Floodplain width is calculated by using a specified height above the stream elevation; the specified height may be a user-defined constant or computed as a function of bankfull depth, similar to the approach of Hall and others (2007).

Most recently, Housman and others (2012) developed a logistic regression approach to modeling valley bottom areas for identifying riparian zones. Representative training data are used to determine the probability of each cell belonging to the valley bottom class by using topographic derivatives: height above the channel elevation, Euclidean distance from the channel multiplied by the ground slope, and topographic position index. Riparian areas are further refined with the use of spectral reflectance information from remotely sensed data.

Our VCA approach builds from many of the techniques used in these previous studies and employs four primary variables: (1) cost-weighted distance; (2) flood height; (3) ground slope; and (4) maximum valley width. The approach is described in detail in Part II and is summarized here. A modified version of the cost-distance approach (distance times ground slope) is used as an initial gross scale technique for identifying relatively flat valley bottoms near streams, while excluding other flat features beyond stream valleys. In this stage, only contiguous polygons meeting the distance times slope threshold that include an adjoining stream channel are preserved for further processing (the VCA does not consider unchanneled valleys). The results from the cost-distance process are refined using a valley filling procedure, which is best described conceptually as flooding the valley to a designated height above the channel elevation in the DEM. This process is similar to the one employed by Hall and others (2007) using transects, except that our method is implemented in a raster environment. A flood height is spread laterally outward from the stream channel until the valley side-slope is intersected. The flood height is controlled by the bankfull depth of the stream channel, predicted as an empirical function of drainage area and precipitation (Hall and others 2007), similar to the approach used by Benda and others (2011). A user-defined “flood factor” is multiplied by bankfull depth to determine the flood height. The resultant flood height and valley extent are thereby scaled to the stream size, similar to Rosgen’s (1994, 1996) flood prone width. In addition, a user-defined ground slope threshold is used to restrict the unconfined valley extent. This parameter may be used in combination with the flood height variable as an additional criterion for constricting valley area, or may be used alone if drainage area and precipitation data are not available for predicting bankfull depth and the flood height parameter. Finally, a user-defined maximum valley width limits floodplain extent in exceptionally wide valleys and plateau regions.

The VCA algorithm uses techniques similar to previous methods, but is unique because extensive user input allows the valley confinement product to be customized for a range of applications. User-defined parameters (flood height, ground slope, maximum valley width, minimum valley bottom area, and minimum valley stream length) can be used to tailor the mapping to one’s specific goals. In addition, processing is predominantly completed on raster datasets, which makes computations at the landscape scale operate more quickly than similar functions using vector data. The algorithm includes an option for computing stream network distance away from unconfined valley bottoms for use in aquatic habitat studies (e.g., Wenger and others 2011). The VCA uses standard, nationally available input data, such as NHDPlus, and the executable can be freely downloaded. The script may also be modified by knowledgeable Python developers. In addition, an online database of valley bottom extent, including the network distance output, is available for download.

Software Requirements and Overview

The VCA program requires ArcGIS version 10.0 or higher, with an ArcInfo level license and the Spatial Analyst extension. Python version 2.6.2 (ArcGIS 10.0) or higher is also required.

The program is run from the ArcToolbox interface as a script. Following installation (see http://www.fs.fed.us/rm/boise/AWAE/projects/valley_confinement.shtml) a Toolbox called Valley Confinement is added to the ArcToolbox interface and a script called Valley Confinement Algorithm will appear within the Toolbox.

Three input GIS files are used by the script, the first two are required and the third is optional: (1) a 10- or 30-m DEM clipped to a watershed boundary, (2) NHDPlus stream lines, and (3) NHDPlus water bodies. A watershed boundary GIS file is also useful to clip all three input layers to the correct spatial domain. A number of user input parameters that modify the algorithm results are required at the program interface.

The algorithm will output one of two possible products: (1) a polygon shapefile representing relatively flat, unconfined valley bottoms, or (2) a polygon shapefile representing relatively flat, unconfined valley bottoms with distance along the stream network measured to the closest valley bottom polygon. These products are referred to as Valley Type 1 and Valley Type 2, respectively. Although both products are generated from the raster DEM, the first output incorporates a line smoothing routine to create more realistic looking valley bottom polygons. The second output does not incorporate a smoothing routine because the nature of stream lines represented in a raster environment precludes this type of enhancement. As a result, the second product has a stair-stepped appearance that mimics the underlying raster data model. Valley Type 1 and 2 will provide slightly different valley bottom results because two slightly different processing procedures are used.

The VCA program and online documentation may be accessed from the Rocky Mountain Research Station (RMRS) valley confinement website: http://www.fs.fed.us/rm/boise/AWAE/projects/valley_confinement.shtml.

Scale Considerations

The USGS National Elevation Dataset (NED; USGS 2006), with a 30-m spatial resolution, is well suited for valley confinement mapping at a landscape scale. These data are generally able to identify relatively flat valley bottoms as small as 60-90 m wide, depending on the VCA user-supplied input parameters and the quality of the DEM. The output will be generally applicable at the valley segment scale (100 to 10,000 m) (Bisson and others 2006; Fausch and others 2002) and suitable for mapping at about 1:50,000 to 1:100,000 scales. Assuming that the DEM processing units are clipped to the subbasin (8-digit) USGS Hydrologic Unit boundaries (USGS 2011), the VCA will run approximately 5 to 10 minutes per subbasin.

DEMs with a 10-m spatial resolution can also be used, but run times will increase substantially. For 10-m DEMs, the program's default ground slope threshold should be decreased because smaller cells will result in less slope averaging at the interface between the valley bottom and side slopes. The user should experiment with different slope thresholds until a suitable value is obtained. Although 10-m DEM data may be used as input for the VCA, 30-m data are recommended due to their availability as part of the NHDPlus dataset.

The smallest unconfined valley that can be resolved by the VCA depends on the cell size of the DEM. In particular, the VCA has difficulty resolving unconfined valleys that are narrower than about two to three times the DEM cell size (60-90 m in width for a 30 m DEM or 20-30 m in width for a 10 m DEM).

Errors may also occur due to interactions between cell size and channel width. As bankfull width approaches two times the DEM cell size, the VCA may misinterpret the channel as a narrow unconfined valley (figure 7). This condition occurs as two or more adjacent raster cells at the same elevation abut perpendicular to the stream centerline, producing the appearance of a relatively flat valley bottom to the algorithm logic. These cells may actually represent the water surface in wider streams. Consequently, care should be exercised when narrow unconfined valleys are predicted in locations where channels have bankfull widths larger than twice the DEM cell size (i.e., bankfull widths larger than 60 m for a 30 m DEM or larger than 20 m for a 10 m DEM).

In addition, some valley bottoms are not mapped accurately in the USGS NED data and may not be identified by the VCA. The NED data were produced using an algorithm called LT4X (USGS 1997). The LT4X program used scanned topographic contours from quadrangle maps, tagged with elevation values, for generating the raster DEM data (Underwood and Crystal 2002). LT4X performed well in areas with sufficient contour density; however, where the concentration of contours changed from dense to sparse at unconfined valley bottoms, elevation errors were sometimes created. This type of error is most obvious in relatively flat, wide valley bottoms with relatively steep adjacent side slopes (Nagel and others 2010). Since these valley bottoms exhibited very little relief, there was a paucity of contours for guiding the LT4X algorithm, resulting in valleys having a “half-pipe” shape that should have a more planar morphology (figure 8).



Figure 7—A channel may be misinterpreted as unconfined because the channel width is larger than twice the DEM cell size. In this case the area of the stream’s surface was interpreted as an unconfined valley bottom.

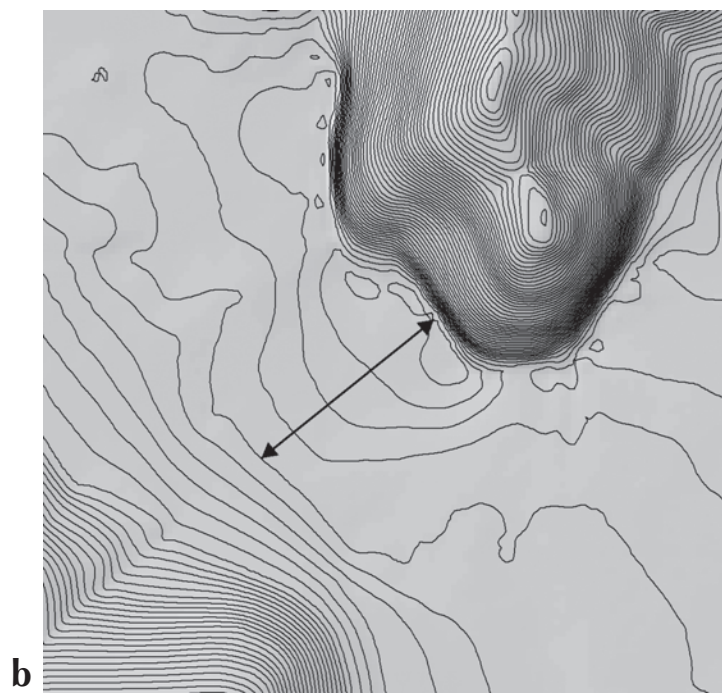
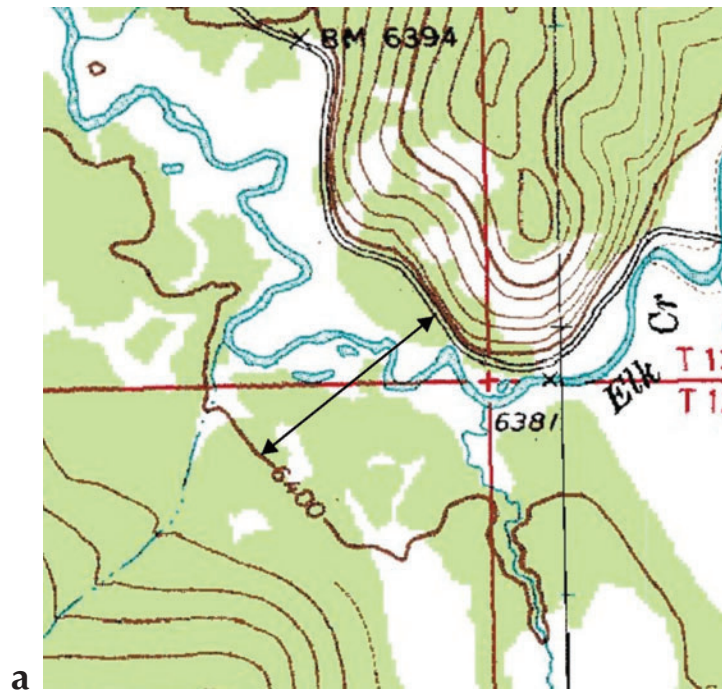


Figure 8—The original quadrangle map (a) from which the DEM data were created does not contain any elevation contours across the unconfined valley at the arrow location. However, 2-m contours derived from the 10-m resolution DEM (b) show an elevation change of at least 6 m across the valley. This gradual “rounding” of the valley bottom creates higher slope readings in the DEM than one is likely to encounter in the field. In addition, the DEM stream channel location is likely to be set deeper into the valley, relative to the valley side slopes, than one would encounter in the field.

Consequently, some valley bottoms may not be accurately captured by the VCA output. Increasing the input ground slope parameter or increasing the flood factor (described in the program parameters section below) may help alleviate this problem.

It should also be recognized that the VCA is unable to capture geomorphic features that are smaller than the resolution of the DEM. As such, ground truthing is advised to identify sub-cell topography, such as small terraces or channel entrenchment that may confine the river and its active floodplain. Riparian vegetation can also confine the river (e.g., Manners and others 2013; Smith 2004) and will not be visible to the DEM.

The VCA has been tested most extensively in montane regions of the Intermountain West and its performance in other landscapes is uncertain. Consequently, we recommend that users validate the VCA results using local field sampling. Low-relief landscapes may be particularly challenging in terms of setting an appropriate lateral ground-slope threshold.

Input and Ancillary Data Overview

It is necessary to download and pre-process five input GIS data themes (one DEM, three shapefiles, and one table) to successfully run the VCA program. This section provides a brief overview of the required inputs. The input data can be obtained from the National Hydrography Dataset Plus, Version 1 (NHDPlusV1) website. Additional information about downloading NHDPlusV1 data is provided in the next section. Instructions for using NHDPlusV2 data are provided on the RMRS valley confinement website.

Average annual precipitation (cm/yr) is needed if using the flood height factor. The precipitation value is implemented as a single value for the watershed being processed, so the GIS data layer is not required as input. The user is required to enter an integer value as an input parameter in the VCA interface. Readily available online sources of precipitation data include the PRISM Climate Group (<http://www.prism.oregonstate.edu/>) or the *nationalatlas.gov* website.

Elevation GIS raster

Source: NHDPlusV1 or USGS NED

NHDPlus download layer name: elev_cm

Format: ESRI GRID

Description: This raster layer is the underlying basis for most computations in the VCA, such as ground slope and flood height. The elevation units are centimeters. If the NHDPlus layer is used, it will need to be converted to meters during the pre-processing phase.

Stream lines GIS layer

Source: NHDPlusV1

NHDPlusV1 download file name: nhdfloflowlines.shp

Format: ESRI shapefile

Description: This layer is used to restrict valley bottoms to relatively flat areas directly adjacent to the stream network. Unchanneled valleys are not considered. The user will join a field to the attribute table called CUMDRAINAG, which may be used to control the minimum drainage area (surrogate for stream size) where valley bottom polygons will be delineated. The CUMDRAINAG field is also used in an equation to control the flood height parameter.

Water bodies GIS layer

Source: NHDPlusV1

NHDPlusV1 download file name: NHDWaterbody.shp

Format: ESRI shapefile

Description: The layer is used to exclude water bodies such as lakes and reservoirs from analysis so that these features are not misinterpreted as valley bottoms.

Drainage area attribute table

Source: NHDPlusV1

NHDPlusV1 download file name: flowlineattributesflow.dbf

Format: dBase

Description: This dBase file must be joined to the stream lines theme using the key field COMID. The attribute of interest from this file is CUMDRAINAG, which is the cumulative drainage area for the stream segment.

Watershed boundary

Source: NHDPlusV1

NHDPlusV1 download file name: Subbasin.shp

Format: ESRI shapefile

Description: This layer is an ancillary shapefile that contains watershed boundaries, which may be used to clip the elevation raster and hydrography shapefiles.

Average annual precipitation

Source: PRISM (Daly and others 1994, 1997) recommended; however, other sources are acceptable

Download file name: Varies with source

Format: ESRI grid or ESRI shapefile

Description: This is a required input if the flood height option is activated for the VCA input parameters; however, only a single integer value is required as input.

Input and Ancillary GIS Data Download Instructions

Obtain NHDPlus data for the production unit of interest from the website:

<http://www.horizon-systems.com/nhdplus/>

Note that these instructions were written for NHDPlusV1. These data can be obtained from the archive site at:

http://www.horizon-systems.com/NHDPlus/NHDPlusV1_home.php.

Data are downloaded under the “Additional information” heading at this website.

NHDPlusV1 data were used to develop the VCA; however, since that time NHDPlus Version 2 (NHDPlusV2) data have been released. NHDPlusV2 data may be substituted for NHDPlusV1. The processing instructions will be very similar, but may require substitution of certain file names. See the RMRS valley confinement website for more information.

Download Instructions:

1. Download the elevation GIS raster, which will have a file description similar to: Region 17, Version 01_02, Elevation Unit a
2. Download the NHDPlus stream lines, water bodies, and subbasins, which will have a file description similar to: Region 17, Version 01_02, National Hydrography Dataset
3. Download the associated attribute tables, which will have a file description similar to: Region 17, Version 01_04, Catchment Flowline Attributes

Input and Ancillary GIS Data Pre-processing Instructions

These pre-processing instructions should provide an intermediate level GIS user with enough information to prepare the input data files for the VCA program. An intermediate level of GIS theory and ArcGIS knowledge is necessary to complete these steps.

Map projection—Choosing an appropriate map projection for processing the data is an important consideration. The elevation raster resides in the following native projection when downloaded from the NHDPlus website:

Albers Conical Equal Area
Standard Parallel 1: 29.5
Standard Parallel 2: 45.5
Longitude of Central Meridian: -96.0
Latitude of Projection Origin: 23.0
False Easting: 0.0
False Northing: 0.0
Datum: NAD 83

This projection may not be appropriate for all study areas. The user may select a more appropriate projection such as Universal Transverse Mercator (UTM) if desired, which will require projecting the elevation raster to the desired coordinate system. In doing so, it is important to intentionally select an output cell size of 30 m to match the native cell size. In addition, the bilinear interpolation or cubic convolution resampling algorithm should be used.

The vector GIS data from the NHDPlus dataset (stream lines, water bodies, and sub-basins) reside in the geographic coordinate system (latitude-longitude). Because this coordinate system is based on units of degrees rather than meters, these shapefiles must be projected to a rectangular coordinate system, such as Albers Conical Equal Area or UTM. It is assumed that the user is experienced in projecting raster and vector data and can accomplish these tasks without detailed instructions.

The workflow for projecting the various GIS layers will vary by user and is complicated by the fact that the NHDPlus elevation and hydrography data reside in different projections. It will be incumbent on the user to devise a workflow for reconciling the GIS layers into a single projection for processing with the VCA.

Watershed boundary—The subbasin shapefile will have been extracted to a folder named \HydrologicUnits. The subbasin data reside in the geographic coordinate system and should first be projected to the NHDPlus Albers coordinate system. This step will produce a subbasin dataset matching the projection of the elevation data. Next, a single watershed should be selected from the projected subbasin dataset to use for clipping the elevation data. The extent of a single subbasin is an appropriate size for implementing a VCA run. Subbasins are defined by 8-digit or 4th code hydrologic units (Seaber and others 1987).

Elevation GIS raster—After unzipping the download file, the DEM data will reside in a folder named \Elev_Unit_x. The DEM raster is named elev_cm. This DEM has vertical units of cm that must be converted to units of meters.

To convert the units with ArcGIS 10 use the Raster Calculator tool as follows:
Arc Toolbox > Spatial Analyst Tools > Map Algebra > Raster Calculator

Raster calculator input box:
Float(elev_cm)/100

Use the subbasin shapefile to extract the elevation data from the NHDPlus DEM.
Spatial Analyst Tools > Extraction > Extract by Mask.

Fill in the required fields. Click the “Environments...” button and then the “Processing Extent” option.

Extent: Use the selected subbasin shapefile name

Snap Raster: Use the DEM name

Output: elevclip

This clipped raster may now be projected to the user’s study area projection, if desired.

Stream lines and water bodies—Use the same selected subbasin shapefile to clip the NHDPlus stream lines from the shapefile called nhdfline.shp, within the \Hydrography folder:

Analysis Tools > Extract > Clip

Output: FlowLine.shp

Also clip the shapefile called NHDWaterbody.shp using the same procedure.

Output: Waterbody.shp.

Project the shapefiles to the appropriate projection as necessary.

Drainage area attribute—Find the table flowlineattributesflow.dbf in the folder \NHDPlusXX. This file will need to be joined to the shapefile FlowLine.shp. Implement the join using COMID as the common ID. Export to a new shapefile.

Output: FlowLineJoin.shp.

The flow line shapefile, water body shapefile and DEM will be used as input by the valley bottom algorithm. All of the files should now reside in the same projection.

Precipitation—Download data from the PRISM Climate Group (Daly and others 1994, 1997) or the *nationalatlas.gov* website. Project the GIS data as necessary and convert units from inches to centimeters if required.

Substituting Higher Resolution Input Data

Higher resolution data such as 10 m National Elevation Dataset (NED) DEMs and 1:24,000 scale National Hydrography Dataset (NHD) may be substituted for the NHD-Plus data. However, care must be taken to ensure that the substituted data adhere to certain consistency standards.

1. It is always a good idea to clip the DEM, stream lines, and water bodies to a watershed boundary. This step ensures that all layers have the same extent and that streams and valleys maintain their full extent.
2. If 1:24,000 scale NHD data or other stream lines are used, the shapefile must contain a numeric attribute field called CUMDRAINAG. This field must be populated with a number, such as the value 1, even if it is a mock number used to satisfy the program requirements. The CUMDRAINAG attribute has two important functions in the VCA program. First, it is used for computing the modeled bankfull depth that, in turn, is used by the flooding function. Second, it is used to exclude streams with a drainage area smaller than the user-defined threshold.
3. If water bodies such as lakes or reservoirs are present in the study area, a water body shapefile, defined as polygon type, should be input into the program. The shapefile may come from the NHDPlus data, another source, or be hand digitized. This layer will prevent water bodies from being identified as unconfined valley bottoms.

Program Inputs, Parameters, and Output

The program inputs, parameters, and output are defined through the Arc Toolbox user interface (figure 9). The interface options are described below.

Inputs

Workspace location—The computer location where the input data are stored and where the output shapefile will be saved. Scratch data are also written to this folder and cleaned up at the end of the process. Available scratch space should equal 12 times the size of the input DEM.

Input DEM—Name of the input 10- or 30-m digital elevation model (DEM), derived from the NHDPlus data, USGS National Elevation Dataset, or other source.

Input streams—Name of the input flow line data derived from the NHDPlus dataset or other source.

Input waterbodies—Name of the input waterbodies shapefile derived from the NHDPlus dataset or other source.

Parameters

Output valley type—Two output products are available: (1) unconfined valley bottoms only, or (2) unconfined valleys with distance measures along the stream network to the nearest unconfined valley.

Maximum ground slope threshold—A ground slope threshold with units of percent slope. Only grid cells below the threshold will be preserved to represent unconfined valley bottom extent.

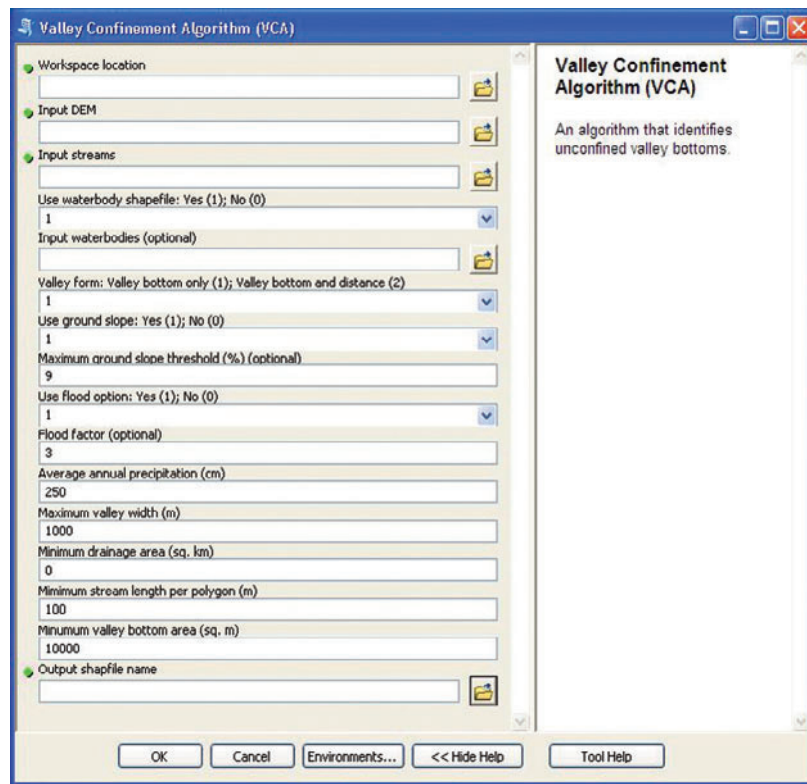


Figure 9—Screen shot of the Arc Toolbox VCA interface.

Flood factor—The flood factor is a dimensionless value that is multiplied by the estimated bankfull depth to generate a nominal “flood height” above the channel elevation (e.g., Hall and other’s (2007) figure 2b). Bankfull depth (h_{bf} , m) is empirically predicted by the VCA as a function of drainage area (A , km²) and average annual precipitation (cm/yr) by combining hydraulic geometry equations developed by Hall and others (2007) for channels in the Columbia River Basin: $h_{bf}=0.054A^{0.170}P^{0.215}$. The flood height (m) is used to conceptually flood the valley floor to a variable height above the channel elevation. Only grid cells that are “submerged” are preserved.

Average annual precipitation—The precipitation value (cm/yr) is used, as described above, to predict bankfull depth and flood height. An average annual precipitation value equal to the highest estimate in the watershed is recommended. Using the highest estimate will produce a more liberal valley bottom extent, helping to compensate for the DEM rounding of valley bottoms discussed above (figure 8).

Maximum valley width—This parameter allows the user to select a width (m) for clipping the extent of the valley floor orthogonal to the channel. This parameter is useful in very low relief regions where a valley side slope is not portrayed in the DEM data, causing the valley bottom polygon to extend beyond the influence of the stream channel.

Minimum drainage area—This parameter deletes valley bottom polygons that are smaller than the user-defined minimum drainage area (km²).

Minimum stream length—This parameter will delete valley bottom polygons that do not contain the specified minimum total stream length (m).

Minimum valley area—This parameter is used to delete valley bottom polygons under a specified minimum area (m²).

Output

Output Shapefile—The name of the output shapefile.

Algorithm Sequence

The input GIS layers work together to create intermediate files that will vary based on the input data characteristics and user supplied parameters. These intermediate files are referred to as variables and fall into two general categories: (1) valley bottom extent variables, and (2) valley bottom exclusion variables. The valley bottom extent variables control polygon initiation and the extent of the valley bottom area. The valley bottom exclusion variables operate on the output from the extent procedures to eliminate selected valley bottom polygons based on user-defined criteria. All calculations are completed using standard programs within ArcGIS version 10.0.

Controlling Valley Bottom Polygon Initiation and Size—Valley Bottom Extent Variables

Four rasters are computed and used as variables for controlling valley bottom initiation and extent: (1) slope cost distance, (2) flood height, (3) ground slope, and (4) maximum valley width. A threshold is applied to each variable to generate a binary (0 or 1) intermediate output. Each output grid has equal weight in the algorithm. When overlain together, each theme must have a value of 1 to instantiate a valley bottom cell. Variable 1 above sets the gross extent of unconfined valleys. Variables 2 and 3 refine the gross valley bottom extent, while variable 4 is a user-defined channel buffer that restricts the unconfined valley width.

Variable 1—Slope cost distance

Function: Generates an initial valley bottom domain that is refined by subsequent procedures in the algorithm.

The slope cost distance variable is derived from the ArcGIS Cost Path tool. A rasterized version of the stream channel is used as the algorithm source. This cell-by-cell operation computes accumulated cost, using a cost grid, as the focal cells are processed with increasing distance from the source cells (stream channel). The cost grid for this operation is the result from the ArcGIS Slope tool, with percent rise as the measurement parameter. The cost at each cell is computed as the cell size (10 or 30 m) multiplied by the cell slope (percent). As distance from the stream channel increases, the accumulated product of slope and distance are computed. In wide unconfined valleys with relatively low ground slope values, the slope cost distance measure increases gradually, whereas in confined valleys with steep side slopes the value increases rapidly. Empirical testing in the Intermountain West indicates that a slope cost distance threshold of 2,500 adequately captures an initial valley bottom domain that can be refined by further processing. This variable has no physical meaning and is simply an empirical rule that is used to set the initial processing domain for subsequent operations in the algorithm. The variable is intended to capture a relatively low-sloped domain near the stream network and eliminate low slope features outside of valleys. The variable threshold intentionally overestimates valley extent to ensure that all legitimate valley bottom cells are included for subsequent processing.

Variable 2—Flood factor

Function: Controls the lateral extent of valley bottom polygons by conceptually raising the stream water surface above the channel elevation.

The flood factor is a user-defined multiplier that conceptually raises the stream water surface to “flood” the valley to a specific height above the channel elevation. Bankfull depth is predicted by the VCA using an equation developed by Hall and others (2007) as described in the previous section. The flood factor variable is multiplied by the predicted bankfull depth to determine the flood height for each stream segment. Stream segments are defined by the NHDPlus data model.

Selecting the most appropriate flood factor is an important component for regulating the VCA results. Previous investigators have used similar approaches for defining valley extent, but different flood heights have been proposed. For example, based on field studies Rosgen (1994, 1996) defined the flood prone extent of a valley as the width measured at an elevation twice the maximum bankfull depth. This value roughly corresponded with the 50-year flood stage or less (Rosgen 1994). However, investigators working with DEM data have found that larger flood height multipliers are needed. Using 10-m DEM data, Hall and others (2007) found that an elevation of three times the bankfull depth provided the best results for estimating the historical floodplain width. In contrast, Clarke and others (2008) used a factor of five times the bankfull depth to estimate the elevation for measuring valley-floor width when using 10-m DEM data. This seemingly high multiplier is necessary because, as discussed above, the rounding of valley bottoms by the DEM may sometimes generate stream channels that are inset deeper into the valley than would be encountered in the field (figure 8). The VCA flood factor parameter defaults to a value of 5; however, a value of 5-7 is recommended based on the user’s familiarity with the terrain and field observations. Comparison of predicted and observed valley extent for field sites in central Idaho (Part III) indicates that a flood factor of seven is most appropriate for 30-m DEMs. The coarser vertical resolution of 30-m DEMs relative to 10-m data requires a larger flood factor (7 vs. 5) to obtain similar results.

For the VCA, the unconfined valley bottom is defined by the “flooded” area below the elevation where the flooded height intersects the valley side slope. This extent is further modified by the ground slope variable.

Variable 3—Ground slope

Function: Sets an upper ground slope threshold controlling the extent of valley bottom polygons.

Ground slope is generated from the input DEM using the ArcGIS Slope tool. Slope is computed by querying the eight neighboring cells to the focal cell and finding the neighbor with the maximum elevation change. Although the VCA queries all nearest neighbors, rather than specifically examining lateral slopes, the steepest slope generally becomes a lateral value as cells approach confining features. Percent slope is computed by dividing the elevation change (rise) by the distance between cell centers (run), and multiplying by 100. Only cell values less than the user-defined slope criteria will be included in the output unconfined valley bottom layer. A default slope threshold of 9% is used by the VCA. This value was derived empirically by generating transects across 30-m DEMs in unconfined valleys that were identified from field surveys in central Idaho (Part III). The slope value of 9% seems high; however, valley bottoms in USGS DEMs are generally modeled at a higher gradient than their true value on the ground (Nagel and others 2010) (figure 8). Users are advised to run the ArcGIS slope program independently to estimate an appropriate slope threshold value for the project area, prior to running the VCA.

Variable 4—Maximum valley width

Function: Controls lateral width of valley bottom polygons at a specific user-defined value.

This parameter is meant to confine the valley extent within wide floodplains and plateau regions. The width parameter (m) includes the entire valley width on both sides of the stream.

Eliminating Valley Bottom Polygons—Valley Bottom Exclusion Variables

Valley bottom polygons can be eliminated from the above data set based on the following criteria.

Variable 5—Drainage Area

Function: Eliminates valley bottom polygons where all of the stream segments are smaller than the minimum specified value (km²).

Variable 6—Stream Length

Function: Eliminates valley bottom polygons with a cumulative internal stream length less than the minimum specified length (m).

This variable is included for fisheries applications where a minimum stream length is necessary to support biological requirements. Total stream length is computed for each valley bottom polygon. The sum is calculated using all stream segments within the polygon, including streams smaller than the minimum drainage area. Polygons with a total stream length smaller than the cumulative stream length threshold will be eliminated.

Variable 7—Valley Area

Function: Eliminates valley bottom polygons smaller than a specified area (m²).

Output Shapefiles

Two output products are possible from any given input dataset as described below. Only one product may be generated per algorithm run.

Output Valley Type 1 – Valley Bottoms Only

Choosing Output Valley Type 1 as the output type will produce a polygon shapefile that only includes the unconfined valley bottoms. The polygon outline for each valley is smoothed to remove the stair-stepped appearance resulting from the underlying raster DEM. The shapefile will have an attribute field called VB_CLASS. All records will be populated with value = 1 (figure 10).

Output Valley Type 2 – Valley Bottoms With Distance Measures

Choosing Output Valley Type 2 as the output will produce a polygon shapefile that includes unconfined valley bottoms as well as confined stream reaches (both represented as polygons). Each polygon feature is attributed with distance along the stream network to the nearest unconfined valley bottom. The polygon outline for each valley is not smoothed for this output type because the linear nature of the confined valleys does not support this procedure (figure 11).

The attribute field will contain integer records representing the following classes:

- 0—Valley bottom polygon
- 1-30—Network distance to nearest unconfined valley bottom (km)
- 31—Distance greater than 30 km
- 50—Lakes and reservoirs

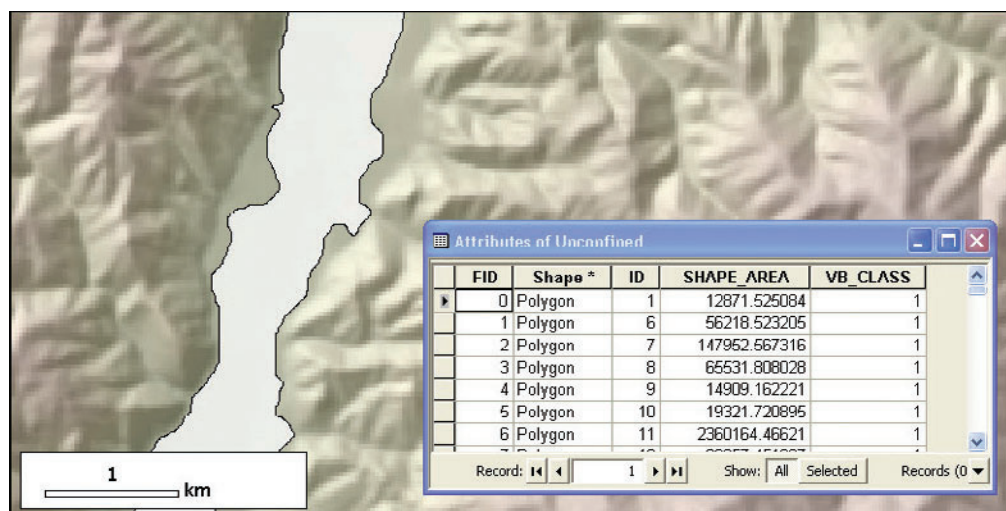


Figure 10—Valley Type 1 with smoothed output polygon and example attribute table. VB_CLASS is equal to value 1 for all records in the attribute table.

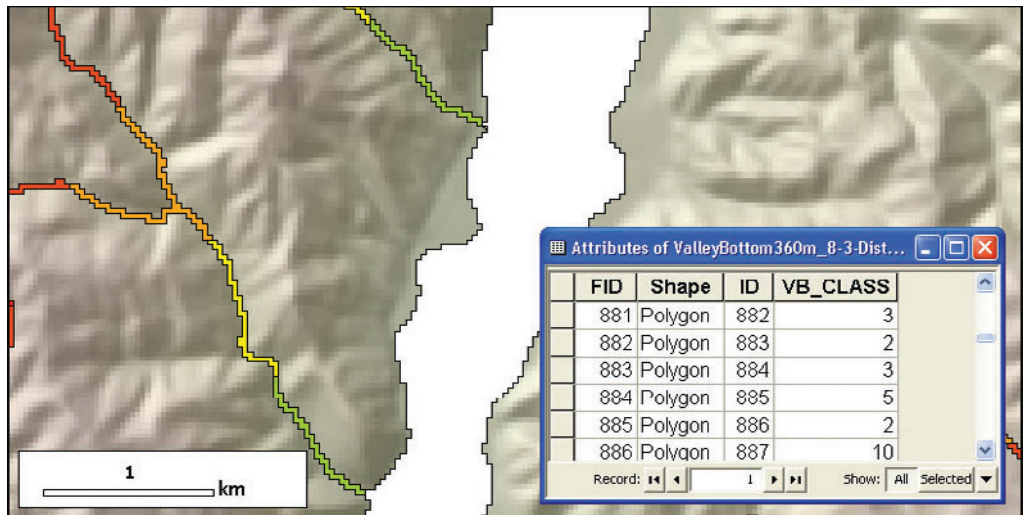


Figure 11—Valley Type 2 with stair-stepped polygon outline and example attribute table. The VB_CLASS field is attributed with distance along the stream network (km) from the nearest unconfined valley bottom. The white polygon is unconfined valley bottom and colored polygons represent distance classes along the stream network.

Part III—Field Assessment

Approach

Field data were collected to characterize channel conditions associated with confined and unconfined valleys mapped by the algorithm in two study areas of central Idaho (figure 12). The first study area was within the Secesh River drainage, located in the northwestern portion of the South Fork Salmon River basin, which is comprised of montane, mesic forests and meadows, with numerous high alpine lakes and a variety of channel morphologies. The second study area covered the South Fork Boise River basin, a more arid and lower elevation watershed, with mesic to dry forest and shrubland environments, also containing a variety of stream types typical of mountain basins.

The VCA was run for each study area and field sites were deliberately chosen to capture a range of valley characteristics. Sites were located near roads and trails for accessibility. In general, field sites were paired to produce an equal number of confined and unconfined samples. The pairs were often arranged near the boundary between confined and unconfined valley segments predicted by the algorithm, intentionally locating one point within, and a second point outside of a valley bottom polygon (figure 13). This configuration made data collection more efficient and also allowed us to evaluate the spatial delineation of the valley bottom polygons at the geomorphic transition zone between confined and unconfined valleys.

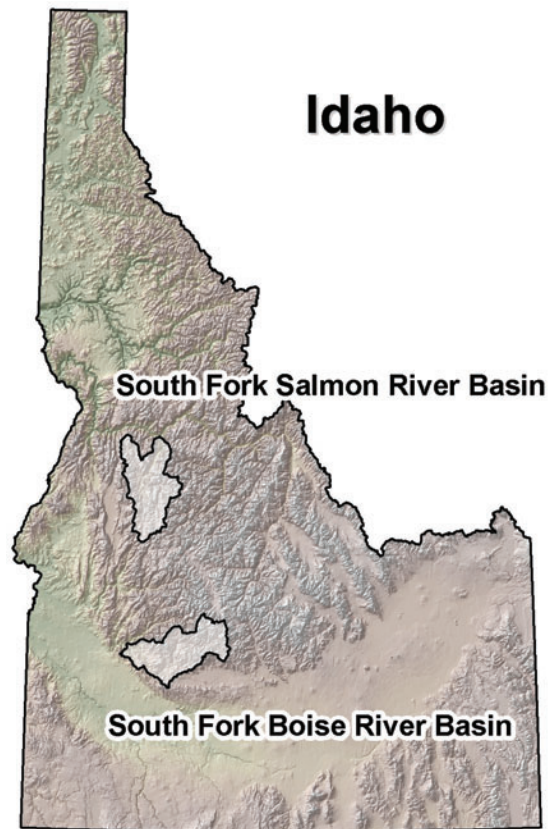


Figure 12—Study sites for field measurements and accuracy assessment of the VCA.

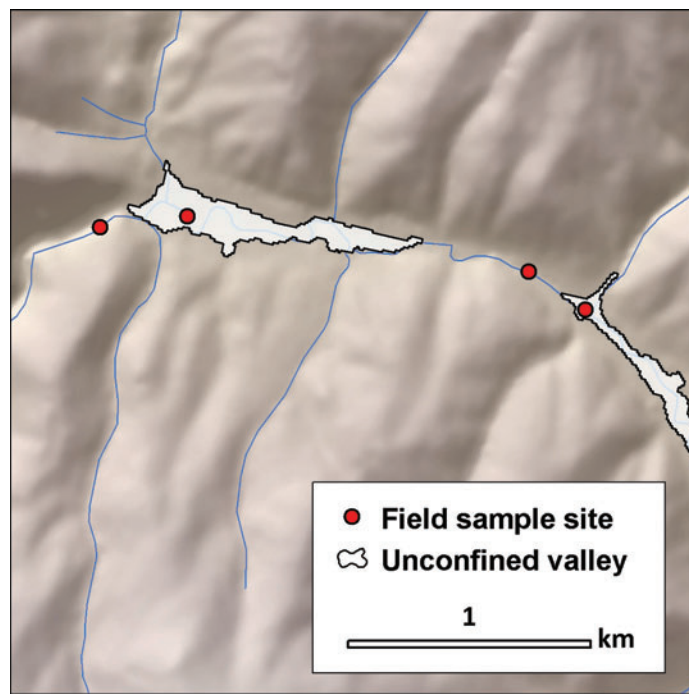


Figure 13—Example of field site locations relative to unconfined valley bottom polygons predicted by the VCA.

Bankfull channel width and valley width were measured at each field site to determine the channel confinement ratio (valley width normalized by bankfull channel width) (Bisson and others 2006; Clarke and others 2008; Hall and others 2007; Moore and others 2002; WFPB 1993). Channel morphology was noted as one of four types: cascade, step-pool, plane-bed, or pool-riffle (Montgomery and Buffington 1997). Channel substrate was classified as either alluvial or bedrock and reach-average grain size was visually estimated using Buffington and Montgomery's (1999) procedure for the relative abundance of primary size classes (sand, gravel, cobble, and boulder). Bankfull width was measured with a tape to the nearest meter, while valley width was measured to the nearest meter using a tape or range finder, depending on the field conditions. Here, valley width corresponds with the active (contemporary) floodplain of the channel. In measuring valley width, small-scale confining features (e.g., riparian vegetation, wood debris, and hummocky topography) were ignored, but larger confining features were included (e.g., river terraces and cut banks of entrenched channels; figure 14). Note that in the case of entrenched channels, the historic valley might be classified as unconfined, but the channel would be classified as confined (i.e., incised into the surrounding valley flat and incapable of flooding the historic valley). Because DEMs typically cannot identify channel entrenchment, field observations are needed to identify such cases. In these instances where channels were entrenched and confined by their cut bank, the confining width was measured at the cut bank rather than the historical floodplain.

The field measurements from both study areas were combined into a single data set. Thirty-eight field sites were sampled in the Secesh River basin and 25 in the South Fork Boise River basin, for a total of 63 sites.

The channel confinement ratio was computed for field locations to classify each site as either confined or unconfined. Channels with a confinement ratio less than 4.0 were deemed confined (figure 15), whereas those with a ratio greater than or equal to 4.0 were considered unconfined (figure 16). Threshold values for confinement ranging from 2.5 - 5 have been used previously by others (e.g., Clarke and others 2008; Moore and others 2002; WFPB 1993). We chose a value of 4.0 to closely align with the threshold of 3.8 used by Hall and others (2007). Channel type and grain size observations were summarized by confinement class as determined by this method, and channel confinement was compared with valley confinement predicted by the VCA.

Findings and Discussion

Measured channel confinement ratios were plotted against the bankfull channel width for each site and compared with the VCA predictions of valley confinement (figure 17). Results show that channel confinement agreed with valley confinement 79% of the time. Further inspection of the data revealed that disagreement between channel and valley confinement occurred due to VCA prediction errors. Although the prediction errors were small overall (79% correct classification), erroneous predictions of unconfined valleys were most common in locations with wide channels (bankfull width >20 m), while incorrect predictions of confined valleys occurred in locations with narrow channels (bankfull width of about 10 m or less) (figure 17).



Figure 14—Examples of wide valley bottoms with entrenched channels, showing the elevation of the abandoned (historic) floodplain.

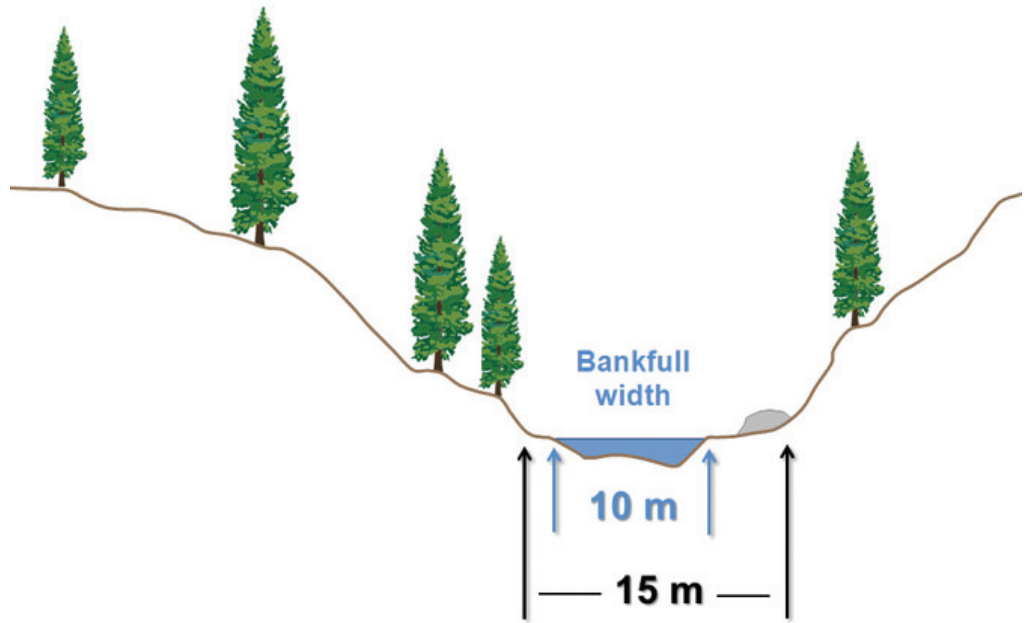


Figure 15—Example of a confined channel (ratio of valley width to bankfull width < 4).

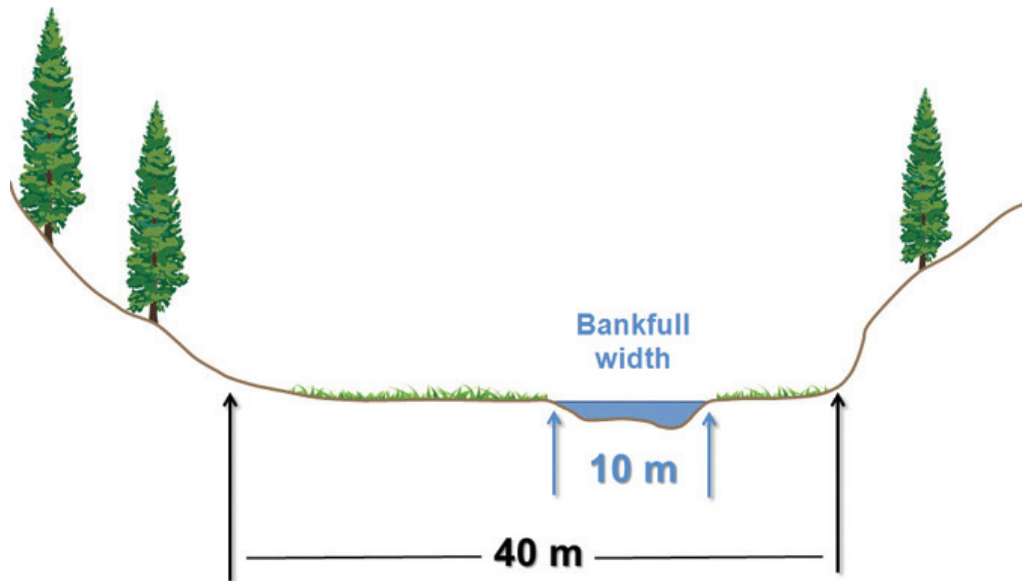


Figure 16—Example of an unconfined channel (ratio of valley width to bankfull width ≥ 4).

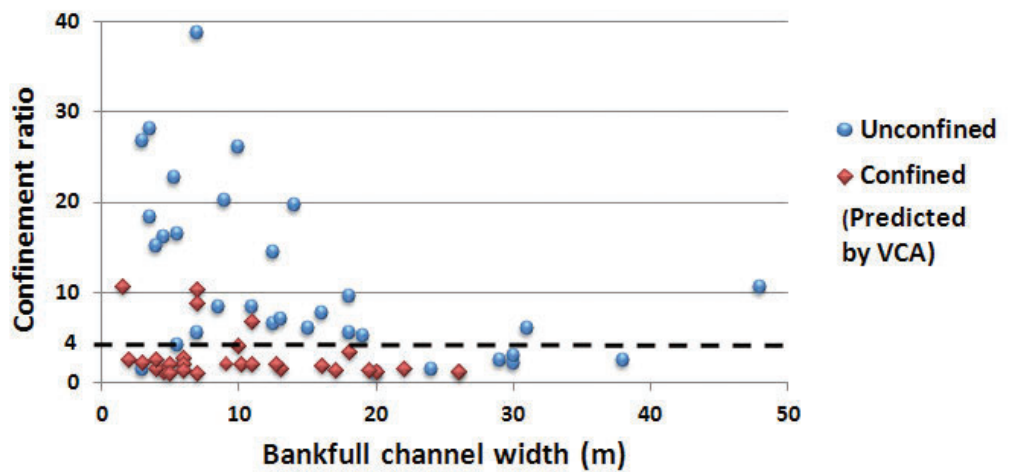


Figure 17—Field measurements of channel confinement ratio (valley width/bankfull width) plotted against bankfull width. The channel confinement threshold (dashed line) is compared with VCA predictions of valley confinement for each site (blue circles = unconfined valleys; red diamonds = confined valleys).

Of the 13 sample sites that were incorrectly classified, eight were errors of commission, where the valley bottom was delineated as unconfined by the VCA but deemed confined in the field. Five of these errors occurred because the channel width was more than two times the DEM cell size (cell size 10 m, channel width > 20 m). As a result the algorithm interpreted the stream surface as an unconfined valley bottom. Two of the errors occurred because the valley was too narrow to be resolved by the DEM and historic terraces were misidentified as unconfined valleys. An additional error occurred because the channel was incised, so the confining feature measured in the field was narrower than the historical floodplain identified by the algorithm in the DEM.

Five of the errors were errors of omission where valleys were not delineated by the VCA, but were deemed unconfined in the field. The errors of omission often occurred because the DEM did not consistently provide a good representation of narrow flat valley bottoms. As noted previously (figure 8), valley bottoms are sometimes over-steepened by the DEM due to a lack of guiding contours on the valley floor. Field observations and predicted valley types are shown in Appendix A.

The field measurements further show that all of the streams in both study areas had alluvial beds, except for one confined channel that was predominantly bedrock. Channel morphology varied substantially with confinement, as expected from prior studies (e.g., Montgomery and Buffington 1997). Unconfined channels were primarily pool-riffle (63%) and plane-bed streams (30%) (figure 18). In contrast, confined channels exhibited predominantly step-pool (58%) and plane-bed morphologies (39%). Example photographs of each channel type are given in Appendix B (figures B1-B4).

As expected, we also found that unconfined channels exhibited smaller grain sizes, with cobble and gravel sediments dominating, while boulder- and cobble-sized material were more prominent in confined channels (figure 19). Example photographs of each substrate type are given in Appendix C (figures C1-C4).

Our observed values of channel confinement, channel type, and grain size in each valley type are generally consistent with those of prior investigations, indicating that the VCA is identifying unconfined valleys with characteristics similar to those previously studied (Bisson and others 2006; Coulombe-Pontbriand and Lapointe 2004; Clarke

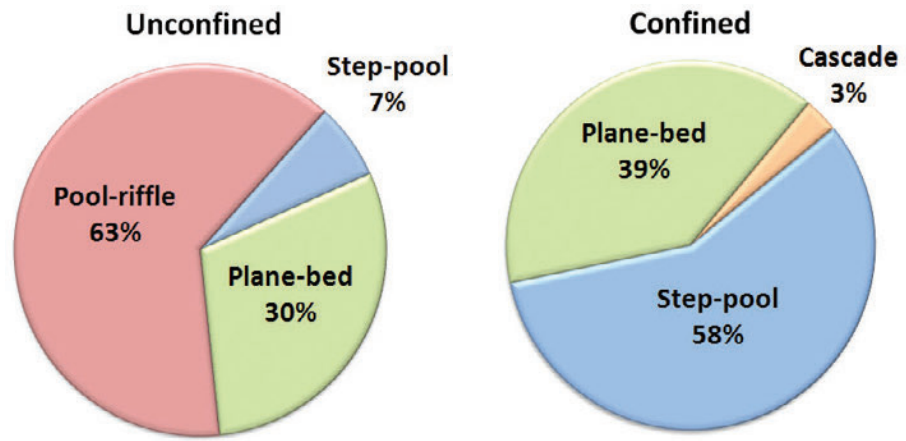


Figure 18—Composition of channel types within unconfined and confined channels.

and others 2008; Hall and others 2007; Montgomery and Buffington 1997; Moore and others 2002; Rosgen 1996; Wilkins and Snyder 2011; WFPB 1993). This finding does not validate the VCA results *sensu stricto*, but confirms that the algorithm is consistent with studies published in other geographic regions. However, our results may be biased because the field sites were not randomly selected and the actual population of confined and unconfined valleys along the stream network is greatly imbalanced, with a higher incidence of confined valleys over the landscape. For a more unbiased evaluation, the sampling of each valley type should be in proportion to its occurrence within the stream network in order to detect type 1 and 2 errors at equal rates (Snedecor and Cochran 1978; Zar 1999). In addition, because the field sample sites were paired near the transition between confined and unconfined valleys, results may be sensitive to how well the VCA locates the boundary between the two valley types; consequently, our agreement between channel confinement and valley confinement is likely lower than if the sites were assigned randomly and located near the center of each valley type. To account for these concerns, a more rigorous assessment of accuracy is provided in Part IV.

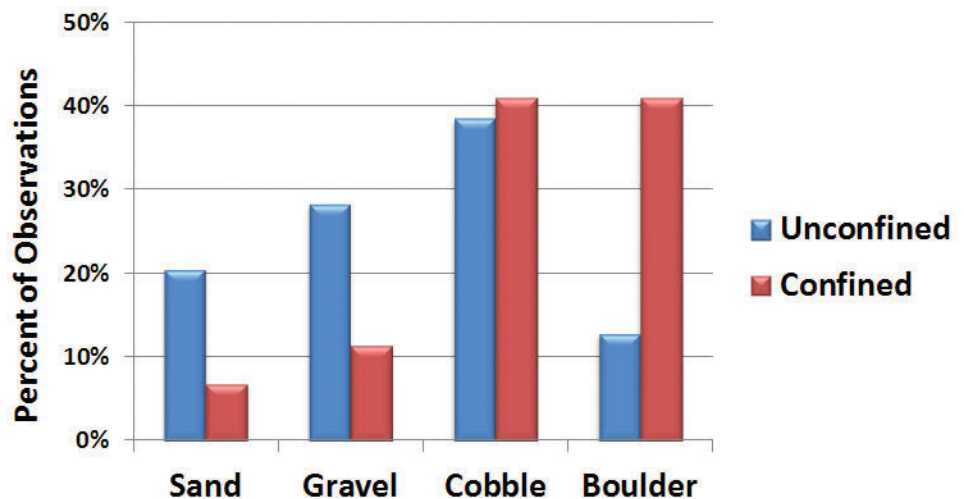


Figure 19—Proportion of grain size by channel confinement class.

Part IV—Statistical Validation

Methods

An office assessment of the VCA was conducted for the two study areas (figure 12). Two sources were used for verifying VCA predictions of valley type: scanned USGS 1:24,000 scale topographic maps and 1-m digital aerial photography. The VCA was run for each study area using the NHDPlusV1 30-m elevation data and 1:100,000 scale stream lines. For each study area, 120 random points were generated along the stream lines, stratified so that an equal number of points fell within confined and unconfined valley types, as identified by the algorithm. For the South Fork Salmon River drainage, a balanced sample of 60 sites in each valley type was generated. For the South Fork Boise River drainage, 61 points were located within unconfined valleys and 59 points within confined valleys. The following VCA program parameters were used to create the polygon output.

Output valley type: Type 1, valley bottoms only
Ground slope threshold: 9%
Flood factor: 3
Average annual precipitation: 115 cm/yr
Maximum valley width: 1000 m
Minimum stream length threshold per valley polygon: 360 m
Minimum polygon size threshold per valley polygon: 10,000 m²

The 9% ground slope threshold was chosen based on empirical evidence indicating that slopes less than 9% in the DEM likely correspond to unconfined valleys, as discussed in Part II, VCA Software, Algorithm Sequence. The flood factor of 3 was based on that recommend by Hall and others (2007) and the average annual precipitation value was derived from PRISM data (Daly and others 1997) for the study area. The 1000 m maximum width is an arbitrary measure, whereas the 360-m stream length threshold was chosen because the narrowest valleys identified by the algorithm are approximately 60-90 m wide. This threshold helped eliminate smaller spurious circular polygons by ensuring that most delineated valley bottoms adhered to an elongated form that was about four times longer than the valley width. The minimum polygon size threshold was set at an arbitrary size of 10,000 m², equal to 1 HA.

An unbiased analyst who was unfamiliar with the VCA output for this region conducted the analysis. At each point location, the analyst inspected the underlying topographic map and aerial photography. Each site was then classified as either confined or unconfined. To be classified as unconfined, a valley was required to meet the following criteria:

1. Valley width between confining topographic contours was greater than 60 m. This width is approximately the narrowest valley that can be identified by the VCA using 30-m DEM data.
2. Distance between upstream and downstream contours along the stream channel was greater than 406 m. Given the contour interval of 40 ft. (12.192 m) on the topographic maps, 406 m is the shortest length for obtaining a 3% stream gradient. This stream gradient approximates the upper limit for the occurrence of plane-bed channels (Buffington and others 2004), which is the steepest channel type generally found within unconfined valleys (Part III).

3. Context indicates a relatively flat, unconfined valley bottom considering the following elements:
 - a. Stream sinuosity. A meandering stream pattern was taken as evidence of an unconfined valley.
 - b. Topographic contour pattern. Specifically, a paucity of contours near the channel along the valley length (indicative of a low-slope, relatively flat valley).
 - c. Riparian vegetation. Meadow or shrub vegetation was used as an indicator of unconfined valleys in predominantly forested areas.

Each sample location was classified as confined or unconfined based on convergence of evidence using the above criteria. Lateral valley width and distance between upstream-downstream contours along the channel were used as quantifiable variables. Stream sinuosity, topographic contour pattern, and riparian vegetation were used as supporting contextual evidence to help make the final classification decision. The contextual characteristics were useful when one of the quantifiable variables did not meet the literal measurement criteria, such as when stream line distance between contours was less than 406 m.

Results

To understand the results of the validation effort it is important to recognize that our sample data are proportionally unbalanced compared to the actual number of unconfined and confined valleys typically found in the field. Our sample sites were chosen from the VCA model output and we chose roughly 50% of our samples in unconfined valleys and 50% in confined valleys, with approximately 60 sites in each class. However, within the South Fork Boise River basin the length of unconfined and confined streams is 296 km and 2995 km, respectively, and for the South Fork Salmon River basin the measures are 299 km and 2301 km, respectively. This imbalance between the class populations would require that we modify our sample proportions to mimic the stream length in order to detect false positive errors and false negative errors at equal rates. However, if the number of sample sites were stratified proportionally to the stream length in each class (assuming 100 sample sites) we would have only 9 sites within unconfined valleys, but 91 sites within confined valleys. To account for this problem, we report our results in two confusion matrices; one standard matrix (balanced sample) and one adjusted (unbalanced sample reflective of the expected occurrence of each valley type) (Baldi and others 2000). The matrices convey the results as described in table 1, where a positive event is associated with unconfined valley polygons and a negative instance refers to confined features. For example, a *true positive* occurs where a predicted unconfined valley was confirmed by the topographic and photographic data. A *true negative* indicates

Table 1—Sample confusion matrix. The predicted values represent the output from the VCA and the actual values represent results from the office assessment based on topographic maps and aerial photography.

| Predicted | Actual | |
|--------------|----------------------|----------------------|
| | Unconfined | Confined |
| Unconfined | True positives (TP) | False negatives (FN) |
| Confined | False positives (FP) | True negatives (TN) |
| Column count | Pc | Nc |

a correctly classified confined valley. False results imply an incorrect classification. The accuracy can then be computed as:

$$Accuracy = (TP + TN) / (PC + NC)$$

where *TP* and *TN* are true positive and true negative counts, respectively. *Pc* and *Nc* are the positive and negative column counts, respectively, which sum to the total number of samples. The above estimate of accuracy should be used with caution since it is not adjusted for the expected occurrence of each valley type; as such, we have a low probability of detecting false positives because few samples fall within confined valleys, relative to their abundance in the data set. To account for this issue an adjusted confusion matrix accompanies each study area, providing normalized values based on the expected proportion of each valley type. In addition, a Matthews correlation coefficient (Baldi and others 2000; Matthews 1975) is computed from the normalized table to assess the significance of the accuracy measure of the original sample set. The procedure yields a statistic between -1 and 1, with -1 indicating all false predictions, 0 implying completely random predictions, and 1 indicating perfect predictions. The procedure also yields a p-value, which represents the commonly understood significance measure, indicating whether the result is statistically different from zero.

For the South Fork Boise River sites, we observed that 109 samples were correctly classified for an accuracy of 91% for the unadjusted data (table 2). The adjusted confusion table was computed for these data (table 3) and a Matthews correlation coefficient of 0.77 was obtained, with a p-value of <0.00001.

Likewise for the South Fork Salmon River basin, we observed that 107 samples were correctly classified for an accuracy of 89% for the unadjusted data (table 4). The adjusted confusion table was computed for these data (table 5) and a Matthews correlation coefficient of 0.70 was obtained, with a p-value of <0.00001.

Table 2—Confusion matrix for the South Fork Boise River study area.

| Predicted | Actual | |
|------------------|---------------|----------|
| | Unconfined | Confined |
| Unconfined | 52 | 2 |
| Confined | 9 | 57 |
| Column count | 61 | 59 |

Table 3—Adjusted confusion matrix for the South Fork Boise River study area.

| Predicted | Actual | |
|------------------|---------------|----------|
| | Unconfined | Confined |
| Unconfined | 10.28 | 3.6 |
| Confined | 1.72 | 102.73 |
| Column count | 12 | 106.33 |

Table 4—Confusion matrix for the South Fork Salmon River study area.

| Predicted | Actual | |
|------------------|---------------|----------|
| | Unconfined | Confined |
| Unconfined | 51 | 4 |
| Confined | 9 | 56 |
| Column count | 60 | 60 |

Table 5—Adjusted confusion matrix for the South Fork Salmon River study area.

| Predicted | Actual | |
|------------------|---------------|----------|
| | Unconfined | Confined |
| Unconfined | 13.25 | 6.96 |
| Confined | 2.34 | 97.45 |
| Column count | 15.59 | 104.41 |

The overall, unadjusted accuracy of 89-91% for our study sites indicates good performance of the algorithm relative to the 85% accuracy standard that is often cited for classifying raster remote sensing data (Anderson and others 1976). The Mathews coefficients (0.70-0.77) indicate that the true accuracy may be lower than the above unadjusted values, but nonetheless demonstrate a high level of correct classification (Mathews coefficients closer to 1 than not). The highly significant p-values for both study areas indicate that a sufficient number of samples were tested for computing the Mathews coefficient.

The above analysis indicates that the VCA is reliable, producing accuracy results similar to other landscape scale classification efforts (Clarke and others 2008; Hall and others 2007). However, accuracy may vary by geographic region and use of the VCA should be limited to montane areas where the algorithm has been validated. We recommend that users conduct additional field work or consult independent digital sources, such as quadrangle maps and remotely sensed data, to ascertain the reliability of the VCA in untested landscapes.

Part V—Online Database

An online database of valley bottom confinement is available for an area covering most of the native range of inland cutthroat trout, except the Rio Grande and Arkansas basins. This database primarily encompasses the montane regions of Colorado, Idaho, Montana, Nevada, Utah, and Wyoming (figure 20) and is organized by USGS 4th code Hydrologic Units. These data were generated to support the research effort published in Wenger and others (2011) to study the distribution trends of cutthroat trout and other trout species.



Figure 20—Extent of USGS 4th code Hydrologic Units processed for the VCA-CT database.

The data were generated using an earlier version of the VCA, called VCA Cutthroat Trout (VCA-CT). There are three primary differences between the VCA-CT and the current VCA version described in this document:

1. The VCA-CT version used an additional 5 x 5 range filter to refine the Euclidean distance * slope variable.
2. The VCA-CT version did not utilize the flood height variable.
3. The VCA-CT version used a stream discharge variable for identifying the minimum stream size to be mapped, rather than the cumulative drainage area threshold.

The following parameters were used to generate the VCA-CT database:

Output valley type – Output option 2, flat valleys with distance measures.

*Euclidean distance * slope* – 850

5 x 5 range filter – 2500 (A VCA-CT option only, not found in the current version of VCA)

Ground slope – 8%

Flood height – Not used

Maximum valley width – 500 m

Drainage area – This variable was not used. A mean stream discharge value of 3.19 feet per second was used instead.

Stream length – 1500 m

Valley area – 3700 m²

These VCA-CT data may be downloaded from the Forest Service Valley Confinement website at:

http://www.fs.fed.us/rm/boise/AWAE/projects/valley_confinement.shtml.

Part VI—Summary

This report describes the Valley Confinement Algorithm (VCA), a GIS program that delineates unconfined valley bottoms and optionally computes the distance along the stream network to the nearest valley bottom for fisheries applications (Wenger and others 2011). Although prior studies have developed similar algorithms, to our knowledge this is the only such program that accepts extensive user input to vary the results for the intended application. As such, the algorithm should appeal to a variety of users for applications in hydrology, geomorphology, aquatic biology, and riparian studies.

The VCA was developed for use at landscape scales and should provide a good approximation of the total area and location of unconfined valley bottoms at a mapping scale of about 1:50,000 – 1:100,000. Field measurements demonstrated that channel confinement agreed with VCA predictions of valley confinement 79% of the time and that channel characteristics were similar to those documented in other studies of confinement. In addition, desk audits using topographic maps and aerial photography showed that the algorithm correctly identified unconfined valley bottoms with an unadjusted accuracy of 89 - 91% at our sample locations.

Although the above results are encouraging, users should be aware of limitations imposed by the resolution (cell size) of the DEM. In particular, because stream width cannot be ascertained from DEM data, the algorithm will identify wide streams greater than twice the width of the DEM resolution (60 m for 30-m resolution DEMs and 20 m for 10-m resolution DEMs) as unconfined valleys, even though the true field condition may be confined. Therefore, care should be exercised in interpreting results where narrow unconfined valleys are predicted in areas containing wide channels. In addition, the VCA has difficulty resolving unconfined valleys that are narrower than about two to three times the DEM cell size (60-90 m in width for a 30-m DEM or 20-30 m in width for a 10-m DEM).

The VCA is one of many emerging GIS tools focused on riverine resources. Recent emphasis on landscape scale analysis highlights the importance of these tools for meeting management goals over regional domains. With a growing body of research emphasizing the importance of valley bottom confinement for aquatic and riparian applications, we believe that the VCA will be a useful tool for mapping and managing resources in riverine landscapes of mountain basins.

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Appendix A. Field Collected Data

| ID | STR_WDTH | VAL_WDTH | RATIO | STRM_TYPE | GRAIN SIZE |
|-------|----------|----------|-------|-------------|-------------------------------|
| S1-1 | 3 | 374 | 124.7 | Pool-riffle | NR |
| S2-1 | 3 | 80 | 26.7 | Pool-riffle | NR |
| S3-1 | 3.5 | 98 | 28.0 | Pool-riffle | NR |
| S7-1 | 8.5 | 70 | 8.2 | Pool-riffle | Gravel |
| S8-1 | 5.5 | 22 | 4.0 | Plane-bed | NR |
| S9-1 | 3.5 | 64 | 18.3 | Step-pool | NR |
| S11-1 | 5.3 | 120 | 22.6 | Pool-riffle | Gravel |
| S12-1 | 6 | 12.5 | 2.1 | Step-pool | Boulder |
| S13-1 | 15 | 88 | 5.9 | Pool-riffle | Cobble |
| S14-1 | 12.5 | 180 | 14.4 | Pool-riffle | Cobble |
| S21-1 | 4.5 | 72 | 16.0 | Pool-riffle | Gravel |
| S26-1 | 24 | 34 | 1.4 | Plane-bed | Cobble |
| S27-1 | 29 | 71 | 2.4 | Plane-bed | Cobble |
| S28-1 | 5.5 | 90 | 16.4 | Pool-riffle | Sand, gravel |
| S29-1 | 18 | 170 | 9.4 | Pool-riffle | Gravel, cobble |
| S30-1 | 14 | 275 | 19.6 | Pool-riffle | Sand |
| S31-1 | 7 | 38 | 5.4 | Pool-riffle | Gravel |
| S32-1 | 19 | 95 | 5.0 | Step-pool | NR |
| S34-1 | 12.5 | 80 | 6.4 | Pool-riffle | Sand, gravel |
| S35-1 | 7 | 270 | 38.6 | Pool-riffle | Sand |
| S40-0 | 3 | 6.5 | 2.2 | Step-pool | NR |
| S41-0 | 7 | 72 | 10.3 | Pool-riffle | NR |
| S42-0 | 7 | 62 | 8.9 | Pool-riffle | NR |
| S43-0 | 6 | 16 | 2.7 | Step-pool | Cobble |
| S45-0 | 6 | 12 | 2.0 | Step-pool | Boulder, gravel |
| S50-0 | 4.5 | 5.5 | 1.2 | Step-pool | Boulder |
| S51-0 | 22 | 32 | 1.5 | Plane-bed | Cobble, boulder |
| S52-0 | 20 | 24 | 1.2 | Plane-bed | Cobble, boulder |
| S57-0 | 5 | 10.5 | 2.1 | Step-pool | Cobble, boulder |
| S58-0 | 17 | 23 | 1.4 | Step-pool | NR |
| S59-0 | 10.2 | 21.4 | 2.1 | Step-pool | Boulder |
| S60-0 | 11 | 22 | 2.0 | Step-pool | NR |
| S61-0 | 13 | 19 | 1.5 | Step-pool | Boulder |
| S62-0 | 12.7 | 26 | 2.0 | Plane-bed | Boulder |
| S63-0 | 7 | 7 | 1.0 | Cascade | Boulder |
| S65-0 | 4 | 6 | 1.5 | Step-pool | Cobble |
| S71-0 | 19.5 | 26 | 1.3 | Plane-bed | NR |
| S72-0 | 5 | 5 | 1.0 | Step-pool | Boulder |
| B6-1 | 18 | 96 | 5.3 | Plane-bed | Cobble, boulder |
| B7-0 | 18 | 60 | 3.3 | Plane-bed | Cobble, boulder |
| B8-1 | 16 | 122 | 7.6 | Plane-bed | Cobble |
| B9-0 | 16 | 30 | 1.9 | Step-pool | Cobble, boulder |
| B10-0 | 11 | 74 | 6.7 | Plane-bed | Cobble, gravel |
| B11-1 | 9 | 181 | 20.1 | Plane-bed | Cobble, gravel |
| B12-1 | 11 | 91 | 8.3 | Plane-bed | Cobble |
| B13-0 | 10 | 41 | 4.1 | Pool-riffle | Sand, gravel, cobble |
| B14-0 | 9 | 20 | 2.2 | Plane-bed | Gravel, sand, cobble |
| B15-1 | 10 | 260 | 26.0 | Pool-riffle | Gravel, cobble |
| B18-1 | 4 | 60 | 15.0 | Plane-bed | Cobble, sand |
| B19-0 | 4 | 10 | 2.5 | Step-pool | Cobble |
| B20-1 | 13 | 90 | 6.9 | Pool-riffle | Cobble, sand |
| B21-0 | 6 | 8 | 1.3 | Step-pool | Cobble, gravel, sand, boulder |
| B30-0 | 1.5 | 16 | 10.7 | Step-pool | Boulder, sand |
| B33-1 | 31 | 182 | 5.9 | Plane-bed | Cobble, boulder |
| B34-0 | 2 | 5 | 2.5 | Step-pool | Sand, gravel |
| B35-1 | 30 | 59 | 2.0 | Plane-bed | Cobble, boulder |
| B36-1 | 38 | 90 | 2.4 | Plane-bed | Cobble, boulder |
| B37-0 | 26 | 30 | 1.2 | Step-pool | Boulder, cobble |
| B38-1 | 20 | 22 | 1.1 | Plane-bed | Cobble |
| B39-1 | 3 | 4 | 1.3 | Step-pool | Gravel, cobble |
| B40-1 | 48 | 504 | 10.5 | Plane-bed | Cobble, boulder |
| B1x-1 | 30 | 86 | 2.9 | Plane-bed | Cobble, boulder |
| B1x-0 | 26 | 30 | 1.2 | Plane-bed | Boulder, cobble |

Key

ID – Unique ID for each site. 1 = unconfined valley delineated by VCA, 0 = confined valley.

STR_WDTH – Bankfull width measured in the field

VAL_WDTH – Valley width measured in the field

RATIO – Confinement ratio (VAL_WDTH/STR_WDTH)

STRM_TYPE – Channel morphology (cascade, step-pool, plane-bed, pool-riffle) (Montgomery and Buffington 1997)

GRAIN SIZE – Grain size observed in the field. NR = none recorded

Appendix B: Examples of Channel Types



Figure B1—Cascade channel type found almost exclusively in confined valleys.



Figure B2—Step-pool channel type most common in confined valleys.



Figure B3—Plane-bed channel type, often intermediate or transitioning between confined and unconfined valleys.



Figure B4—Pool-riffle channel type, most common in unconfined valleys.

Appendix C: Examples of Substrate Types



Figure C1—Sand substrate commonly found in unconfined valleys.



Figure C2—Gravel substrate typical of unconfined valleys.



Figure C3—Cobble substrate common in either confined or unconfined valleys.

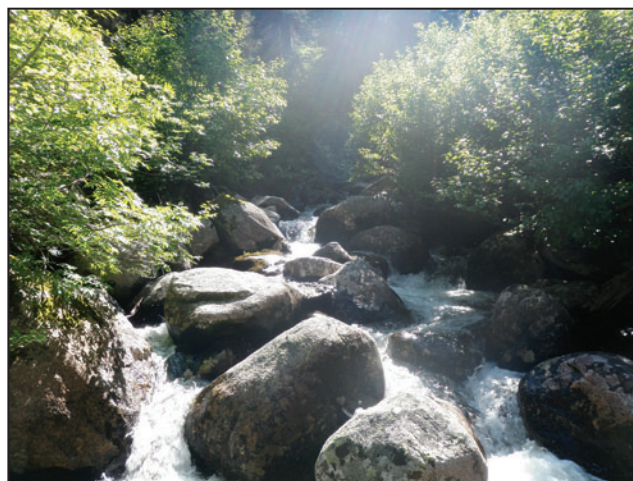


Figure C4—Boulders found most often in confined valleys.



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