MAPPING ECOLOGICALLY FUNCTIONAL RIPARIAN CORRIDORS USING LIDAR AND HYDROLOGIC LANDSCAPE ANALYSIS

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Geographic Information Science

by

Tom Shawn Robinson

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CERTIFICATION OF APPROVAL

I certify that I have read Mapping Ecologically Functional Riparian Corridors Using LiDAR and Hydrologic Landscape Analysis by Tom Shawn Robinson, and that in my opinion this work meets the criteria for approving a thesis submitted in partial fulfillment of the requirement for the degree Master of Science in Geographic Information Science at San Francisco State University.

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MAPPING ECOLOGICALLY FUNCTIONAL RIPARIAN CORRIDORS USING LIDAR AND HYDROLOGIC LANDSCAPE ANALYSIS

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Alluvial riparian corridors and their associated geomorphic landforms and vegetation communities have been significantly degraded in California, prompting an expansion of efforts to delineate riparian corridors and identify priorities for conservation via deed restrictions and easements. Common delineation techniques for these purposes (fixed-width buffers and manual digitization from aerial photos) do not accurately incorporate all landforms that are important to stream function. To improve riparian zone delineation, we developed a new GIS terrain model based on LiDAR and hydro-geomorphic relationships that can be used to map riparian corridors that vary with topography and incorporate ample space for dynamic fluvial geomorphic and hyporheic processes that create and maintain river morphology and vegetation and sustain ecological interactions over time. To quantify the inefficacy of existing delineation techniques, we present a case study of an alluvial reach of Mark West Creek in Sonoma County, California, where new and existing delineation techniques were compared against their respective coverage of three mapped proxies for riparian function: depth to groundwater, shading and material contribution, and wetlands. To demonstrate the utility of the new model to conservation practitioners, four sequentially-expanding acquisition scenarios based on the model were evaluated for their respective coverage of the mapped proxies of function. Coverages were combined with purchase cost estimates to produce a benefit-to-cost ratio (BCR).

I certify that the Abstract is a correct representation of the content of this thesis.

Chair, Thesis Committee | Date

PREFACE AND/OR ACKNOWLEDGEMENTS

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

GLOSSARY OF TERMS

50-year floodplain—The floodplain inundated under a 50-year flood flow. The 50-year flood is associated with the amount of precipitation that has a 1 in 50 (2%) probability of occurring in any given year.

BFD, 3xBFD, 18xBFD—Bankfull depth (see bankfull below), three times the depth at bankfull, and eighteen times the depth at bankfull.

Alluvial reach—A stream reach in which the bed and banks are made up of mobile sediment and/or soil. Alluvial rivers are self-formed, meaning that their channels are shaped by the magnitude and frequency of the floods that they experience, and the ability of these floods to erode, deposit, and transport sediment.

Bankfull—The water level, or stage, at which a stream or river is at the top of its channel banks and any further rise would result in water moving into the flood plain.

Effective flow depth—Effective channel flow is the flow necessary to mobilize sediment that moves as bedload in alluvial channels. Florsheim et al. (2014) suggest that bar height might be used as 71% of effective channel flow depth – which itself is the same as bankfull for a stable channel. In this way, bar height could be used as a proxy predictor, such that 1/0.71 or 1.4 * bar height should be the effective flow depth.

Flood-prone width—The lateral width associated with twice the depth of bankfull.

Flow accumulation—In raster-based (i.e., pixel-wise) calculation of upslope contributing area, flow accumulation refers to the summation of pixels (or proportions of pixels) that are "upstream" of a focal pixel.

Functional Riparian Zone—A definition of the riparian zone that incorporates material inputs and outputs; hydrological, ecological, and biogeochemical processes; and the spatial and temporal requirements for natural ecological functioning to occur. Regarding the spatial dimension, Ilhardt et al. (2000) offer the following: "Riparian zones are the three-dimensional ecotones of interaction that include terrestrial and aquatic ecosystems, that extend down into the groundwater, up above the canopy, outward across the floodplain, up the near-slopes that drain to the water, laterally into the terrestrial ecosystem, and along the water course at a variable width."

Hydroenforced DEM— High-resolution DEMs (from ALSM or LiDAR) contain an extremely high level of topographic detail. Road and railroad grades are mapped but often not the culverts and bridges that maintain hydrologic flow. Hydrologic-enforcement (hydroenforcement) of these high-resolution digital elevation models (DEMs) modifies the elevations of artificial impediments to flow to simulate the culverts and bridges that in reality maintain hydrologic flow. Thus, hydroenforcement is essential to the modeling of riverine flow and flow accumulation when using high-resolution DEMs. (USGS)

Topographic Wetness Index (TWI)—From Sørensen, Zinko, and Seibert (2006): "TWI was developed by Beven and Kirkby (1979) within the runoff model TOPMODEL. It is defined as ln(a/tan_) where a is the local upslope area draining through a certain point per unit contour length and tan_ is the local slope. The TWI has been used to study spatial scale effects on hydrological processes and to identify hydrological flow paths for geochemical modelling as well as to characterize biological processes such as annual net primary production, vegetation patterns, and forest site quality.

Upslope contributing area—The area that drains water to a specific spot in the watershed or channel. Calculated values of upslope contributing area depend on the flow accumulation algorithm used.

1.0 Introduction

Alluvial river valleys and their associated geomorphic landforms (e.g., channels, backwater sloughs, floodplains, and terraces), vegetation communities (e.g., riparian forests and wetlands), and stream-valley aquifers are among the most biologically productive and ecologically important biomes (Tockner & Stanford, 2002). The riparian biome is shaped by frequent hydrologic disturbances that produce diverse terrain profiles, complex habitat structures, rich assemblages of plant communities, and wet conditions that support unusually high levels of biodiversity (Naiman, Decamps, & Pollock, 1993; Naiman and Decamps, 1997; Sabo et al., 2005; Roland et al., 2007). Riparian zones, particularly alluvial reaches, provide several valuable ecosystem services to human communities including filtering and transporting drinking water and reducing downstream flooding (Costanza et al., 1997).

Perhaps no other biome is as ecologically important to wildlife and humans as alluvial riparian corridors. Despite their importance, alluvial riparian corridors have been significantly degraded globally (Nilsson & Berggren, 2000; Turner, Lambin, & Reenberg, 2007). In California, Katibah (1984) estimates that 95% of pre-European acres of riparian habitat in the Central Valley have been lost to human activities.

Degradation of alluvial riparian corridors results from geomorphic modifications and water diversions to accommodate human uses such as agriculture and settlements (Brinson & Malvárez, 2002; see Table 1 in Grantham, Merenlender, & Resh, 2010). Modifications and diversions disrupt historical hydrologic regimes that maintain water and sediment discharge equilibrium and lead to changes in channel morphology such as excessive incision, entrenchment, and aggradation. These changes sever essential hydrological and ecological linkages (Ward and Stanford 1995; Kondolf 1997; Ward 1998; Deitch, Kondolf, and Merenlender 2009), which in turn alter hydraulic, hydrological and bio-geochemical processes (e.g., flooding, deposition, channel meander and migration, large wood and sediment recruitment, groundwater-surface water interactions) that drive riparian ecological functioning (Kondolf et al., 1996; Boulton et al., 1998). The result is a decrease in the unique ecosystem services riparian corridors provide terrestrial and aquatic wildlife (e.g., maintenance of baseflow, food production, cover, migration routes, rearing habitat, temperature regulation) (Kondolf et al., 1996) and humans (e.g., soil conservation, drinking water supply, stormwater storage and attenuation, groundwater infiltration, pollution filtration, greenhouse gas sequestration, recreational values, and economic values) (Costanza et al., 1997; Brauman et al., 2007; Murray et al., 2009; Palmer et al., 2009; Dlugolecki, 2012; Lewis et al., 2015).

The loss of riparian ecological function is a long-standing concern of natural resource and fishery managers due the importance of the biome to maintaining biodiversity in the aquatic and surrounding upland landscapes (Gregory et al., 1991; Naiman, Decamps, & Pollock, 1993; Brinson & Malvárez, 2002). It is increasingly a concern among land-use and transportation planners and water resource and other infrastructure managers in light of existing and predicted effects of climate change. Expected changes include dramatic shifts in temperature and precipitation regimes, hazards due to storms with increased energy and precipitation, and greater stress on natural systems from longer periods of extreme heat and drought (Easterling et al., 2000; Wilby & Perry, 2006; Palmer et al., 2008). These climatological stressors, particularly dramatic departures in streamflow from existing regimes, are predicted to significantly impact riparian functioning and associated hazard-buffering and water-provisioning services (Palmer et al. 2009). Hydrological interactions with human impacts, such as anthropogenic impervious surfaces and devegetation, are intensifying degradation of riparian ecological function (Palmer et al., 2009), decreasing groundwater storage (Brauman et al., 2007), presenting hazards to infrastructure and human safety (Palmer et al., 2008), and negatively affecting local economies (Dlugolecki, 2012).

Conversely, where riparian ecological function is intact (i.e., erosion and deposition is at equilibrium and natural vegetation succession is occurring; Brooks, Flolliott, & Magner, 2003, p. 391), riparian zones are better able to store and release water, attenuate storm energy, provide habitat, and otherwise mitigate damage and environmental stressors caused by climate change (Naiman & Turner, 2000; Seavy et al., 2009). Lewis and others (2015) demonstrated the significant capacity of intact riparian vegetation and soils to sequester atmospheric carbon dioxide, which mitigates anthropogenic greenhouse gas emissions that cause climate change.

Natural resource and infrastructure managers at all levels of government are beginning to recognize the that ecosystem resilience and public hazard mitigation depend on riparian system function (e.g., Rijke et al., 2012; EPA, 2014; California AB 1608, 2017-2018). Among the planning strategies put forth to increase function and resilience and reduce societal and biological vulnerability, a top prescription is the protection and restoration of riparian zones, particularly alluvial reaches where storm energy attenuation and flood water storage capacity are highest (Seavy et al., 2009).

A key concept advanced by these new strategies is conserving enough lateral space to allow riparian processes and ecological functions to occur over their natural spatial and temporal scales. For example, channel migration—a continuous process essential for the development of aquatic habitat through the recruitment of large woody debris and coarse sediments—may extend laterally across the entire floodplain and requires connectivity to material inputs (e.g., water, wood, sediment, and nutrients) in lateral and longitudinal directions (Gregory et al., 1991; Ilhardt, Palik, & Verry, 2000).

Consequently, the effectiveness of riparian conservation depends largely on mapping technique as the two primary protection means—regulation (e.g., California Wetland and Riparian Area Protection Policy) and voluntary measures (e.g., purchase of conservation easements)—require the geographic delineation of a zone where human impacts are limited or development rights are purchased and extinguished. The two most common delineation techniques, fixed-width buffers from stream centerlines, typically between 10 m to 50 m (Fernández et al., 2012), and manual delineation of streamside vegetation as visible in orthophotography, have been shown to inadequately encompass riparian processes and functions (Ilhardt, Verry, & Palik, 2000; Hicky & Doran, 2004; Verry, Dolloff, & Manning, 2004; Holms and Goebel, 2011).

In order to effectively and efficiently conserve alluvial riparian zones, planners need accurate maps of the ecologically functional riparian corridor that can be used to guide conservation activities at the property scale but can be generated across whole catchments for prioritization of acquisition, restoration, or jurisdictional zoning activities. They also need mapping tools to assess the ecological trade-offs of narrower corridors as it may be infeasible to protect full riparian corridors due to a variety of socioeconomic reasons (e.g., landowner needs or expectations) (Hickey and Doran, 2004). Due to the high cost of comprehensive field measurement, these methods need to maximize the use of desktop mapping and remotely sensed data.

Several riparian zone delineation tools have been developed that use geographic information systems (GIS) and grid-based digital elevation models (DEMs) to synthesize geomorphology, hydrology, and ecological function into riparian zone delineations. For example, NetMap (Benda et al., 2007) employs hydrogeomorphic relationships (i.e., regional curves of hydraulic geometry) to map the future potential channel meander corridor. The USFS Riparian Buffer Delineation Model (Abood, Maclean, & Mason, 2012) uses the 50-year flood elevation and ecological inputs to define the riparian zone. The variable-width corridors these and similar tools produce can be seen as advances over previous techniques (e.g., fixed-width buffers) and should be considered for use by local resource management and hazard mitigation departments.

Although these tools are guided by an ecologically functional definition of “riparian” and produce boundaries that often match the extent of river-influenced landforms (e.g., channels and floodplains as in Benda et al., 2007, and Abood, Maclean, & Mason, 2012) and/or vegetation (e.g., riparian wetlands as in Shoutis, Patten, & McGlynn, 2010), what is lacking is a prescription for generating corridors that extend far enough into the upland fringe to ensure robust ecological connectivity. That existing tools target only the fluvial landscape is understandable because areas that are likely to be inundated within short to medium temporal scales are potential human safety hazards and/or critical for fish populations, both of which are significant drivers for mapping innovation. But voluntary, incentive-based land conservation, with its unique opportunities to protect the full ecologically functional corridor, requires modeling beyond flood-prone areas.

Conservation practitioners currently have no way of gauging conservation success beyond acquiring “as much as you can” or following one of many fixed-width buffer guidelines (e.g., Fischer & Fischenich, 2000; Hickey & Doran, 2004). To our knowledge, a framework does not exist that incorporates mapped indicators of riparian function and reports them in such a way that practitioners can assess the ecological and economic trade-offs of a variety of corridors. The method we advocate here employs GIS-based scenarios of variable-width corridors that are evaluated against their relative contribution to three indicators of riparian function: riparian aquifer recharge, stream shading, and presence of palustrine wetlands. We present our method through a case study of an alluvial reach of Mark West Creek, a large tributary of the Russian River in Sonoma County, California. The objectives of the study are threefold: 1) Develop a method for mapping the fluvial landscape (i.e., 100% probable riparian) and the ecologically functional riparian corridor (the “ideal” area to conserve), as well as a gradation of variable-width corridors between the two; 2) evaluate four conservation scenarios using the three indicators of riparian function above as a demonstration for land conservation practitioners; and 3) compare and contrast examples using common techniques (buffers and manual delineations) with the functional riparian corridor from contemporary terrain analysis.

1.1 Riparian Functions and Probability of Being Riparian

Riparian functions include energy flow, nutrient cycling, water cycling, hydrologic function, and plant and animal life histories and dynamics (NRCS, 1996). The aim of conservation should be to maximize protection of areas that accommodate riparian functions (Opperman et al., 2010). Riparian functions maintain terrestrial and aquatic ecosystem health and operate through interactions between components of the riparian zone (e.g., vegetation, wildlife, soils, geology, hydrology, and geomorphology) and the ecological, hydraulic, and geomorphic processes that act on them (e.g., erosion, seed dispersal, plant succession, hyporheic exchange, and retention of organic material and inorganic sediment) (Gregory et al., 1991).

Riparian functions generally decrease with distance from the water's edge, but the degree to which a riparian area extends into the terrestrial ecosystem varies with the type and strength of each function (Ilhardt, Verry, & Palik, 2000). Riparian functions include channel stabilization, temperature regulation through shading, contribution of woody debris and fine litter, maintenance of water quality through the retention of nutrients and sediment, riparian aquifer recharge, and wildlife habitat provision (Naiman, Decamps, & Pollock, 1993). The latter three continue well past riparian delineations that are based solely on soils, vegetation, or flood frequency (Ilhardt, Verry, & Palik, 2000; Emanuel et al., 2013).

The idea that riparian function strength generally decays with distance from the river can been described conceptually in terms of probability of the ecosystem being riparian (Fig. 1), with channels and floodplains—the fluvial landscape—considered to have 100% probability of being riparian (MFRC, 1999; Ilhardt, Verry, & Palik, 2000). On the terrestrial end, riparian functions eventually give way to upland functions, at which point there is very little probability of being riparian.

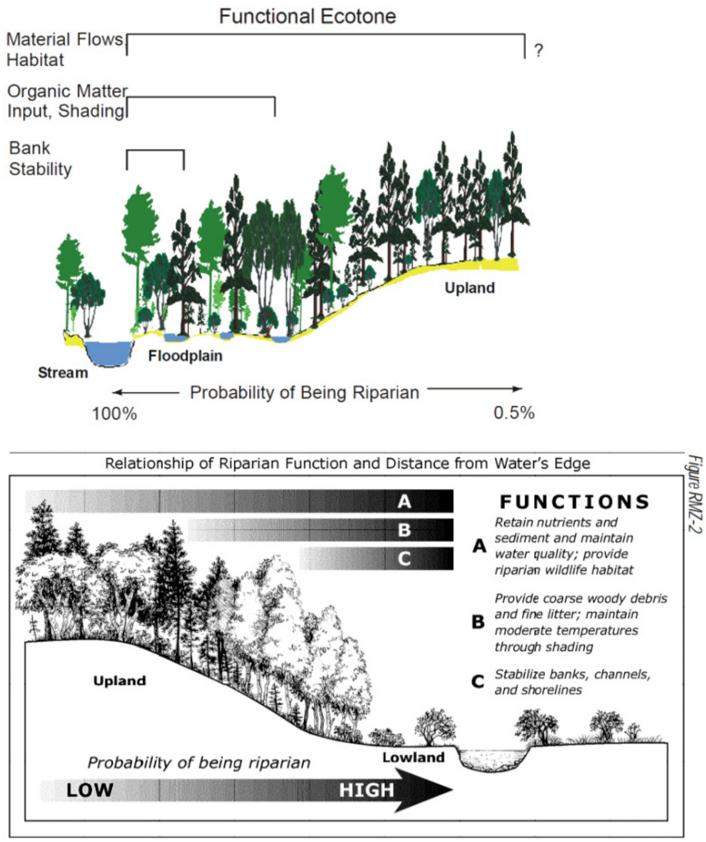

Fig. 1 Two illustrations of the relationship between riparian function, distance from the water's edge, and probability of being riparian (from Ilhardt, Verry, & Palik, 2000 [left] and MFRC, 1999 [right]).

For conservation purposes, it is important to consider the expected changes over time in the fluvial landscape. Over time, through lateral migration, the channel will eventually occupy all parts of the floodplain and bring with it hydraulic processes that shape adjoining morphology and vegetation (Dunne & Leopold, 1978, p. 605). Benda, Miller, and Barquín (2011) termed the area encompassing both the existing and potential future channels and floodplains the "predicted fluvial landscape" and showed that it corresponds to the area inundated by a height above the channel equal to three times bankfull depth (3xBFD). This area is important for conservation as it can act as a minimum for preserving fluvial riparian functions.

Riparian aquifer recharge is under-represented as a factor in existing riparian delineation techniques and design recommendations compared with other functions (e.g., shading, nutrient retention, bank stabilization). It is often discussed only in context of nutrient pathways (e.g., see Appendix E in Kennedy, Wilkison, & Balch, 2003) and thus the focus is on minimum distances from surface water required for nutrient buffering. This omission is relevant for conservation for at least three reasons: First, riparian aquifer recharge contributes to base flow and thus is critical to fish populations. Second, riparian zones capture and store precipitation when soils are intact (i.e., uncompacted, vegetated, and covered with organic material) and have well developed connectivity with groundwater—indicated by elevated soil moisture (Jencso et al., 2009). Third, notwithstanding the presence of aquitards (e.g., clay lenses), recharge is facilitated by the permeable geology (e.g., alluvial deposits) of valley landforms (e.g., fans, terraces, floodplains). The spatial extents of these physical phenomena are do not follow a uniform width and are governed by topography (Sørensen & Seibert, 2007). Delineations for conservation purposes should include the full extent of landforms that facilitate riparian aquifer recharge.

1.2 Hydrological Terrain Analysis in the Literature

As mentioned above, new riparian zone delineation methods focus on topographic controls on riparian hydrology and landforms in order to better model the shape of riparian valley bottoms. These methods employ digital elevation models (DEMs) and terrain analyses to derive variable-width riparian corridors. This is accomplished via several methods (summarized in Table 1) including relative elevation above the channel (e.g., Shoutis, Patten, & McGlynn, 2010; Abood & Maclean, 2011; Benda, Miller, & Barquín, 2011; Dilts, Yang, & Weisburg, 2011), cost distance functions (e.g., Smith et al., 2008), flow accumulation (e.g., Jencso et al., 2009), spatial disaggregation and aggregation procedures (e.g., Alber & Piégay, 2011; Roux et al., 2014), and others. For the purposes of this study, we focus on elevation above the channel (EAC; also known as height above the river) which has the advantage of being scalable when coupled with field-based regression curves of channel geometry (e.g., depth) against drainage area—also known as regional curves of hydraulic geometry as described by Dunne & Leopold (1978) (further described below).

Table 1. Summary of terrain-based riparian zone modeling techniques.

Modeling Technique	Summary	Uses Relative Elevation	Inputs	References
Manual delineation from topography	Manual delineation from contours. Extent varied between 4 stream types based on Rosgen groupings (e.g., A, G, F, & B).	Yes	Contours; 4 stream types	Holmes & Goebel (2011); Verry et al. (2004)
Path-distance allocation	Association with the riparian system decreases with increased distance and slope (calculated from DEM) from channel. Cost thresholds, beyond which the land is not considered part of the riparian zone, are user-defined and vary with stream order.	No	DEM; Stream network by order (Strahler); Slope	Strager, Bull, & Wood (2000); Smith et al. (2008)
Least-cost allocation	Associates upland cells with closest stream channel elevation based on distance weighted by intervening relief. Associated channel elevation is subtracted from DEM to derive an "elevation above channel" raster. Riparian zones are estimated based on multipliers of Bankfull depth.	Yes	DEM; Stream network; Slope; Bankfull depth	Benda, Miller, & Barquín, (2011)
Cone transects	Samples DEM elevation at points along 11 automated cone (radial) transects emanating from regularly spaced points along a stream. Deletes sample points if difference from channel elevation exceeds user-defined flood height (e.g., 1-meter 50-year flood height). Remaining points are rasterized to create floodplain extent.	Yes	DEM; 50-year flood height	Abood & Maclean (2011)
Linear transects	Samples DEM elevation at points along automated linear transects at 100m intervals along the stream. Rectangular "altimetric reference plans" of uniform elevation at the bankfull position are subtracted from DEMs to produce "relative DEM." Cells up to 10 m above the altimetric reference plan form the valley bottom that contains riparian/floodplain zone.	Yes	DEM	Alber & Piégay (2011); Roux et al. (2014)
Kernel density	Calculates a distance-weighted average of river elevations for a user-defined search radius. Weighted average river elevation is subtracted from DEM to derive a "height above river" raster.	Yes	DEM	Dilts, Yang, & Weisburg (2011)

Accumulation via flow paths	Triangular multiple flow direction algorithm ("MD∞") produces hillslope-based flow accumulation. As accumulation thresholds (e.g., 40 ha) are met, cells are classed as "creek." Riparian zones are determined by selecting creek cells above a user defined elevation above the stream link (separate raster) cell it flows into.	No	DEM; Flow accumulatio n (MD∞)	Seibert & McGlynn (2007); Jencso et al. (2009); Shoutis et al. (2010)

1.2.1 Elevation Above the Channel

EAC is computed as a continuous grid of elevations above the nearest stream pixel elevation (Fig. 2). In some cases (e.g., Abood & Maclean, 2011; Alber & Piégay, 2011), upslope elevations are sampled via automated transects and compared against the elevation of the associated point along the stream. Regardless of technique, however, relative elevation is combined with a threshold value to generate lateral extents that approximate the spatially variable 2-dimentional riparian zone. Threshold values are based on a variety of factors including multiples of bankfull depth (the depth of the channel), flood stage heights (e.g., 50-year), and upslope contributing area.

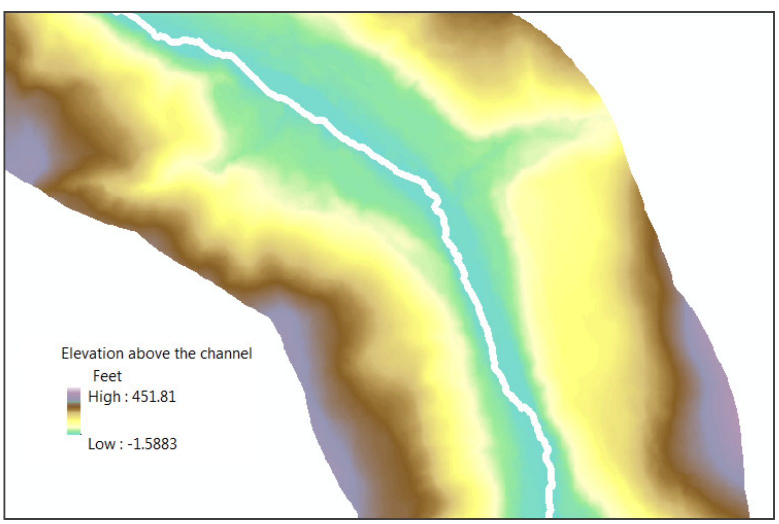

Fig. 2. Example of relative elevation above the channel following Dilts, Yang, & Weisburg (2011) and using 1-m DEM (channel in white).

1.2.2 Hydro-geomorphic Relationships

Generalized relationships between hydrology and geomorphology are particularly useful in digital terrain modeling. With established relationships and appropriately scaled DEMs, the modeler can translate a measurable geometry (e.g., channel depth) into mapped fluvial features, such as floodplain width.

A generalized relationship is observed by Rosgen (1994, 1996) between maximum bankfull depth (depth of the non-flood channel) and flood-prone width. Flood-prone width is defined as "the width measured at an elevation which is determined at twice the maximum bankfull depth" (Rosgen 1994, pp. 181-182). Based on field observations, Rosgen suggests that flood-prone width is coterminous with the 50-year floodplain, a hydrologic extent Verry, Dolloff, and Manning (2004) promote as a sound proxy for riparian zones in stream valleys. This may not be applicable in all situations. Fernández and others (2012) found when they evaluated the 50-year floodplain in a range of watershed settings with large variation in channel morphology, several multiples of bankfull depth (as opposed to solely twice maximum bankfull depth) would be needed to accurately estimate the 50-year floodplain width. Based on their work mapping existing and past channel positions across multiple stream valleys, Benda, Miller, and Barquín (2011) promote the use of the width at three times bankfull depth to estimate possible future channel positions, or the "predicted fluvial landscape", given channel migration over time. For defining bankfull, these studies assume natural stream conditions. Florsheim et al. (2013) suggest that effective flow depth (rather than bankfull) may the best geometric determinant of the channel-forming flow in anthropogenically degraded stream systems.

Bankfull hydraulic geometry relationships, otherwise known as regional curves, were originally published by Dunne and Leopold (1978) for several regions in the U.S.A. Regional curves relate channel geometry (e.g., bankfull depth, width, discharge) to drainage area, a metric that changes with position within a catchment and is simple to quantify using DEMs and GIS terrain analysis software. In this way, regional curves give the advantage of scaling bankfull dimensions to whole catchments (Benda, Miller, & Barquín, 2011). Many subsequent research efforts have expanded and localized the almanac of regional curves. For example, Collins and Leventhal (2013) published a field-based regional curve for wadeable streams developed from 28 field measurements in Sonoma and Marin counties (N. California), the general location and similar context of the present study.

1.2.3 Depth to Groundwater, Soil Moisture, and the Topographic Wetness Index

Depth to the water table and soil moisture affect the processes responsible for near-channel aquifer recharge, nutrient and pollutant buffering, maintenance of riparian vegetation communities, and water discharge into the stream (Boulton et al., 1998; Brooks, Ffolliott, & Magner, 2003, pp. 389-398). Recent research is focused on hydrologic connectivity (surface and hyporheic) between hillslopes, riparian zones, aquifers, and channels in order to understand landscape-level spatial patterns of saturation (e.g., Rains, Mount, & Larsen, 2004; Grabs et al., 2009; Jencso et al., 2009). In these studies, soil moisture is a proxy for alluvial aquifer connectivity as it indicates depth to the water table and facilitates alluvial aquifer recharge.

Topographic Wetness Index (TWI) is an estimate of topographic control on hillslope hydrology and saturation (Sørensen, Zinko, & Seibert, 2006). TWI is defined as $\ln(\alpha/\tan\beta)$, where α is the local upslope area draining through a certain point per unit contour length and $\tan\beta$ is the local slope (Beven & Kirkby, 1979). Derived solely from a DEM, TWI considers only slope and drainage area effects on runoff. Bio-physical factors such as surface roughness, antecedent soil moisture, permeability, aquitards, and others are not considered. Despite these considerable local factors, TWI has been shown to correlate with soil moisture and depth to groundwater generally (e.g., Western et al., 1999). In this way, TWI can be used to show likely zones of exchange between surface water and groundwater that in turn connect to the channel and affect the presence and succession of riparian vegetation.

Grabs et al. (2009) caution against the use of TWI for estimating the position of riparian aquifers in very flat topographies since in these settings local slope (tanβ) is not necessarily an adequate representation of downslope hydraulic gradient. However, it is our assumption that tanβ is an adequate representation of hydraulic gradient in mid-watershed tributaries where alluvial floodplains are relatively small and have steeper topographic gradients as compared to reaches in the depositional zone where Grabs et al. (2009) conducted their work.

TWI value depends on the flow accumulation method used to calculate α (Güntner et al., 2004). Sørensen, Zinko, & Seibert (2006) showed that the use of a new Triangular Multiple Flow Direction (MD∞) algorithm developed by Seibert and McGlynn (2007) provided the best correlation between TWI and depth to groundwater. The increased accuracy is claimed to be due to advantages the MD∞ algorithm has in avoiding unrealistic hydrologic dispersion on planar or concave hillslopes while allowing multiple flow directions on convex hillslopes. In subsurface flow applications, DEM resolution affects the result of the MD∞ flow accumulation result. Emanuel et al. (2013) found that the use of a 10m DEM reduced the confounding effects of microtopography that can be found in higher resolution DEMs and thus represented subsurface flow paths more accurately than a 1m DEM.

2.0 Materials and Methods

2.1 Case Study: Mark West Creek, Sonoma County, California, U.S.A.

2.1.1 Study Area

This case study was developed in the Upper Mark West Creek Watershed (106 km^2), a tributary of the Russian River (3,846 km^2) that drains to the Pacific Ocean (Fig. 3). The

Upper Mark West Creek (UMWC) Watershed is located approximately 80 km north of San Francisco, CA, on the western side of the Mayacamas Mountains in Sonoma County. The UMWC Watershed ranges from 50 m to 700 m in elevation and is mountainous with an average slope of 18 degrees. The drainage pattern is dendritic and characterized by both short, high-gradient headwater streams and longer, low-gradient alluvial reaches of mid-watershed transfer zones with highly variable valley widths that rarely exceed 300 m. The climate is Mediterranean, with a cool wet season from November to April (112 cm/year) followed by a warm dry season with little precipitation. Land cover is a mosaic of mixed montane hardwood, Douglas fir, annual grassland, vineyards (2% of the watershed), and impervious surfaces (3.3% of the watershed) from an extensive road network (3 km/km^2) and rural residential and agricultural development (approximately 31 structures/km^2; SCVMLC 2013).

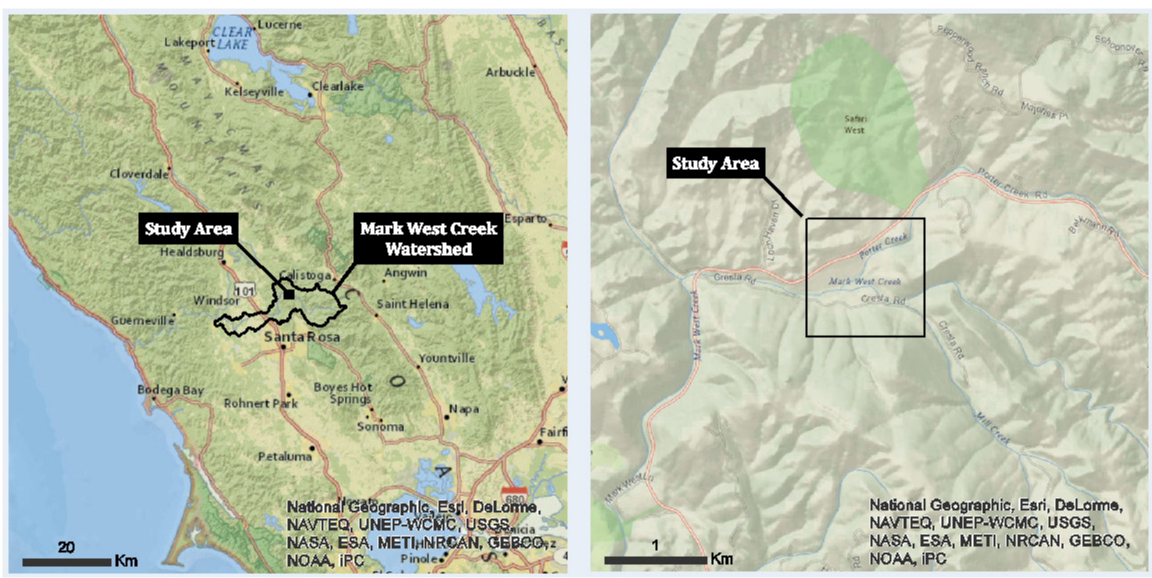

Fig. 3. Study area in Upper Mark West Creek Watershed, Sonoma County, CA.

Major soil groups in the study area include Haire Clay Loam, Laniger Loam, Overwash Yolo Loam, Red Hill Cobbly Clay Loam, Toomes Rocky Loam, and riverwash. Riparian soil types are 0.32 – 2.0 m deep, dark colored clay loams and gravelly loams high in organic matter (NRCS, 2017).

The UMWC Watershed supports several ecologically important aquatic and riparian wildlife species such as endangered Coho salmon (*Oncorhynchus kisutch*) and steelhead trout (*O. mykiss*), foothill yellow-legged frog (*Rana boylii*), northwestern pond turtle (*Actinemys marmorata*), and Northern Spotted Owl (*Strix occidentalis caurina*). Although not considered a riparian obligate species, *S. occidentalis* requires forest habitat with permanent water (Forsman 1976) and daytime roosts near water (Barrows and Barrows 1978)).

The watershed also contributes to a local water system that supplies drinking water to approximately 600,000 local residents. Groundwater is the primary source of drinking and irrigation water for Upper Mark West Creek Watershed residents and vineyards. Downstream communities—including southern portions of the Town of Windsor, northern portions of the City of Santa Rosa, a regional airport, and several business parks—could be impacted by flooding if the watershed were further developed.

The UMWC Watershed is a management priority for numerous public agencies and conservation organizations: National Marine Fisheries Service (NMFS, 2016), California Department of Fish and Wildlife (CDFW, 2004), Sonoma County Water Agency (SCWA, 2012), Sonoma County Permit and Resource Management Department (PRMD, 2014), Russian River Coho Water Resources Partnership (Sonoma RCD, 2015), Sonoma County Agricultural Preservation and Open Space District (SCAPOSD, 2006), Laguna de Santa Rosa Foundation (Honton and Sears, 2006), and Sonoma Land Trust (SLT, 2003). Management goals for the watershed include recovering salmonid populations through instream habitat enhancement; restoring forests to delay runoff, reduce erosion, and promote aquifer infiltration; and purchasing conservation easements to maintain ecological and hydrological connectivity within riparian zones and improve stream flow by limiting land uses (e.g., increased impervious surfaces) that impact surface water and groundwater.

The case study focused on a 1.1 km reach of Mark West Creek at its confluence with Porter Creek (25 km^2). The reach is an ideal site to test new modeling techniques due to its near-pristine condition and its relevance to local conservation efforts. The site was acquired in 2007 as part of a 340-acre purchase by the Sonoma County Agricultural Preservation and Open Space District (SCAPOSD) for its aquatic, riparian, and upland habitat values. Due to the presence of high quality spawning and rearing habitat, the site is used for the release of captive-bred Coho salmon as part of a multi-agency salmon recovery program and is monitored annually for Coho salmon and steelhead (UC Sea Grant, 2016).

Riparian woodland vegetation on the site includes valley oak-dominated savannahs with California bay laurel and coast live oak on the terraces, while near-stream woodlands include red alder, cottonwood, and multiple willow species. Wildlife species observed include river otter (*Lontra canadensis*), Pileated Woodpecker (*Dryocopus pileatus*), and western toad (*Anaxyrus boreas*).

2.1.2 Method Overview

We developed a GIS model similar to Benda, Miller, and Barquín (2011) that uses a DEM and regional curve of hydraulic geometry to map the fluvial landscape, defined as the area below an elevation of three times bankfull depth relative to the channel elevation. A map of terrestrial riparian landforms was created using field measurements of morphology, soil, and vegetation. The GIS model parameters were increased to map the full riparian zone, an extent beyond the fluvial landscape that encompasses all terrestrial riparian landforms, including the upland fringe. Three indicators of riparian function (shading, wetland habitat, and depth to groundwater) were mapped within the area between the fluvial landscape and the terrestrial edge of the riparian zone. Four sequentially expansive acquisition scenarios were generated within that same area and evaluated for their relative contribution of riparian function. Finally, four alternative delineations of the riparian zone—three fixed-width buffer following county, state, and national regulations and guidelines, and a manual delineation from aerial photography—were generated for comparison to the field-surveyed riparian zone. Fig. 4 outlines the analysis steps.

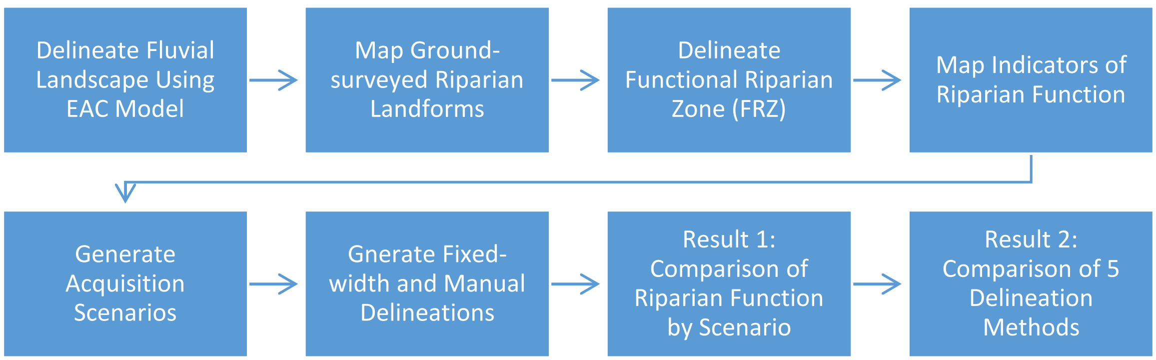

Fig. 4. Illustration of analysis steps.

2.2 EAC Model: Delineating the Fluvial Landscape

To delineate the fluvial landscape, we developed a GIS model using ModelBuilder in ArcGIS 10.3 (ESRI, 2013) that creates a raster grid of values equal to a user-specified elevation above the channel (EAC) in units of bankfull depth (BFD). The EAC model requires three inputs: 1) a digital elevation model (DEM) with absolute elevation values, 2) a flow accumulation raster (D8 method following Jenson & Domingue [1988]), and 3) a stream raster derived from the DEM via ArcHydro Tools (ESRI, 2013) or similar.

We obtained a hydroenforced 1-meter resolution bare earth digital elevation model (DEM) generated from Airborne Laser Swath Mapping (ALSM, A.K.A. Light Detection and Ranging or LiDAR) from the Sonoma County Vegetation and LiDAR Consortium (horizontal RMSE ≤ 1.5 cm; vertical RMSE ≤ 2.0 cm). The ALSM data were collected during the peak of the dry season in October 2013, two years prior to field data collection for this study. It is expected that the channels in the study reach had very little water depth (< 0.25 m) during the ALSM collection.

The model is composed of four routines. The first routine converts stream cells—derived from the D-8 flow accumulation algorithm in ArcHydro Tools (ESRI, 2013)—to points and samples flow accumulation (drainage area) and absolute elevation to each point. The second routine calculates expected BFD at each point along the stream based on the Collins and Leventhal (2013) regression curve of BFD against drainage area (BFD = $1.0195x^{0.3667}$, where x = log-transformed drainage area). The third routine extrapolates to neighboring upland cells the expected depth at bankfull discharge (BFD) multiplied by three (3xBFD) to derive the fluvial landscape following Benda, Miller, & Barquín (2011). The Inverse Distance Weighting (IDW) tool in ArcGIS (ESRI, 2013) was used to extrapolate BFD values. IDW is commonly used for interpolation, however, it performs well as an extrapolation method in this application given linear arrangement of the stream points. The final routine subtracts the grid representing 3xBFD from the DEM (Fig. 5).

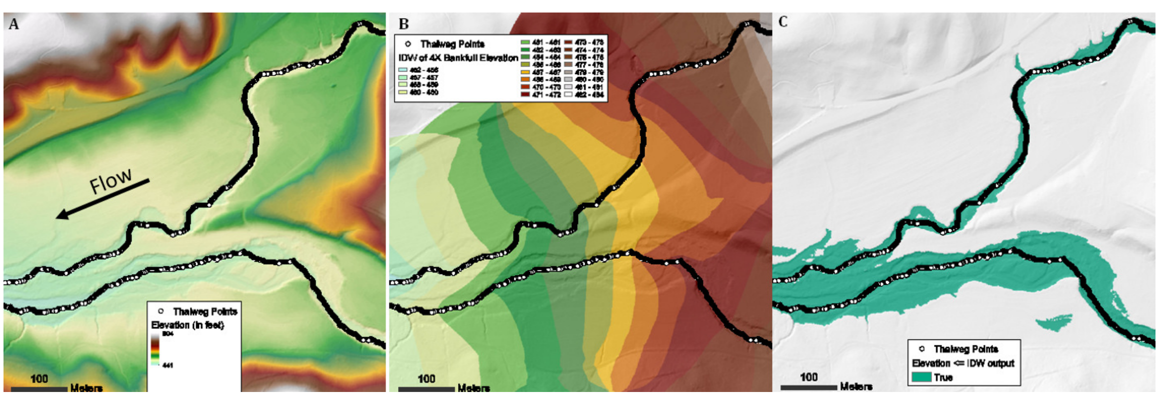

Fig. 5. Absolute elevation with stream points (A), elevation relative to 3 times the channel depth extrapolated from stream points via IDW (B), and the areas where absolute elevation + relative elevation ≥ absolute elevation (C).

The output of the EAC model as a proxy for the fluvial landscape—where flooding and channel migration occur—was corroborated by field evidence of flooding in areas of 3xBFD surveyed immediately after a significant storm event (Fig. 6).

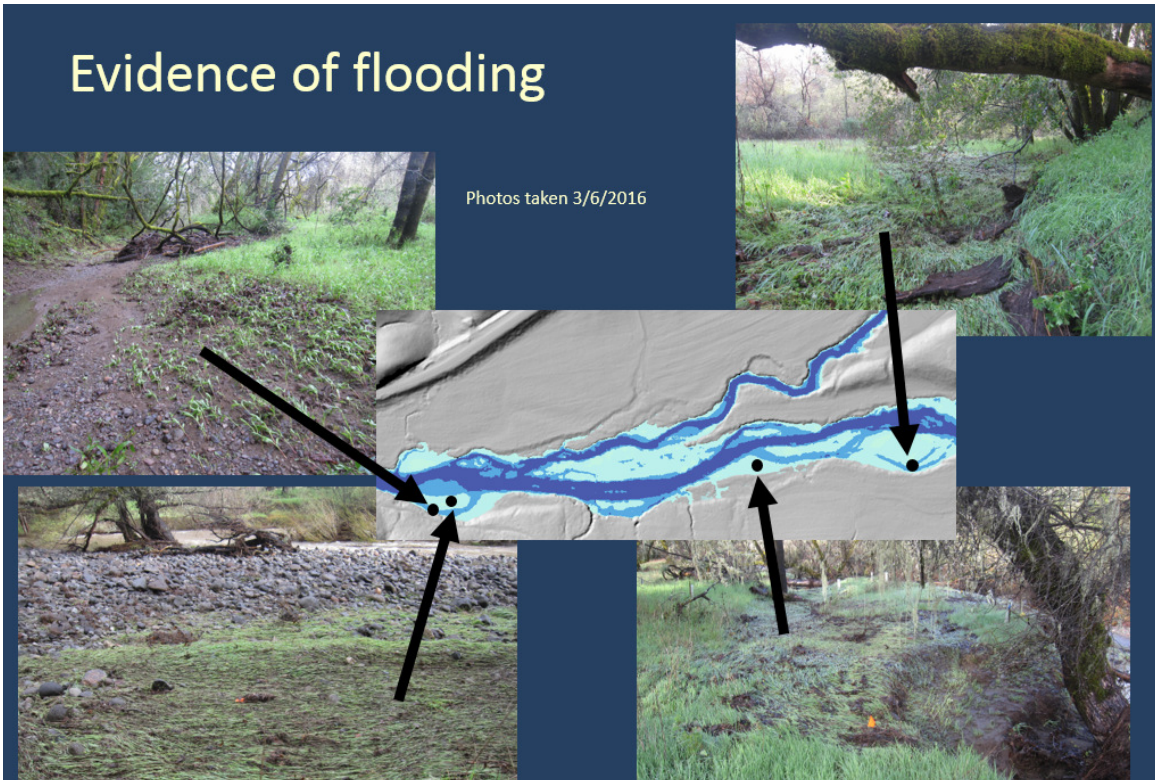

Fig 6. Evidence of flooding beyond the channel (1xBFD, dark blue) and onto 2xBFD (medium blue) and 3xBFD (light blue).

Georeferenced orthophotography taken in 1942 provided evidence that channel migration had occurred within areas of 3xBFD (Fig. 7).

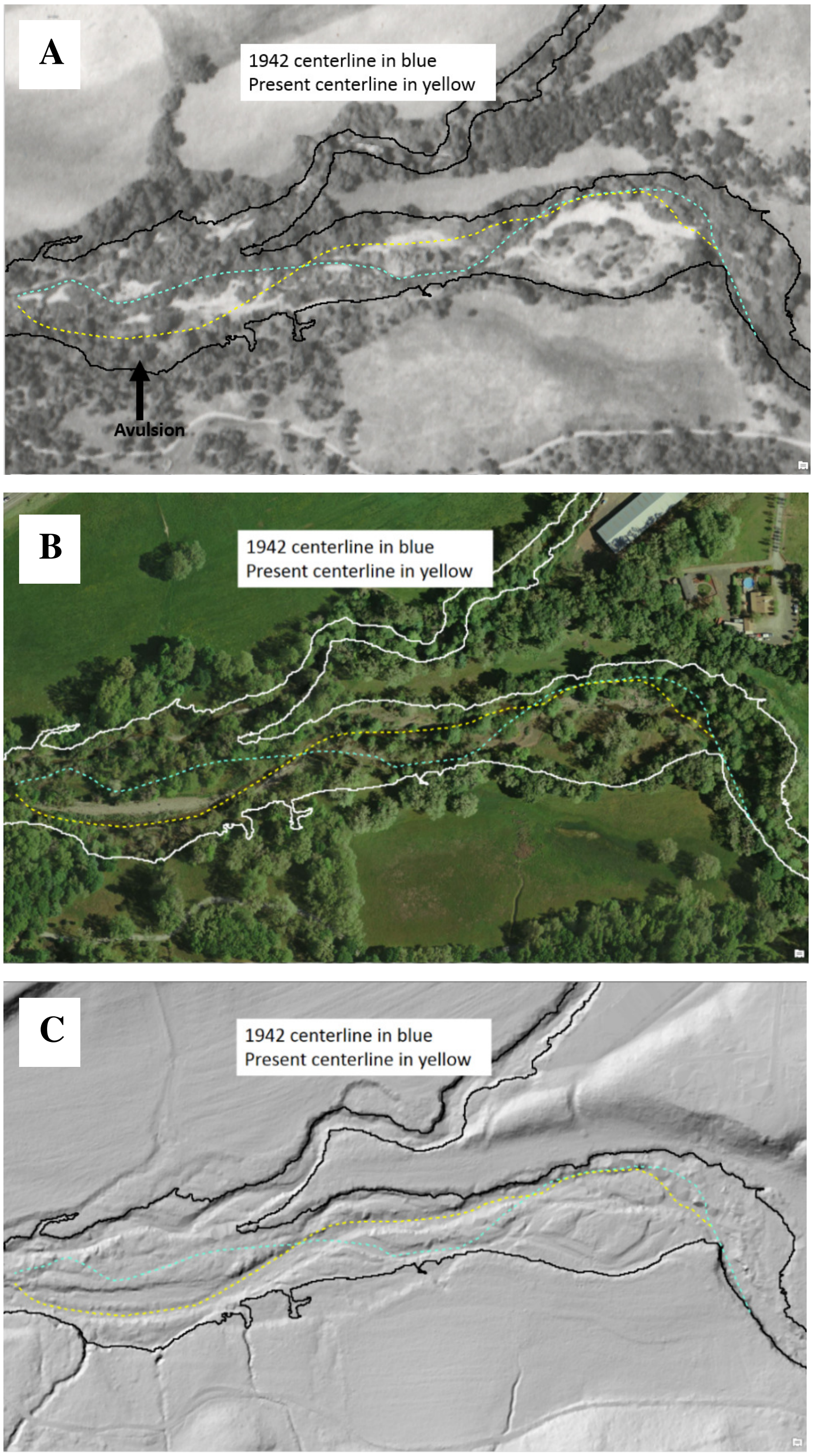

Fig 7. Evidence of channel migration within 3xBFD (outlined in black) since 1942 (A). The 1942 stream centerline is shown in blue and the present centerline is shown in yellow. Present conditions are shown in (B) and (C).

2.3 Buffers and Manual Delineation

2.3.1 Fixed-width Buffers

Three buffers widths were chosen for comparison purposes. These widths (summarized in Table 2) were based on 1) the Sonoma County Permit and Resource Management Department's Riparian Corridor Combining Zone (PRMD, 2014), 2) the Watercourse and Lake Protection Zone (WLPZ) of the California Forest Practice Rules (CDFFP, 2016), and 3) the widest buffer recommendation for riparian habitat and flood attenuation cited in a design guidelines report prepared by the U.S. Army Corps of Engineers (USACE; Fischer & Fischenich, 2000). Buffers were produced using the BUFFER tool in ArcGIS 10.3 (ESRI, 2013). The two buffer regulations and the federal guideline stipulate that buffering should be measured from "top of bank". However, top of bank is defined differently. For example, the Sonoma County regulation references the "top of the higher bank", which equates to the beginning of the high floodplain in typical alluvial reaches, while the USACE references the "level of bankfull discharge" (i.e., the top of the channel). The California WLPZ generically references the "top of bank". Therefore, for the latter two delineations, we began each buffer from the edge of the modeled channel (1xBFD) (Fig. 8). For the Sonoma County delineation, we began the buffer from the edge of the modeled fluvial landscape (3xBFD) (Fig. 8).

Table 2. Three fixed-width buffers based on county, state, and federal regulations and guidelines.

Buffer Source	Width (m)	Source
County Riparian Corridor Combining Zone	15-60 (50-200 ft)	PRMD (2014)
State Forest Practice Rules Watercourse and Lake Protection Zone	23* (75 ft)	CDFFP (2016)
Widest recommendation from USACE design guidelines	150 (500 ft)	Fischer & Fischenich (2000)

*Class I stream (fish seasonally present onsite, including spawning habitat) with Slope Class <30 carries protective measure of 75-foot buffer measured from top of bank.

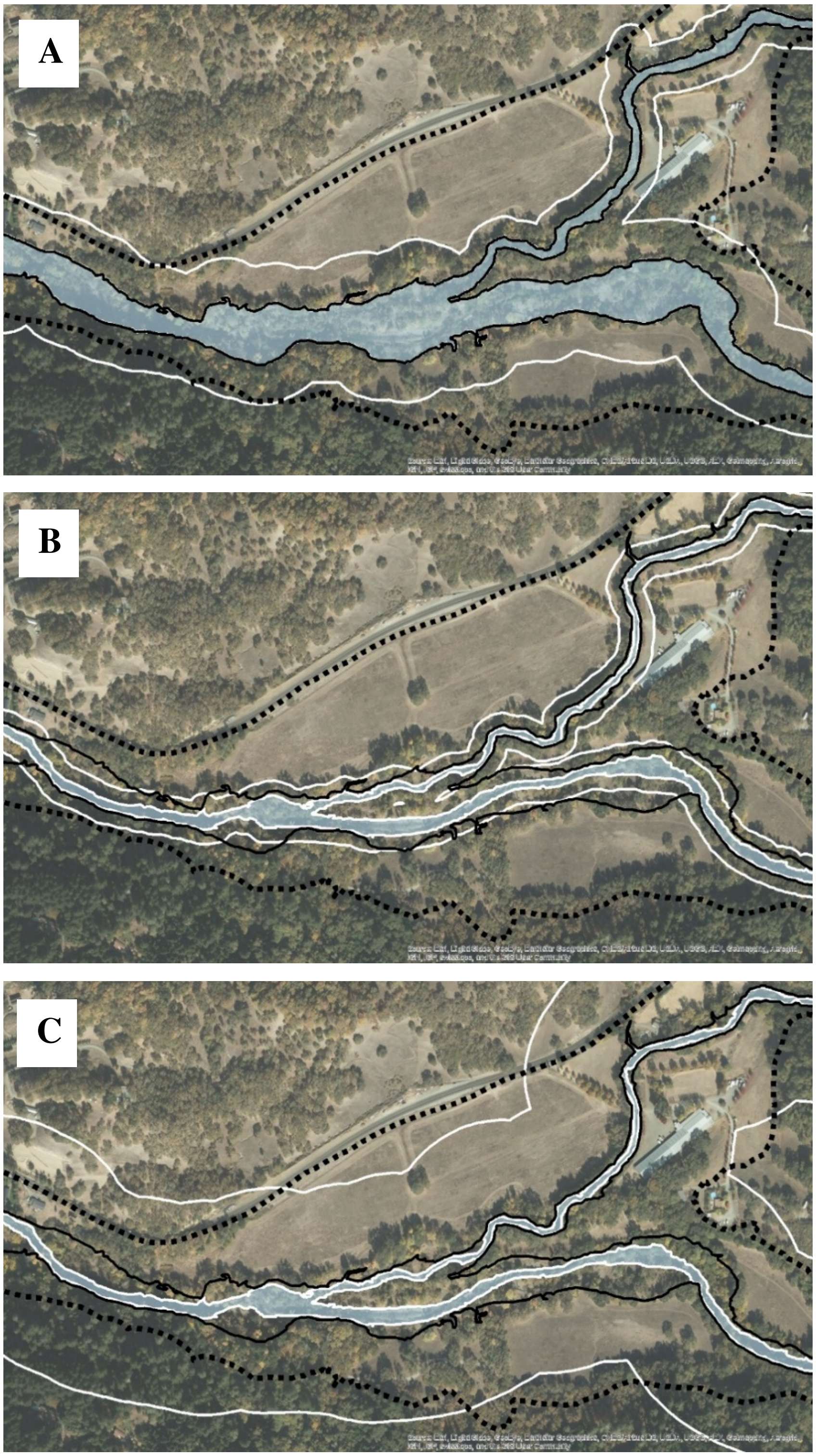

Fig 8. Results of three buffer regulations and guidelines (in white): County Riparian Corridor Combining Zone (15-60 m) (A), State Forest Practice Rules Watercourse and Lake Protection Zone (23 m) (B), and USACE design guidelines (150 m) (C). For reference, the fluvial landscape is outlined in solid black and shaded in blue; the extent of the functional riparian zone (FRZ) is in dashed black. Note: the state and federal buffers (B and C) start at the “top of bank”, defined here as 1xBFD.

2.3.2 Photo-based Manual Delineation

We obtained color orthophotography from the Sonoma County Vegetation Mapping and LiDAR Consortium and manually digitized a riparian zone following the line of visually conspicuous woody vegetation adjoining the watercourse (Fig. 9). The purpose of the manual delineation was to simulate practices currently common in land conservation where it is used for expediency or because aerial photography is the only data available to the practitioner with a sufficient resolution to distinguish features at the site scale.

Fig 9. Results of a manual delineation (in white) based on conspicuous woody vegetation associated with the stream corridor. For reference, the fluvial landscape is outlined in solid black and shaded in blue; the extent of the functional riparian zone (FRZ) is in dashed black.

2.4 Mapping Indicators of Riparian Function

2.4.1 Topographic Wetness Index

As stated above, TWI has been used effectively as a surrogate for soil moisture and depth to groundwater (Zinko, 2004). However, TWI is dependent on the flow accumulation algorithm used (Güntner et al., 2004). Based on the findings of Grabs and others (2009) and Emanuel and others (2013), TWI was calculated (Fig. 10) using the Triangular Multiple Flow Direction (MD∞) flow accumulation algorithm (Fig. 11) developed by

Seibert and McGlynn (2007) that has been implemented as an option in the TWI module within the open source modeling platform System for an Automated Geoscientific Analysis (SAGA; Conrad et al., 2015).

Studies show that DEM resolution affects TWI results and thus its application to hydrology (Beven, 1997; Sørensen & Seibert, 2007; Wu et al., 2008). Sørensen and Seibert (2007) remark that a lower resolution DEM may produce more accurate model results in the case of using TWI to estimate depth to groundwater and soil moisture as these variables can be expected to follow a generalized topographic representation, depending less on small-scale variations. Heeding the findings of Sørensen and Seibert (2007) and others, Emanuel et al. (2013) resampled a 1 m DEM to 10 m before calculating MD∞ for their modeling purposes. Usery et al. (2004) found strong correlation between the elevation values of a 3 m DEM and a resampled 30 m DEM. Coarser resolution DEMs also require less computational time. Therefore, following the observations of these studies, the DEM in the present study was coarsened using bilinear interpolation from 1 m to 30 m prior to running the TWI (and MD∞) module.

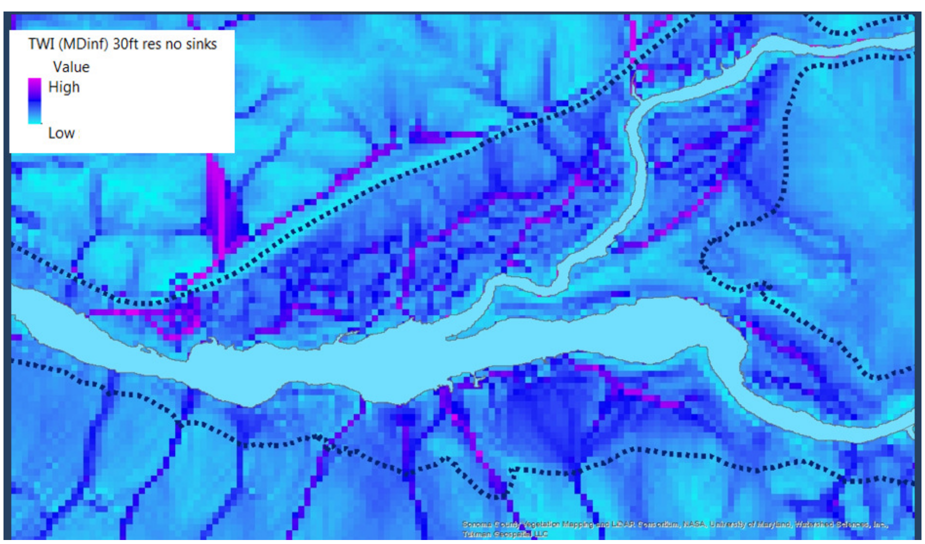

Fig. 10. Topographic Wetness Index (TWI).

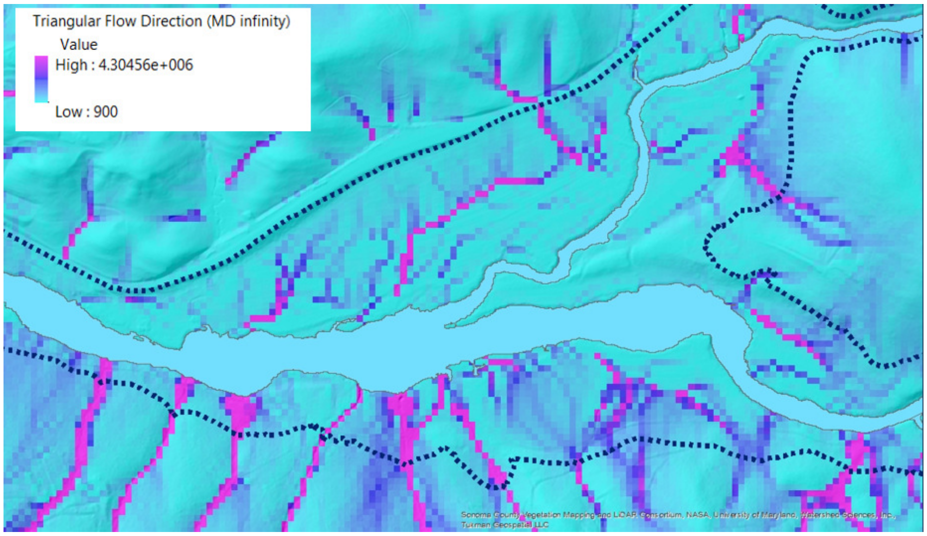

Fig. 11. Triangular Multiple Flow Direction (MD∞) flow accumulation.

The TWI results were reclassified into four classes (low, medium, high, very high) using the natural breaks method as only high and very high classes would be used in the scenario comparison.

2.4.2 Wetlands

The exchange of water between uplands and the stream channel is an important riparian function (Jencso et al., 2009) and is indicated by the water table being at or near the soil surface in riparian zones (Brooks, Ffolliott, & Magner, 2003, p. 175). Palustrine wetland plant communities form in riparian zones where saturation is sufficient to support hydrophytic plants and hydric soils (Brooks, Ffolliott, & Magner, 2003). Therefore, in riparian zones, the presence of palustrine wetlands indicates proper hyporheic function, which is contrasted by the lack of wetlands that can result from reduced hydrologic connectivity caused by excessive pumping of groundwater or development of recharge zones (Winter et al., 1998).

Palustrine wetlands in the study area were characterized by the presence of scouring-rush horsetail (*Equisetum hyemale*), a hydrophyte species usually found in wetlands (USFWS, 1997). Wetlands were manually digitized using GPS and aerial photography (Fig. 12).

Fig. 12. Palustrine wetlands in the study area.

2.4.3 Stream Shading and Inputs of Organic Material and Woody Debris

Plant communities in and near the fluvial landscape facilitate multiple functions including providing appropriate organic materials for aquatic organisms such as leaf litter and large woody debris that fall directly into the stream system. Shading from trees along streams limits solar radiation and photosynthesis that can promote excessive growth of algae and other hydrophytes that deplete dissolved oxygen when broken down by microbes (Gregory et al., 1991; FISRWG, 2001).

Stream shading was mapped using a 1-meter resolution digital terrain model (DTM) of vegetation produced from the ALSM data described above. All pixels classified as vegetation and greater than three meters in height were selected within 23 meters of the edge of the fluvial landscape (Fig. 13). The 23-meter distance is equal to the average height of surrounding mature trees (as measured by the ALSM DTM) and thus the zone of direct influence on the fluvial landscape via shading and organic material inputs.

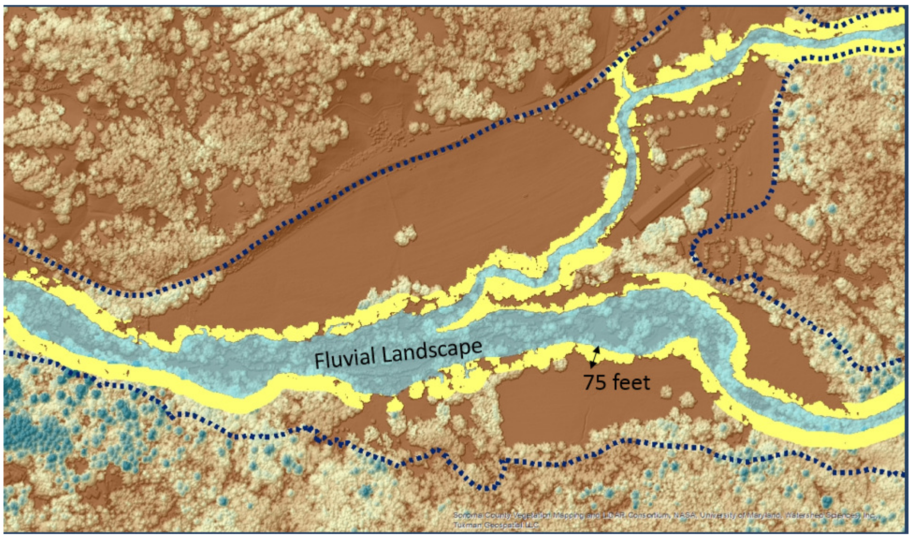

Fig. 13. Stream shading and direct organic material contribution.

2.5 A Ground-truthed Riparian Landform Map

To accurately identify all riparian landforms within the study area, morphometric surveys (cross sections, longitudinal profile), soil samples, a map of vegetation communities, and an ALSM-derived hillshade grid were used to construct a landform map.

2.5.1 Geomorphometry

Cross sections are useful for characterizing the landforms of a stream system (e.g., stream channels, floodplains, terraces, and alluvial fans). Three cross section profiles (Xsn A – C) were measured using a Leica Total Station Builder (model 503) and a Trimble GeoXH6000 GPS unit capable of sub-meter accuracy (Fig. 14).

The study reach contains the confluence of two streams. The locations of the cross sections were chosen to capture geomorphology upstream, amid, and downstream of the confluence. In order to fully characterize the riparian zone, the cross sections were surveyed across the entire valley floor to obvious slope breaks demarcating the upland fringe (Fig. 14).

Longitudinal profile surveys are useful for mapping the stream thalweg and identifying channel pattern (e.g., braided, meandering, straight), type (e.g., pool-riffle, plane-bed, step-pool), gradient, and bed material. Longitudinal profiles were surveyed at least 40 meters upstream and downstream of each of the three cross sections (Fig. 14; Table 3).

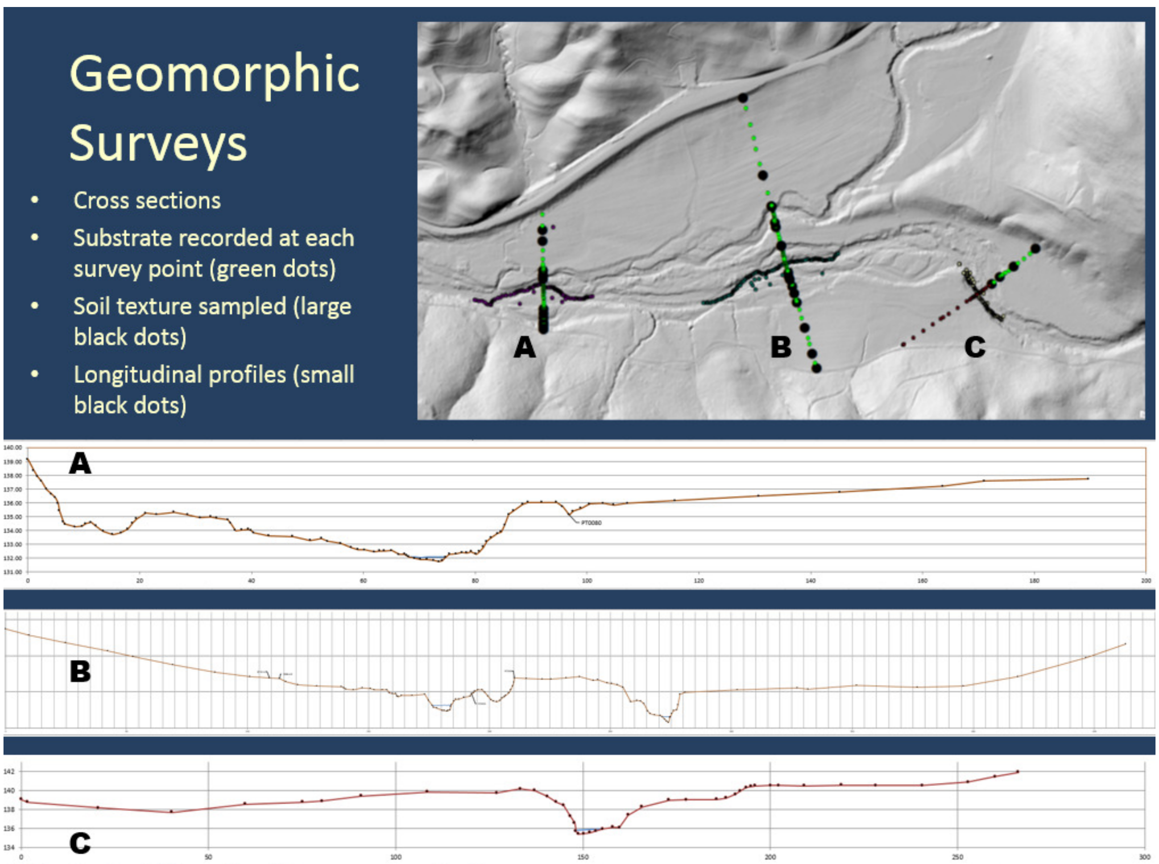

Fig. 14. Cross section, substrate record, soil texture samples, and longitudinal profiles.

Table 3. Characteristics of longitudinal profiles intersecting three cross sections.

Long. Profile	Length (meters)	Channel Gradient (m/km)	Water Surface Gradient (m/km)	Channel Pattern/Type*	Bed Material (Decreasing prevalence)
LP A	106	31.6	11.5	Braided/Pool-riffle	Cobbles, sand, gravels, bedrock
LP B	256	12.2	11.4	Braided/Pool-riffle	Gravels, cobbles, sand
LP C	217	32.7	18.7	Wandering/Pool-riffle	Cobbles, gravels, sand, bedrock

*Buffington & Montgomery, 2013

2.5.2 Soil samples

In alluvial riparian zones, soil characteristics in the upper horizon generally transition from well-developed soils (e.g., dark, sandy or clay loam) on terraces and upland fringe to silt and sand on the floodplains (FISRWG, 2001). Soils were sampled using a bucket auger to a depth of 50 cm at approximately evenly spaced intervals along cross section transects (Fig. 15). Soil texture was characterized visually using the USDA soil classification (NRCS, 2017). Distance from and height above the stream thalweg were calculated via GIS (Fig. 16).

Fig. 15. Visual soil texture sampling.

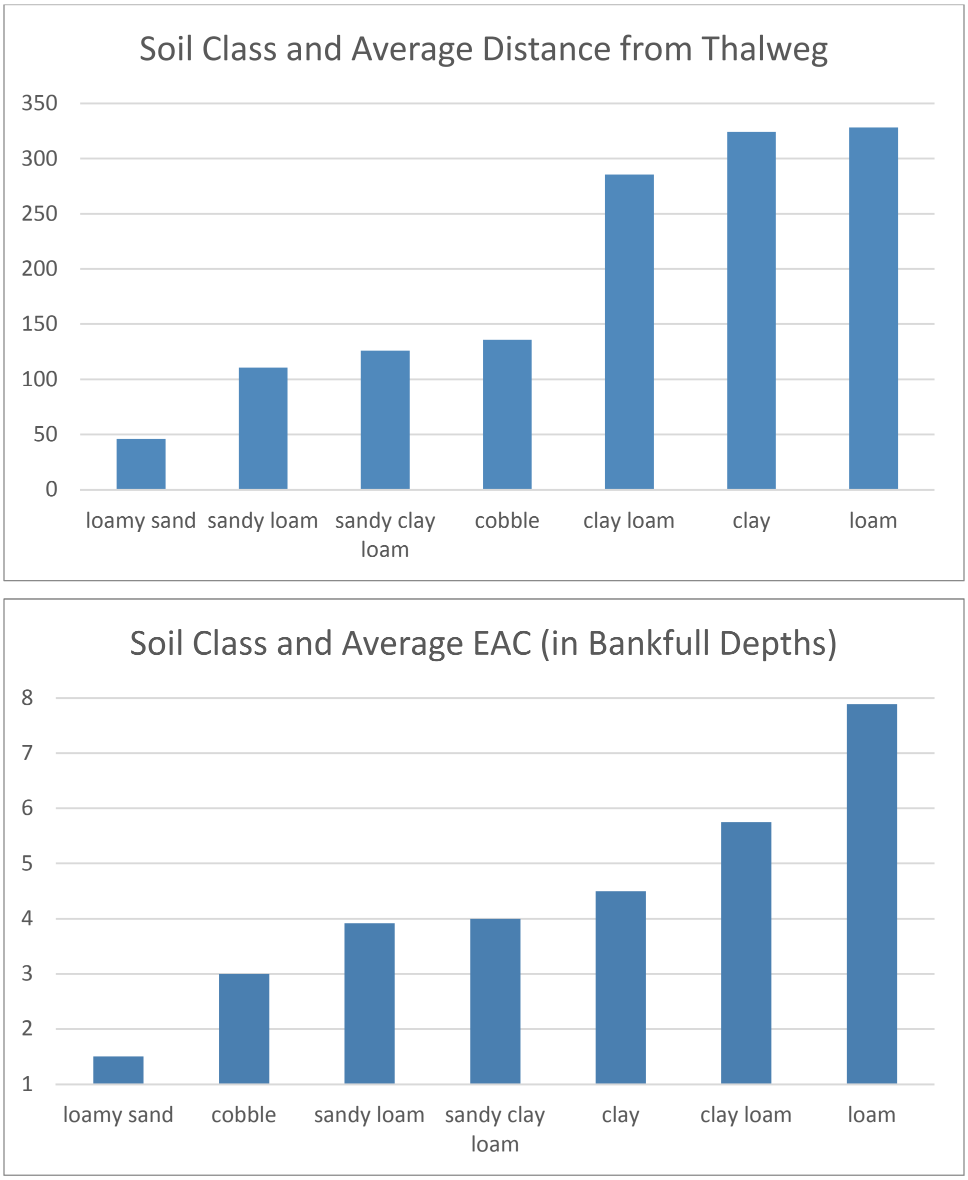

Fig. 16. Soil class by distance from thalweg (in meters) and average elevation above channel (in BFD).

2.5.3 Vegetation map

A fine-scale map of vegetation was obtained from the Sonoma County Vegetation Mapping and LiDAR Consortium (SCVMLC, 2016). The vegetation map was produced using the same aerial photo used for the manual delineation (see Fig. 9 above) and employed automated image segmentation and supervised classification based on extensive field sampling (SCVMLC, 2016; Klein, Keeler-Wolf, & Evens, 2015). Vegetation communities were distinguished by their riparian or upland association (Table 4) and combined to create a binary map of riparian or upland vegetation (Fig. 17).

Table 4. Mapped vegetation communities and their association to riparian or upland.

Vegetation Community	**Description (from Klein, Keeler-Wolf, & Evens, 2015)**	**Association**
Acer macrophyllum Alliance	*Acer macrophyllum* dominates or co-dominates with *Umbellularia californica* or, occasionally, *Fraxinus latifolia* in riparian.	Riparian
Quercus lobata Alliance	*Quercus lobata* dominates or co-dominates with *Fraxinus latifolia* and/or *Quercus agrifolia* in the tree overstory. Stands are typically found along valley bottoms, lower slopes, and summit valleys on seasonally saturated soils that may flood intermittently.	Riparian
Vancouverian Riparian Deciduous Forest Group	*Alnus rhombifolia*, *Fraxinus latifolia*, and/or *Salix lucida* are dominant, co-dominant, or characteristic of broadleaf riparian tree vegetation. Found along riparian corridors, incised canyons, seeps, stream banks, mid-channel bars, floodplains, and terraces.	Riparian
Western North American Freshwater Marsh Macrogroup	Freshwater or brackish stands dominated by *Argentina*, *Carex pansa*, *C. obnupta*, *C. praegracilis*, *Juncus effusus*, *J. lescurii*, *J. patens*, *Oenanthe*, *Schoenoplectus*, *Scirpus microcarpus*, and/or *Typha,* where water is present throughout all or most of the growing season.	Riparian
Herbaceous	Native and non-native annual forb/grass vegetation and native perennial grasslands growing within the California Mediterranean climate.	Riparian
Arbutus menziesii Alliance	*Arbutus menziesii* is either dominant with sub-dominant *Quercus agrifolia* or is dominant to co-dominant with *Quercus kelloggii* and/or *Umbellularia californica*; characterize moist, coastal, mixed evergreen forests and woodlands.	Upland
Notholithocarpus densiflorus Alliance	*Notholithocarpus densiflorus* is strongly dominant in the tree canopy or co-occurs with subdominant to co-dominant *Arbutus menziesii*; characterize moist, coastal, mixed evergreen forests and woodlands.	Upland
Pseudotsuga menziesii - *Notholithocarpus densiflorus* Alliance	Vegetation characterized by a mixture of *Pseudotsuga menziesii* and *Notholithocarpus densiflorus* in the canopy; cool-temperate coniferous forests and woodlands influenced by warm, relatively dry summers and cool, rainy winters.	Upland

Pseudotsuga menziesii Alliance	*Pinus ponderosa* is dominant to co-dominant with *Pseudotsuga menziesii;* cool-temperate coniferous forests and woodlands influenced by warm, relatively dry summers and cool, rainy winters.	Upland
Quercus Alliance	Three or more oak species are present and collectively dominate or co-dominate the broadleaf canopy.	Upland
Quercus garryana Alliance	*Quercus garryana* dominates or co-dominates with other broadleaf trees or *Pseudotsuga menziesii*; Stands are of relatively dense woodlands without a significant understory herb component.	Upland
Quercus kelloggii Alliance	*Quercus kelloggii* dominates or co-dominates with *Pseudotsuga menziesii*, *Q. agrifolia*, and/or *Umbellularia californica* in the tree overstory. *Arbutus menziesii* is often present as a subdominant species. Stands are found inland, above maritime influence, on northern exposures.	Upland

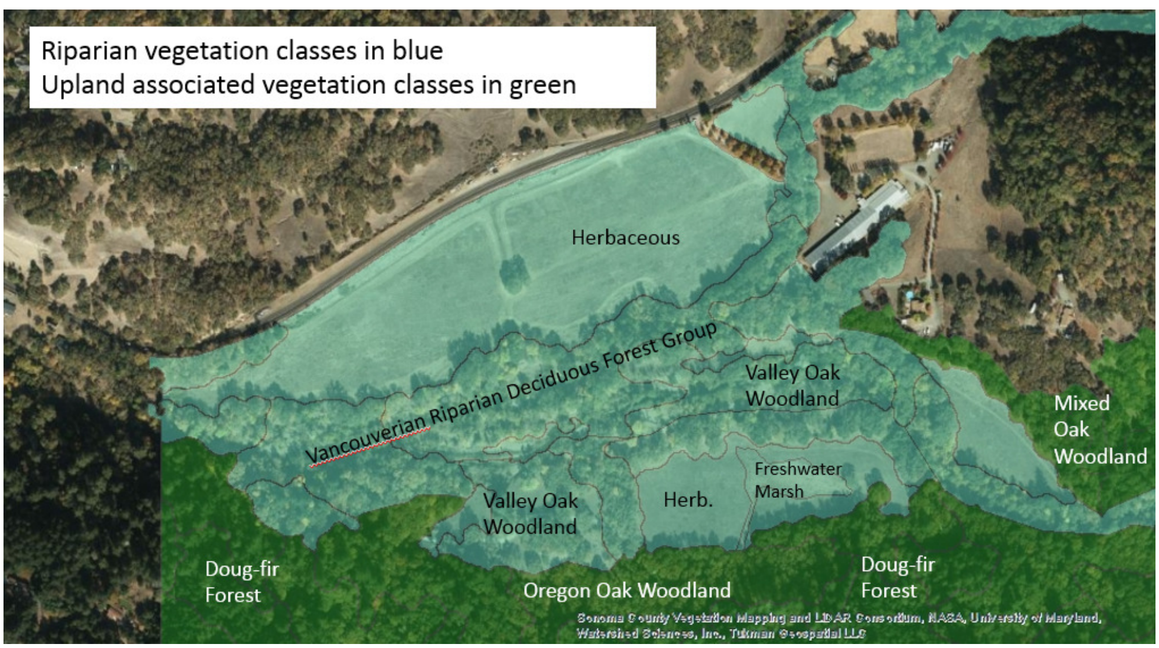

Fig. 17. Riparian-upland binary vegetation map.

2.5.4 Landform Mapping

Eleven riparian and channel landforms were observable in the study area, including channel, gravel bar, secondary channel, active floodplain, topographic floodplain, scarp, low terrace, high terrace, swale, alluvial fan, and hillslope tributary. Topographic slope breaks were identified in the cross section profiles and individual survey points were assigned a riparian or channel landform class (Fig. 18).

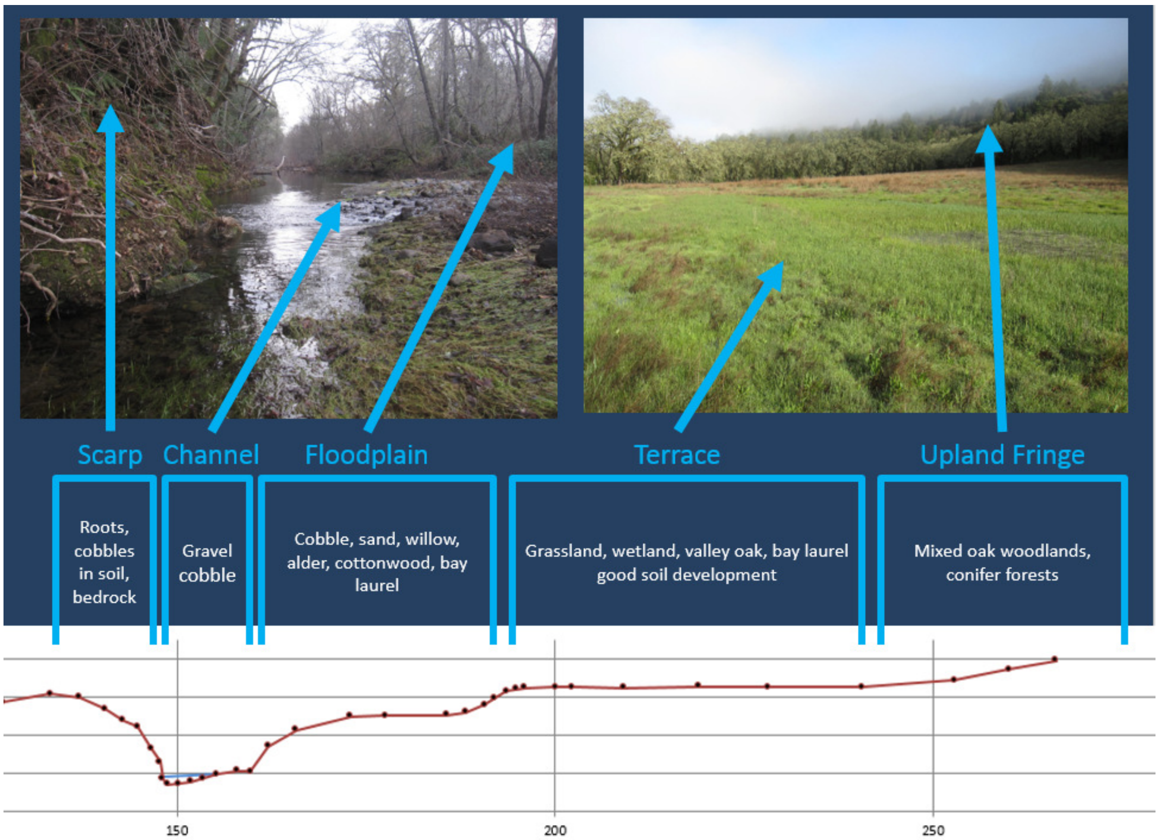

Fig. 18. Classification of cross section survey points by landform.

Landforms were manually interpolated between the classified cross section survey points using a 1-meter DEM hillshade from ALSM data (described above) as a visual guide for landform coherence and contiguity. The result was a channel and riparian landform map with the eleven landform classes and the upland fringe demarcated (Fig. 19). The binary riparian/upland vegetation map, when overlaid atop the landform model output, corroborated the position of the upland fringe.

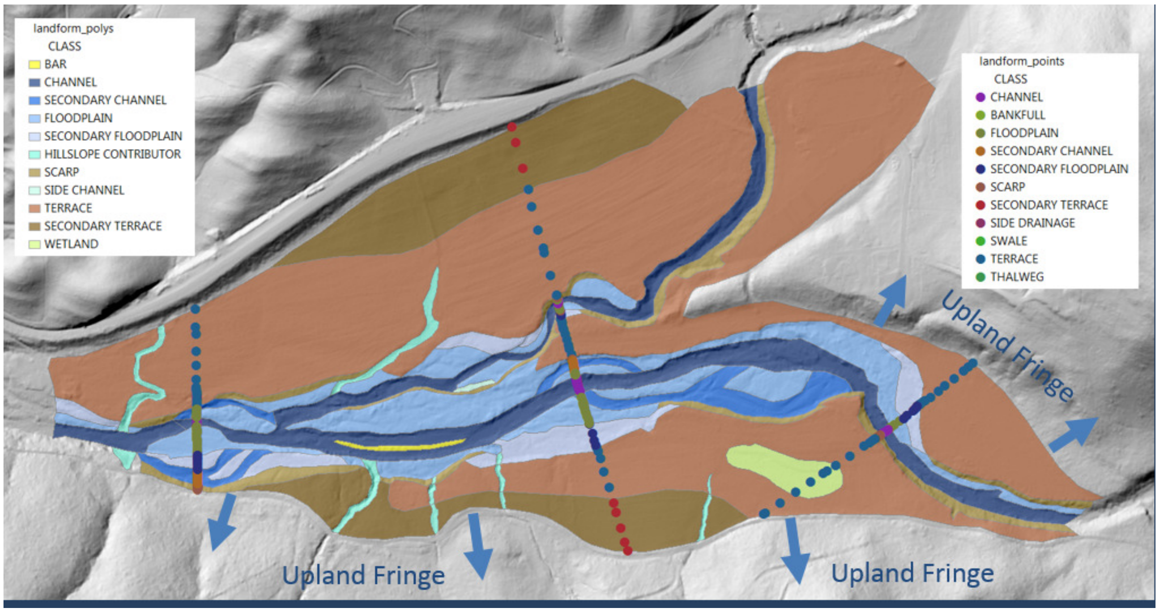

Fig. 19. Interpolation of classified cross section survey points into 2-dimensional riparian landform map.

2.5.5 Riparian Zone Delineation

The EAC model parameter for multiples of BFD can be increased from 3xBFD for the fluvial landscape to larger values that result in wider, variable-width corridors that follow local topography. We increased the parameter to 18xBFD in order to extend the output past the riparian landforms and into to the upland fringe as identified in the landform mapping process described above. The edge of the 18xBFD model output thus defined the functional riparian zone for the study area (Fig. 20).

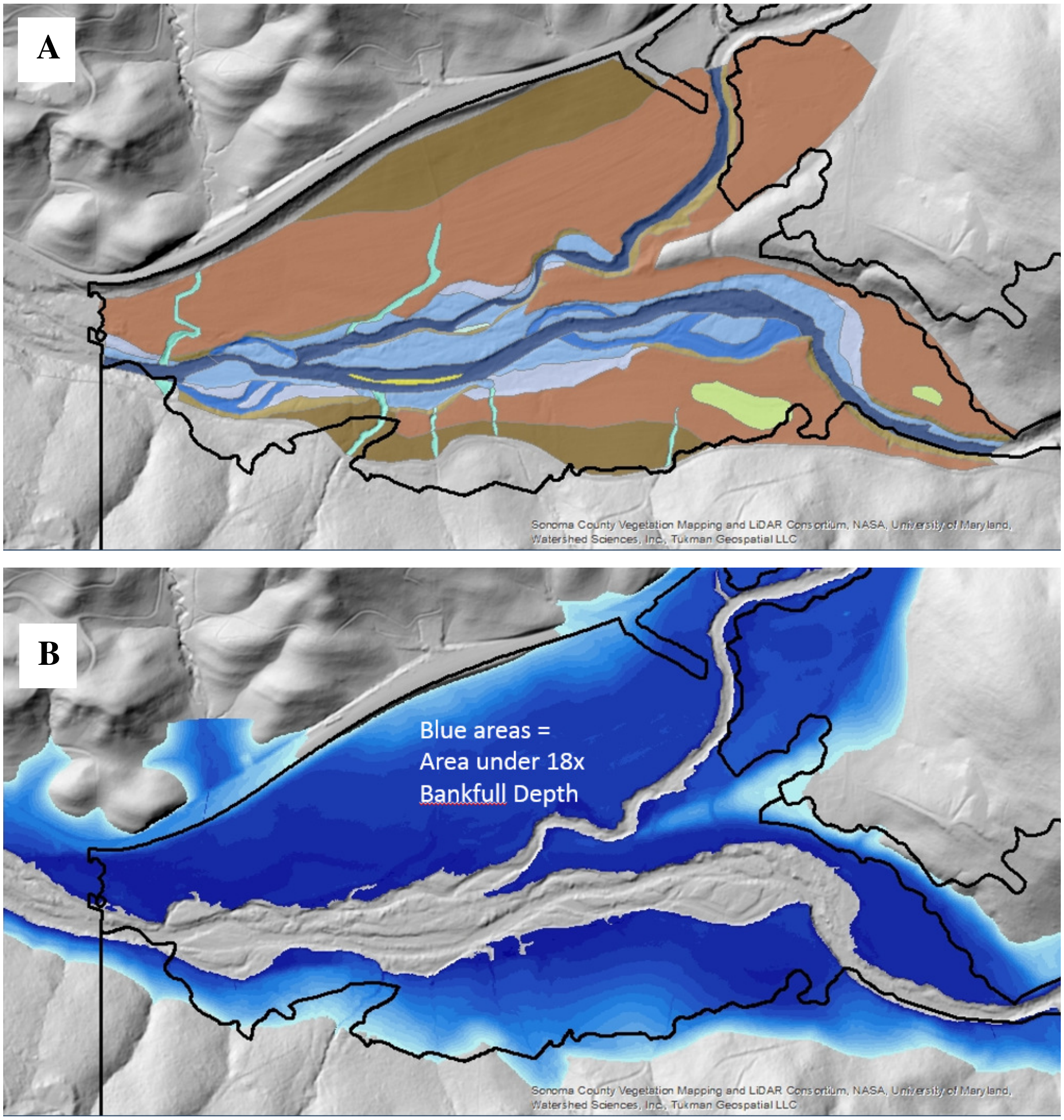

Fig. 20. Riparian landform map with riparian-upland vegetation transition outlined in black (A). Area under 18xBFD in blue (B).

It should be noted here that deriving wider corridors by increasing the multiples of BFD was done solely to derive a topographically-dependent corridor. To our knowledge, this has not been shown in the literature to represent an actual hydro-geomorphic relationship as has been done for the flood-prone area (e.g., Rosgen, 1996) and predicted fluvial landscape (e.g., Benda, Miller, & Barquín, 2011). Future studies could investigate the possibility of a BFD multiple that covers the entire riparian zone in alluvial systems in the same way, for example, Ilhard, Verry, and Palik (2000) have suggested a width equal to ten times bankfull channel width is an adequate delineation for the riparian zone in certain very low slope valleys where the channel is greater than 10 feet wide.

2.6 Acquisition Scenarios

Four variable-width corridors were generated to serve as acquisition scenarios for evaluation of costs and benefits (i.e., function), two key considerations when negotiating with willing sellers. We assumed the fluvial landscape would be a given as a conservation goal and thus focused scenario generation in the area between the fluvial landscape and the functional riparian zone extent. Scenarios can be generated using a variety of quantitative methods (e.g., equal interval or natural breaks). However, since the model output is in units of BFD, as opposed to continuous relative elevation, we chose instead to select scenarios that visually appeared to provide the appropriate sequential increases in area (Fig. 21). The scenarios and the BFD multiple each was based on are as follows: Scenario A = 5xBFD, Scenario B = 6xBFD, Scenario C = 10xBFD, and Scenario D = 18xBFD.

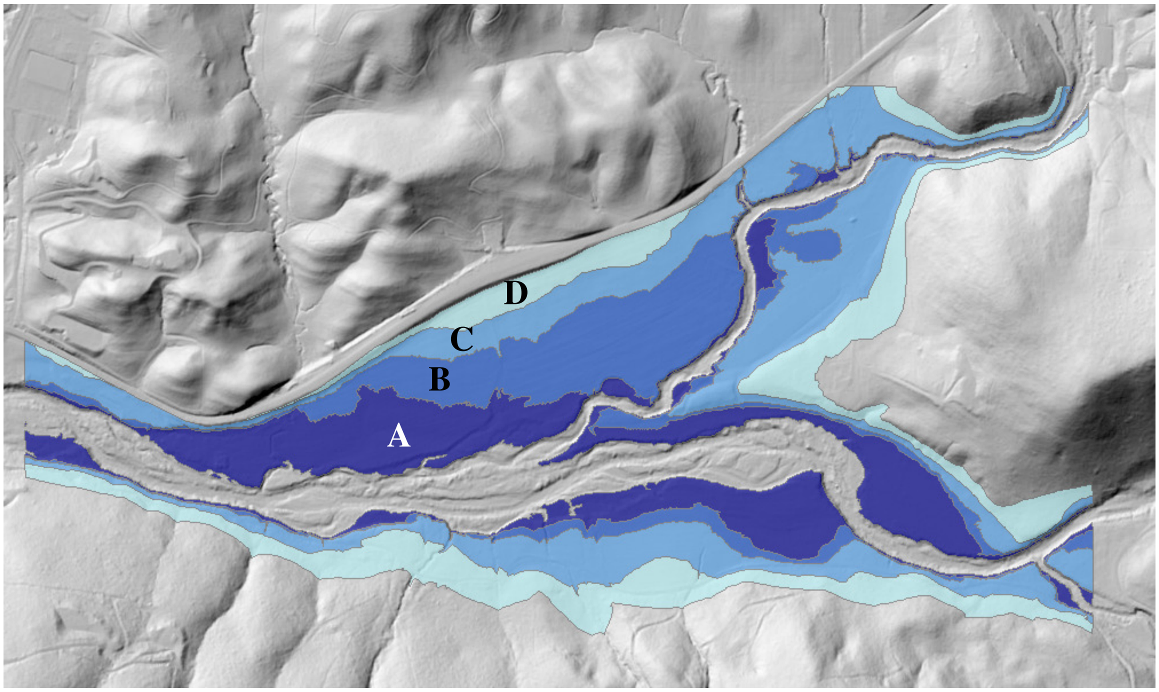

Fig. 21. Acquisition scenarios A – D.

3.0 Results

3.1 Comparison of Riparian Function within Acquisition Scenarios

We compared the marginal gains of function associated with each scenario. Marginal gains were computed via a geometric intersection of the mapped indicators (stream shading, wetlands, and soil moisture) and the scenarios (Table 5).

Table 5. Comparison of function, area, and estimated acquisition cost between four acquisition scenarios.

Acquisition Scenario	Additional Shading Canopy (ha)	Additional Wetlands (ha)	Additional High Soil Moisture (% of High TWI)	% of Functional Riparian Zone Covered (cumulative)	Total Land Area (ha)	Acquisition Cost* ($)
A	6.1	0.32	31.0	26	11.1	$244,200
B	2.2	0.20	26.6	46	19.4	$426,800
C	3.4	0.03	31.7	77	32.4	$712,800
D	0.9	0	10.7	100	42.2	$932,800

*Based on $22,000/ha estimate from Sonoma County Agricultural Preservation and Open Space District.

Marginal gains for the Additional Wetlands function decreased continuously from Scenario A (closest to the fluvial landscape) to Scenario D. Additional Shading Canopy and Additional High Soil Moisture increased by 19% and 55%, respectively, between Scenario B and Scenario C. In order to evaluate the rate at which overall function (per the indicators) decreases between scenarios, an overall estimate of function value was calculated by summing the normalized marginal gains of each function per scenario (these sums were again normalized for inclusion in Fig. 22). Overall function was highest in Scenario A, remained approximately constant between scenarios B and C, and decreased sharply in Scenario D where only Additional Soil Moisture and Additional Stream Shading contribute modestly. In Scenario C, the low Additional Wetlands were counterbalanced by the high Additional High Soil Moisture, keeping overall function change minimal between scenarios B and C.

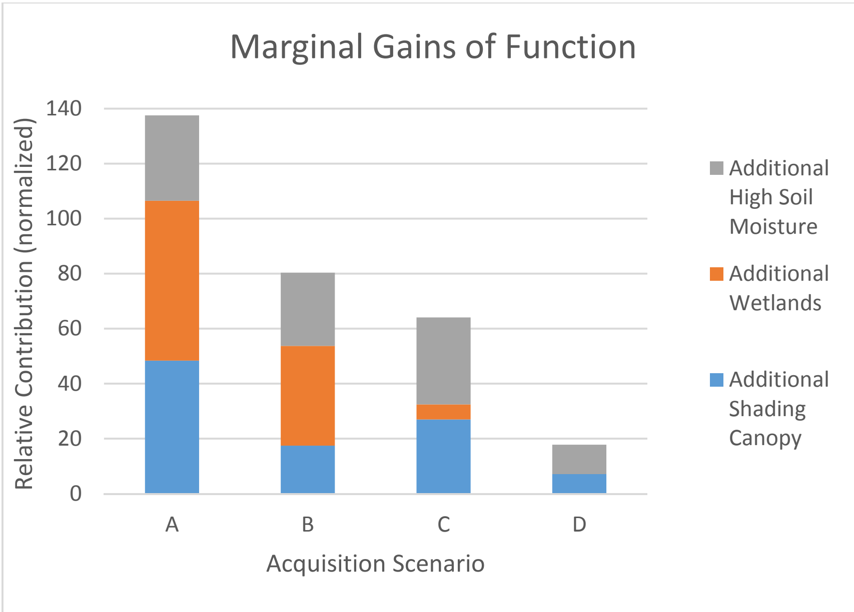

Fig. 22. Relative composition of functions per scenario.

We produced a simple benefit-to-cost (BCR) ratio by calculating the relative increase in overall indicators of function in each scenarios and dividing that amount by the cost of acquiring the additional area using a per-hectare acquisition cost estimate ($22,000/ha) supplied by the SCAPOSD (Table 6). Traditionally, BCR values higher than 1 are considered good investments. However, since we are not monetizing the benefits, the BCR values we present are only relative to each other. For instance, the additional land associated with Scenario D may be an excellent investment despite having a BCR value of 0.27. The BCR merely suggests that the land associated with scenarios A, B, and C are better investments.

Table 6. Benefit-to-cost ratio (BCR).

Acquisition Scenario	Relative Increase of Indicators of Function (%)	Additional Land Area (ha)	Acquisition Cost of Additional Area ($)	Benefit-to-Cost Ratio*
A	46	11.1	244,200	1.88
B	27	8.3	182,600	1.47
C	21	13.0	286,000	0.75
D	6	9.8	220,000	0.27

*Relative increase in indicators of function (benefit) was multiplied by 10,000 to scale to acquisition cost.

3.2 Comparison of EAC Model, Buffers, and Vegetation-based Manual Delineation

The proportion of mapped indicators of riparian function covered by the five delineation methods were computed by geometric intersection and compared (Table 7). The five delineation methods were 1) the EAC model calibrated to 18xBFD to match the ground-truthed riparian zone map, 2) the 15-60-meter (50-200-foot) composite fixed-width buffer based on the Sonoma County Riparian Corridor Combining Zone, 3) the 23-meter (75-foot) fixed-width buffer based on the California State Forest Practice Rules Watercourse and Lake Protection Zone, 4) the 150-meter fixed-width buffer from the USACE design guidelines, and 5) the manual delineation based on vegetation.

The delineation from the EAC model defines the Functional Riparian Zone (FRZ) and is the baseline for comparison in this study. The USACE recommendation from Fischer & Fischenich (2000) covers nearly all of the indicators of function but also approximately 44% (or 33 ha) of the delineation is not considered riparian according to the ground-truthed riparian zone. The County zoning buffer comes closest in terms of coverage of indicators of function without including significant non-riparian (10%).

Table 7. Comparison of riparian function per riparian delineation method.

Delineation Method	Shading Canopy (% of total)	Wetlands (% of total)	High Soil Moisture (% of High TWI)	% of Functional Riparian Zone Covered	Land Area (ha)	% Inside/Outside /Missed Functional Riparian Zone
EAC Model (18xBFD)	100	100	100	100	42.2	100% inside FRZ 0% outside FRZ
County Zoning Buffer	100	67	48	56	26.3	90% inside FRZ 10% outside FRZ
CA Forest Practice Rules	42	0	6	18	13.5	57% inside FRZ 43% outside FRZ
USACE Guidelines	100	100	94	92	74.7	52% inside FRZ 48% outside FRZ
Vegetation-based Manual Delineation	55	0	9	22	7.6	100% inside FRZ 0% outside FRZ

3.3 Scaling to the Catchment Level

Since the EAC model uses a regional curve that is based on drainage area, a readily calculable measurement in GIS, it is possible to scale the FRZ output (the width at 18xBFD) to the whole catchment. The model required approximately two hours to process a 1-meter grid with 17,116 columns and 10,107 rows (2.70GHz processor, 32.0 GB RAM, 64-bit OS). Visual analysis of the result shows several potential alluvial riparian sites (Fig. 23).

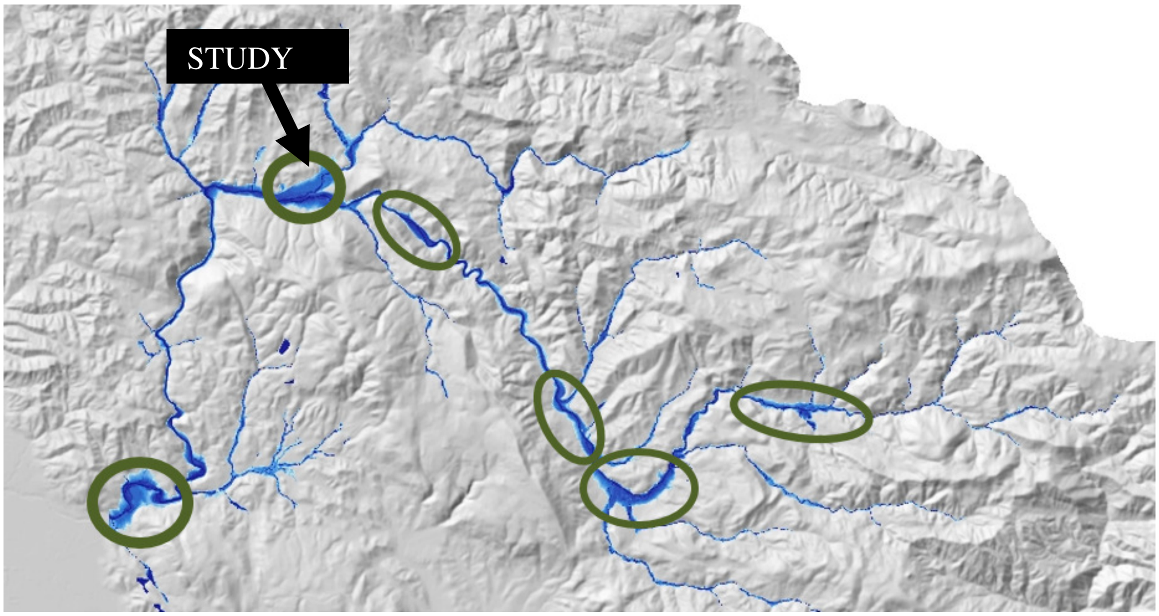

Fig. 23. EAC at 18xBFD for UMWC Watershed. Potential alluvial reaches are visible (circled).

4.0 Discussion

The objectives of the study were focused on supplying conservation practitioners with a framework and a rationale to transition away from mapping riparian zones based on fixed-width buffers to more efficient and accurate maps generated using contemporary hydrologic landscape analysis techniques. To that end, we developed a method for mapping the fluvial landscape (i.e., 100% probable riparian) and the ecologically functional riparian corridor (the "ideal" area to conserve), as well as a gradation of variable-width corridors between the two. We also evaluated four conservation scenarios using the three indicators of riparian function above as a demonstration for land conservation practitioners; and compared and contrasted example delineations using common techniques (buffers and manual delineations) with the functional riparian corridor from contemporary terrain analysis.

4.1 Mapping the Ecologically Functional Riparian Corridor

4.1.1 The Fluvial Landscape

EAC Model Performance

The EAC model accurately mapped the fluvial landscape—the area that encompassed channel migration and other fluvial processes (e.g., flooding, deposition, and avulsion) that occur over variable spatial and temporal scales. The use of a regional curve in the model enables mapping the fluvial landscape anywhere to which the regional curve applies.

This makes the model of great value to conservation practitioners as it can be used to establish a “bare minimum” zone within which uses and construction (e.g., bank armoring, vegetation removal) that restrict or alter fluvial processes essential to riparian ecological function can be extinguished or restricted. The EAC model was run on an alluvial stream reach within the transfer zone of the Maacama Creek Watershed (approximately the same area as UMWC Watershed) 11 km north of the study reach where aerial imagery shows 100 meters of channel migration have occurred between 1993 and 2004. A comparison between the model results and a typical manual delineation from aerial photography shows that a conservation easement based on the manual delineation would have missed the new main channel and floodplain whereas one based on the EAC model would have adequately covered these new landscape features (Fig. 24). Therefore, the EAC model and others that incorporate the fluvial landscape concept could suggest a better alternative to buffers and manual delineations based solely on existing channel locations and vegetation.

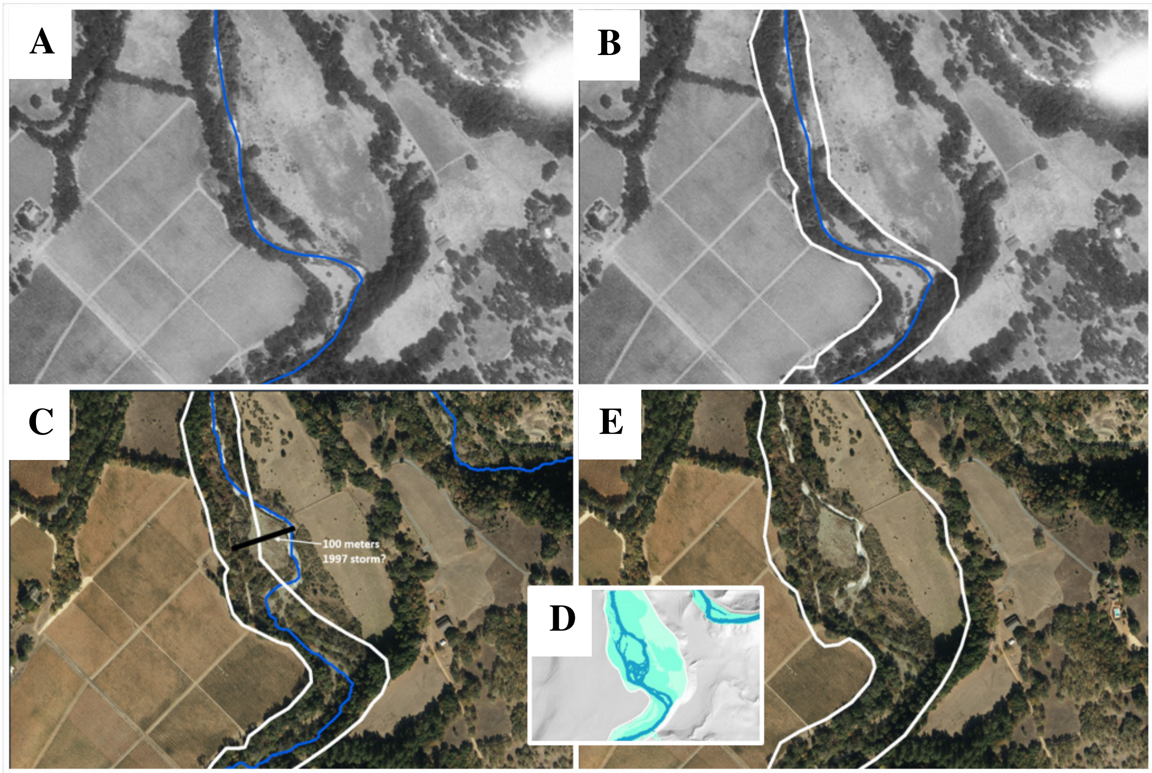

Fig. 24. Aerial orthophotograph cir. 1993 of Maacama Creek, Sonoma County, California with stream center in blue (A). Manual delineation of riparian zone based on conspicuous woody vegetation in photo (B). Channel migration observable in cir. 2004 photo, with new stream center located 100 meters to the ENE (C). Results of EAC model for fluvial landscape (D) and minimum area for land use restrictions (E).

EAC Model Limitations

Several limitations on the use of the model exist. First, for accurate results, the watershed and stream conditions of the reaches of interest must fall within the range of conditions found in the sample reaches used to develop the regional curve. In addition to topographic controls, multiple factors determine channel geometry, including sediment and hydrologic regimes and degree of anthropogenic physical impacts. In this case, field measurements for the regional curve were recorded in relatively natural stream systems (Collins & Leventhal, 2013). In heavily aggraded or incised systems, the model either over-estimates or under-estimates the fluvial landscape, respectively. As an illustration of this problem, Fig. 25 shows EAC model results for an incised alluvial reach of Green

Valley Creek (22 km from the study site) in the vicinity of a culvert identified as a source of local incision. To account for the degree of aggradation or incision, future study could focus on the incorporation of an index that would alter the Bankfull calculation by adding to or subtracting from the DEM-sampled streambed elevation in order to produce a simulation of the fluvial landscape under more natural ground conditions. A possible source for such an index is from Florsheim et al. (2013), who suggest a "relative incision" ratio that when near 1.0 approximates a general threshold of channel stability. Relative incision is defined as the ratio of terrace height (h_t) to effective channel flow (d_e) and is proposed to be used to determine the extent of incision in incised alluvial channels. Bankfull might be considered an appropriate denominator in the ratio. However, Florsheim *et al.* (2013) point out that bankfull, which was developed for natural systems, is not as useful in heavily incised or aggraded channels. Instead, they suggest using *effective channel flow*. They suggest bar surface elevation can be used to estimate the height of effective channel flow. The authors refer to a previous study which found that bar surface elevation was 71% of bankfull. In their field study, bar surface elevation was determined to be 0.6m. Extending the relationship with bankfull, the authors thus infer effective flow depth to be 0.85m (0.6m/.071 = 0.85m). This represents a practical approach to using the bankfull concept for the relative incision ratio while accounting for effects of anthropogenic disturbance such as in Fig. 25.

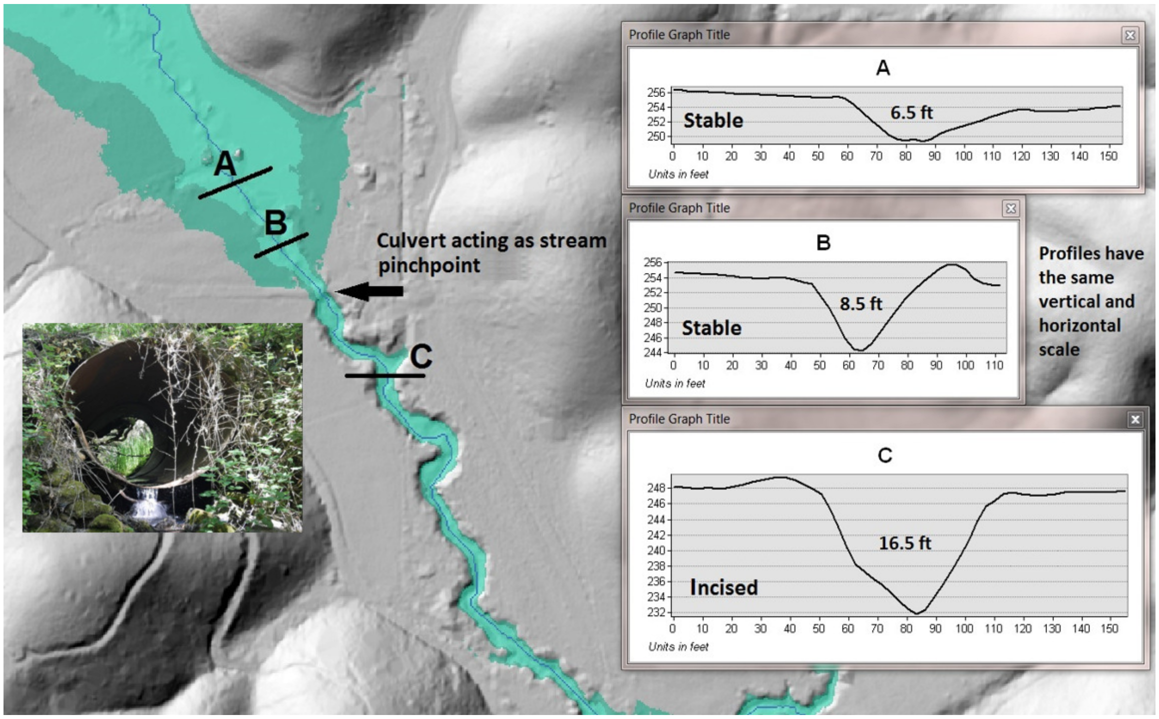

Fig. 25. Model results upstream and downstream of a culvert likely acting as a stream pinchpoint that has led to severe incision as depicted by the significant difference in cross-section profiles between B and C.

Second, since the elevation of the streambed is a key parameter, the model is highly dependent on the accuracy of the DEM. Two accuracy factors that deserve particular attention for this application are the quality of the ALSM "bare earth" point cloud classification and the amount of water present in the stream during ALSM collection. Low shrubs can be easily classified as ground and add artificial elevation to streambank morphology (Gould, 2013). Since typical ALSM wavelength frequencies do not penetrate water, pools and standing water can artificially fill streambed depressions and obscure the thalweg when calculating the stream raster model input. In the present case, the ALSM data were captured at the peak of the dry season (October) in the middle of a significant regional drought. Thus, the stream reach was virtually devoid of water. But such optimal imagery may not be available in all cases.

Third, drainage area, the independent variable of the regional curve, is calculated from a D-8 flow accu1mulation algorithm which is highly sensitive to local topographic features such as road embankments and other anthropogenic barriers that are commonly captured by high-precision ALSM-derived DEMs. In reality, there are usually engineered passages for water through these barriers, but these are not captured by ALSM. Without enforcing hydrologic connectivity, false hydrologic termini are assumed by the flow accumulation algorithm, resulting in artificially low drainage area values in the stream raster. Therefore, hydroenforcement is essential to proper model function.

Care must be taken when applying these methods to other sites due to differing sources of elevation data and regional curves. Although we did not test the effects, we assume DEM resolution significantly affects model results. Future study should compare model results between different resolution terrain data (e.g., 1, 5, 10, and 30-meter pixels). Future comparisons could include ALSM data of varying point densities (e.g., 1, 2, 8, and 16 points/sq meter) to determine a minimum precision level to minimize data acquisition costs. Local conditions should be considered since heavily vegetated landscapes may require higher point densities.

4.1.2 The Functional Riparian Zone

Use of the EAC model for defining the FRZ

The EAC model was used as an automated means to define the FRZ by increasing BFD to the point where the ground-truthed riparian landforms and vegetation map were sufficiently encompassed. This technique is admittedly subjective as there is no hydrogeomorphic significance of 18xBFD. However, a high degree of agreement was observed in the geographic variation of the three components (see Fig. 20 from section 2.5.5). Due to these promising results, we argue that further study is warranted to determine the transferability of a BFD multiple to other reaches and watersheds. Future research should involve repeating the study for multiple sites stratified by climate, topographic gradient, stream condition, and other factors. The goal of such a study could be the development of a general "rule of thumb" for estimating the FRZ for alluvial reaches throughout a watershed or planning area.

Scaling to the Catchment Level

Notwithstanding the known limitations of scaling the model to a whole catchment based on the findings of one site (e.g., 18xBFD is likely strongly influenced by local conditions), we did so to illustrate the potential benefits to riparian conservation planning. Of the six potential alluvial reaches identified by scaling 18xBFD to the catchment level (see Fig. 23 from section 3.3), it was determined that four are already permanently protected. Inspection of aerial photography and a bare earth ALSM DEM of the remaining two showed that one is mostly developed (and presumably with armored banks to protect structures) and the last one is relatively intact (Fig. 26). This demonstrates how, with minimal effort, a conservation organization can identify remaining, intact alluvial reaches to target for conservation. Restoration agencies and mitigation bank designers might target the altered reaches.

Ultimately this framework could help conservationists determine where to target investment. There are many miles of streams requiring protection and this method shows promise in showing where the potential wide alluvial riparian habitat may lack protection and, by extension, where ecosystem services are at risk. On the ground evaluations of select reaches could follow in order to gauge the degree of non-native plant invasion, biological richness, and presence of salmonid spawning habitat. As with any GIS planning effort, on the ground verification of mapping efforts is essential, but a catchment-level map of potential alluvial reaches would increase efficiency through strategic targeting of high-quality.

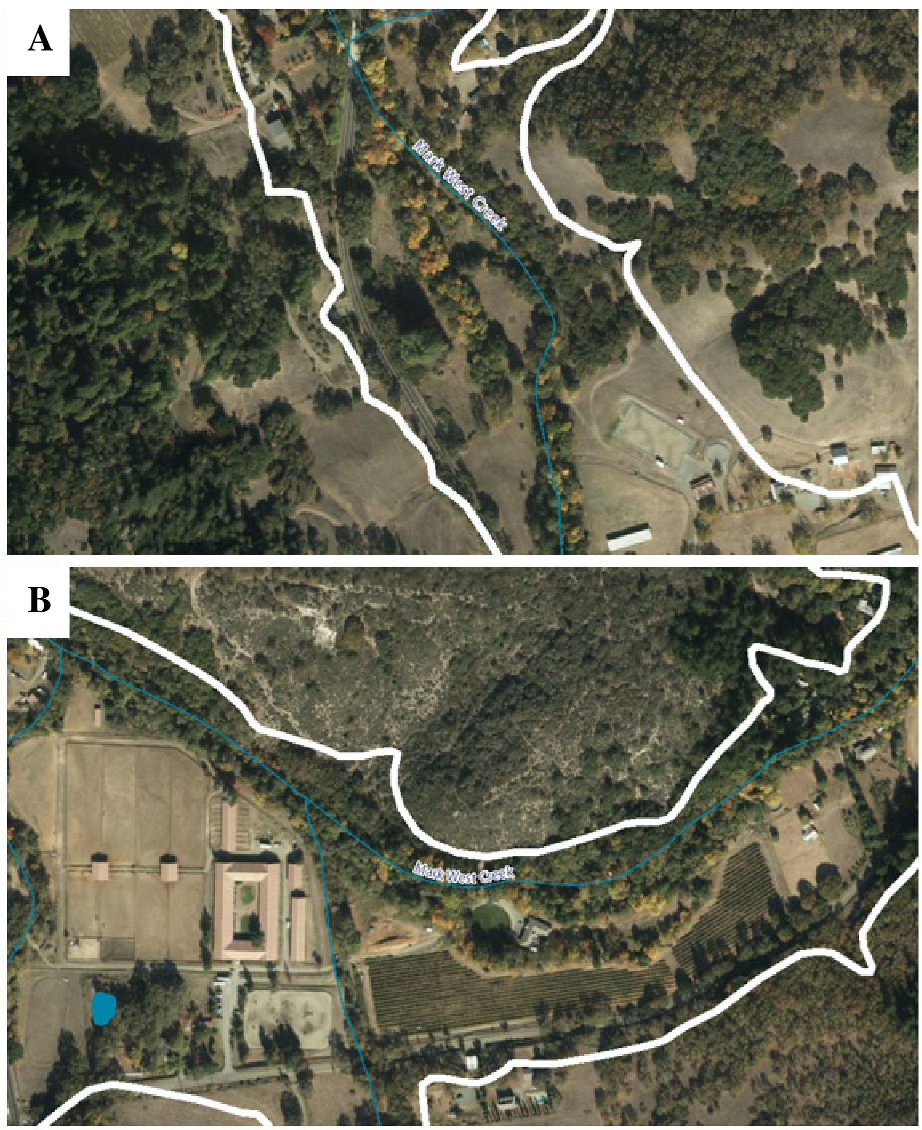

Fig. 26. Relatively undeveloped (intact) alluvial riparian zone (A). Mostly developed alluvial riparian zone (B). The width at 18xBFD outlined in white.

4.2 Acquisition Scenario Evaluation Using Indicators of Function

4.2.1 Marginal Gains

Marginal gains of indicators of riparian function within the four acquisition scenarios generally decreased with increasing distance from the fluvial landscape. However, the decrease was non-linear due to the spatial heterogeneity of the three indicators of function chosen for the study. The construction of the scenarios using multiples of BFD, as opposed to linear methods, ensures that they follow topographic controls on hydrology and overlay indicators of function in a consistent fashion (i.e., the functions under a consistent relative elevation).

To our knowledge, this is a first look at evaluating acquisition scenarios based on degree of function per a suite of indicators. The results are promising, but there are at least three elements that require further investigation. First, other indicators of riparian function should be included. In particular, more sensitive indicators of riparian and ecological function (e.g., nesting locations and feeding behavior of avian riparian obligate species) would complement the physical-based indicators used in the study. Second, DEM resolution affects TWI. Sørensen and Seibert (2007) showed that pixel size influenced flow accumulation and thus TWI. They suggest that purpose should determine resolution. For instance, modeling groundwater flow and connectivity may be better suited to less-detailed pixel sizes given that it follows a general topographic pattern. Third, Grabs et al. (2009) showed that TWI is static and does not account for seasonal fluctuations in soil moisture and subsurface flow patterns. They argue that model-based wetness indices that incorporate climatological and hydrological information perform better provided those data are available.

4.2.2 Benefit-Cost Ratio

Analysis of the acquisition scenarios from a benefit-cost perspective provides further quantitative information for conservation decision-making. When land area and cost are factored in, new differences are illuminated between scenarios. For example, B and C were no longer roughly equal as they were in terms of marginal gains of function. Instead, the difference in BCR constituted a significant breakpoint (0.72 points) between the two. Another breakpoint of note is between scenarios C and D where the relatively small amount of addition function of scenario D (6%) would cost an additional $220,000.

Quantitative and monetized information of this sort would be valuable in conservation contexts where scarce funds must be used efficiently.

Several factors should be considered before putting the BCR into practical use. First, the price per acre estimate may not remain static across the landscape; input from an appraiser may be required. Second, we must use care when deconstructing a natural system. There is an implicit assumption that the functions operate independently, which of course they do not, and that functions in aggregate are better than an individual function. We may instead assume that high values for any one function are sufficient cause for acquisition.

5.0 Conclusions

The results of this case study support a shift in conservation practice to an ecologically functional definition of the riparian zone and demonstrated improvements that can be made in the way riparian zones are delineated in land and natural resource conservation contexts. We used a combination of terrain analysis and field survey methods to delineate the ecologically functional riparian zone and compared the results to other, more common delineation techniques. Our results demonstrate that terrain-based modeling techniques offer greater accuracy than ubiquitous buffering and manual delineation methods. The greater accuracy in riparian zone delineation that results from our methods can lead to increased efficiency and effectiveness in riparian zone protection whereby conservation investments are targeted toward parts of the riparian zone that encompass functional elements. The methods presented include a scenario-based framework for the evaluation of multiple acquisition options, which fills a current strategic information need of land conservation practitioners by enabling the determination of a point of diminishing returns when it is not feasible to protect the full ecologically functional riparian zone. The modeled variable-width corridor associated with 18 times the depth at bankfull stage matched a field-surveyed estimate of the functional riparian corridor that includes the fluvial landscape, terraces, lateral tributaries, and alluvial fans, and extends partially into the terrestrial upland ecosystem. Through the use of a regional curve of hydraulic geometry, the model results were scaled to the whole catchment, allowing for the rapid identification of potential alluvial reaches warranting consideration for protection. Further research is needed to examine application of these techniques in differing watersheds and climate regions. Future testing of EAC modeling should focus on improving results in heavily incised, aggraded, or otherwise disturbed stream systems, as well as on effects of DEM resolution on model results.

The methods we put forward here may offer a superior delineation method to buffering and digitizing. The comparison of delineation practices demonstrated that buffers have to be extremely wide in order to cover the widest parts of the FRZ. This results in significant amounts of land outside the FRZ being included. Thus, buffers are not suitable for demarcating boundaries of riparian conservation easements in alluvial reaches. Vegetation-based manual delineations from aerial imagery are expedient and do result in boundaries that follow natural features. However, as the woody vegetation near channels gives way to heterogeneous vegetation communities of the terrace and alluvial fans, it becomes difficult for the digitizer to distinguish what is and is not riparian, and thus the delineations tend not to extend into these important areas. As the results for the vegetation-based manual delineation show, significant portions (78%) of the FRZ were missed.

This work has implications for increasing the accuracy of spatial boundaries of perpetual conservation easement or fee title acquisitions of alluvial riparian areas and preserving the space required by riparian ecological functions over large temporal scales. The method we present joins recent GIS-based methods that bridge the gap between the conceptual model of the ecologically functional riparian corridor as defined by Gregory et al. (1991), Naiman and Decamps (1997), Ilhardt, Verry, and Palik (2000), and others, with the practical mapping needs of voluntary and regulatory riparian conservation practices. Specifically, this work demonstrates a scientific basis and technical methods to operationalize a functional definition of *riparian*, one that is based not one single issue (e.g., sediment retention) but on multiple functions, including those that extend into the upland fringe. It also illustrates the efficiencies gained with accurate riparian zone delineations. More broadly, improved riparian zone delineation accuracy may result in increased riparian protection, which has implications for many societal benefits including flood hazard risk reduction, drinking water filtration, groundwater recharge, sequestration of greenhouse gas, and recovery of salmonid populations.

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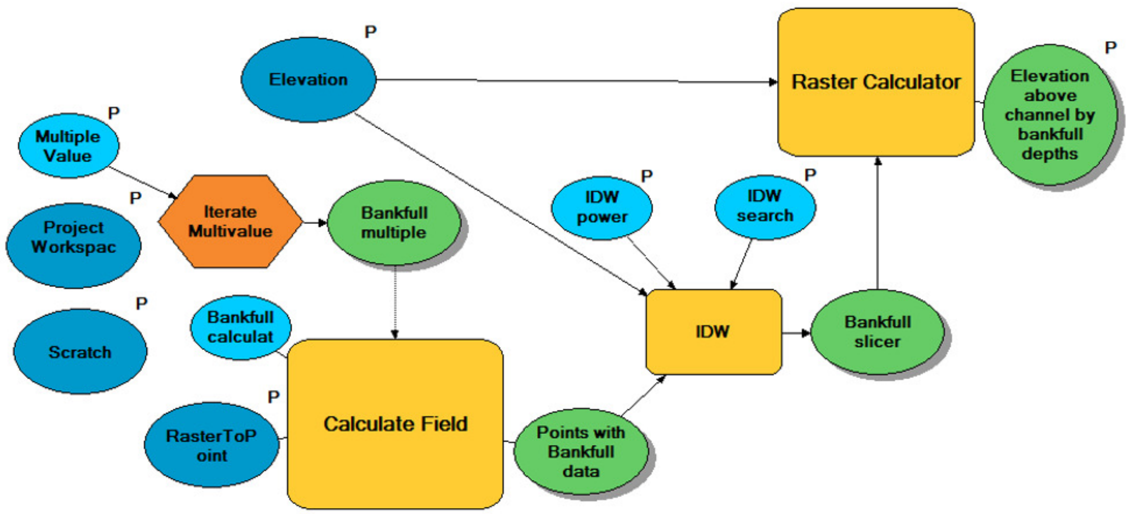
APPENDICES

Appendix 1: Elevation Above Channel (EAC) Model Diagram



The EAC model was constructed using ModelBuilder (ESRI, 2013). Inverse Distance Weighting (IDW) was used as an interpolation method. The model parameters are:

- IDW Power Value
- IDW Search Type (fixed)
- IDW Search Distance (select distance larger than the valley floor)
- Number of Bankfull multiples

The model inputs are:

- DEM
- Stream points (generated from converting a stream raster to points)

Environmental variables include:

- Scratch location

- Project workspace