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Comparison of Methods to Map California Riparian Areas

Final Report
Prepared for the California Riparian Habitat Joint Venture

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Comparison of Methods to Map California Riparian Areas

Executive Summary

The purpose of this report is to compare and contrast definitions and methods for mapping existing and potential riparian areas throughout California. This report has been produced for the California Riparian Habitat Joint Venture (RHJV); the use of any of the findings or recommendations from this report by any government agency or other organization is voluntary.

The riparian definition adopted by the RHJV was developed by the National Research Council in 2002. It is more inclusive than the definitions commonly used in California. Simply stated, the NRC definition indicates that every length of every lakeshore, stream or river channels, estuarine or marine shoreline, and wetland margin is riparian to some degree. The more traditional definitions focus almost exclusively on vegetation along the banks of rivers and streams.

The broader definition offered by the NRC presents two challenges for mapping riparian areas. The first challenge is to map all boundaries of all aquatic and semi-aquatic areas. First-order channels in the uppermost reaches of watersheds are especially important and challenging to map. Although they usually comprise most of the drainage network of a watershed, they are seldom well represented on existing maps and are often inconspicuous in the available imagery. The amount of first-order riparian areas can be estimated from samples, however. The second challenge is to decide how wide the riparian areas are when they are not obviously delimited by vegetation or other visible features. This challenge is met by setting width rules based on existing studies relating width to riparian function for various environmental settings, and using these rules to automate riparian mapping in a Geographic Information System (GIS).

Six methods for mapping existing riparian habitat have been developed using combinations of rules supported by the scientific literature. These methods range from just mapping what is obviously riparian vegetation (Method 1), to accounting for the effects of vegetation height and topography on the width of riparian areas for broad suites of riparian functions (Method 6). Four methods of mapping potential riparian habitat were also compared. These methods range from simply adopting the FEMA 100-yr flood hazard maps (Method 7) to predictive maps based on regional relationships between fluvial channel geometry and drainage area (Method 10).

Based on their accuracy and cost, Method 6 for mapping existing riparian areas and Method 10 for mapping potential areas seem optimal. Method 10 needs further development, however, to work well in all settings. Method 6 is best at identifying the full extent of riparian form and function. It can be standardized throughout California by many work centers using existing data.

Given that the RHJV definition of riparian habitat is not yet widely recognized in California, we recommend that further analyses of its ramifications for existing state environmental policies and programs be encouraged. This report can help inform those analyses by showing how different mapping methods translate the definition into measures of the existing and potential extent of riparian resources. We also recommend that this report be published through formal peer review to further establish its scientific credibility. Finally, we note that one or more of the methods discussed in this report will be used in the existing State Wetland Demonstration Project (WDP) of the Resources Agency and related projects funded through the State Coastal Non-point Source Program during 2007-09. The RHJV might participate in the WDP Steering Committee to help assess the efficacy of these riparian mapping methods as they are being implemented.

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Comparison of Methods to Map California Riparian Areas

Purpose

The purpose of this report is to compare and contrast definitions and methods of mapping existing and potential riparian areas throughout California. This report has been produced for the California Riparian Habitat Joint Venture (RHJV); the use of any of the findings or recommendations from this report by any government agency or other organization is voluntary.

Background

A comprehensive map of California riparian areas is needed for their conservation and restoration. This need is reflected by the State's increasing awareness of the ecological and economic importance of riparian areas. In 1993 the State adopted a Wetland Conservation Policy calling for a statewide inventory of wetlands (67). Pursuant to Assembly Bill 2286 (2000), which was passed to help implement the Wetland Conservation Policy, the California Resources Agency is working with the National Wetlands Inventory (NWI) of the U.S. Fish and Wildlife Service and other partners to develop a comprehensive State Wetlands Inventory (68). It is a compilation of existing and new NWI maps, some parts of which predate the State's and NWI's interest in riparian mapping and therefore do not include riparian areas. But the need to include riparian areas in future inventories of the state's natural resources is well recognized (181). Updates to the Forest Practice Rules in 2000 (74, 75) increased attention to riparian resources. The State is developing a comprehensive vegetation map (72, 73) that identifies riparian vegetation types (i.e., plant species that are indicative of riparian condition), although it does not indicate the extent of riparian areas per se (see section below on riparian definitions). As the interest in riparian conservation has grown, hundreds of ecological restoration projects that involve riparian areas in California have been initiated that highlight the need for a consistent riparian definition and mapping approach (69). The California Resources Agency has recently begun working with other state agencies to develop a comprehensive program for wetland and riparian assessment and monitoring (70, 181). The program plan calls for a statewide inventory of riparian areas as well as wetlands, and involves new, standardized methods of riparian assessment (71, 181). The North Coast and San Francisco Bay Regional Water Quality Control Boards are drafting amendments to their Water Quality Control Plans (Basin Plans) to protect stream and wetlands systems including riparian areas and floodplains (79). There is a clear need to standardize the definition and mapping approach for riparian areas.

The Riparian Habitat Joint Venture (RHJV) has been working since 2001 to develop a comprehensive map of California riparian areas. The RHJV has produced workshops with riparian experts from academia, science-based NGOs, the private sector, and federal and state agencies to outline a technical approach. The workshops have included representatives from NWI, the State Wetlands Inventory, and the State's wetland monitoring demonstration project in hopes of developing an approach to riparian mapping that will satisfy the needs of these related programs. This study is an outgrowth of those workshops.

Intellectual Framework

Definition of Existing Riparian Area

The term, riparian, has numerous definitions in the technical and policy-related literature. The lack of a consistent definition impedes coordination among federal and state programs to protect riparian areas (1, 81). Appendix A provides a sample of definitions from such programs in California. The National Research Council (NRC) has synthesized a definition that seems fundamental to most interests (57, 58). This definition has been adopted by the California Riparian Habitat Joint Venture (RHJV) and is therefore used in this report:

"Riparian Areas are transitional between terrestrial and aquatic ecosystems and are distinguished by gradients in biophysical conditions, ecological processes and biota. They are areas through which surface and subsurface hydrology connect water bodies with their adjacent uplands. They include those portions of terrestrial ecosystems that significantly influence exchanges of energy and matter with aquatic ecosystems. Riparian areas are adjacent to perennial, intermittent, and ephemeral streams, lakes and estuarine-marine shorelines." It's clear from the NRC report that the term, waterbody, refers to wetlands as well as streams, lakes, and estuaries.

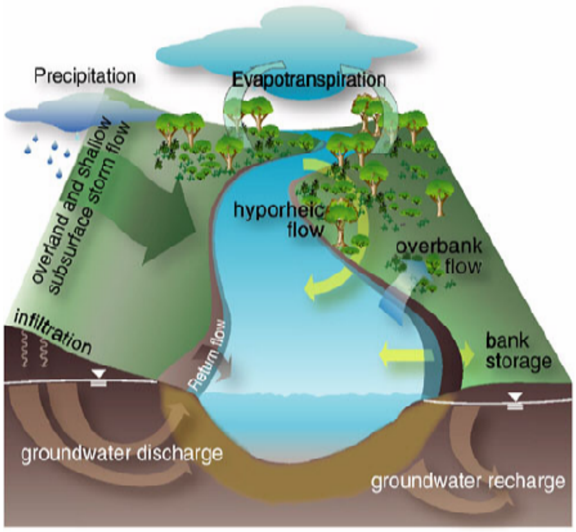


Figure 1: Diagram of terrestrial, riparian, and freshwater aquatic system in the context of the hydrological cycle; from National Research Council 2002 (58).

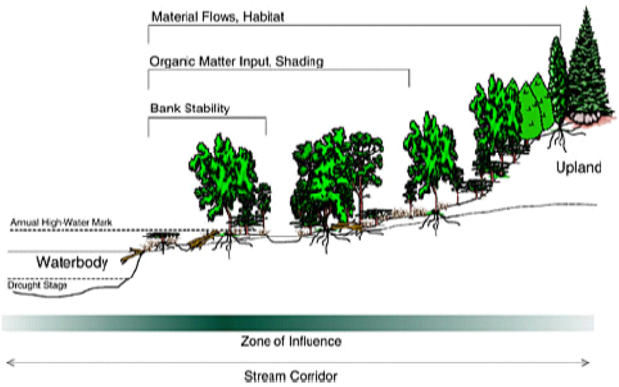


Figure 2: Diagram of zonation of riparian functions between uplands and adjacent waterbodies; from National Research Council 2002 (58).

Numerous technical studies and reviews (e.g. 23, 37, 56) recognize that riparian areas consist of two or more zones of varying widths and distinguishing structure and function that parallel the adjacent waterbody (Figure 2). The zone nearest the stream features tightly coupled stream-riparian interactions (e.g., bank stabilization, predation on aquatic biota). The next zone further from the channel features processes of the riparian area itself (e.g., shading, flood water storage). Another zone further from the channel is more about buffering the other zones and the stream from upland stressors (e.g., non-point source runoff, encroachment by people). In British Columbia, riparian interests commonly combine the first two zones into one (37). A similar scheme has been suggested for the United States (89).

Figure 3: Examples of (A) a lacustrine wetland with overhanging riparian forest canopy, and (B) a vernal pool with less distinctive riparian grassland.

The subdivision of riparian areas into functional zones is justified by the changes in physical and ecological conditions that naturally occur between the aquatic and terrestrial environments, and by the need to accommodate associated changes in land use objectives and policies. Many studies emphasize, however, that the apparent riparian zones and the adjacent aquatic and terrestrial environments function together as river corridors, estuarine and lake shores, or as wetland ecosystems, and that the boundaries between them vary in location and distinctiveness in space and over time (e.g., 1, 3, 4).

Wetlands and their riparian areas `can be difficult to distinguish. Both occupy the transition between dry and wet environments. But wetlands are restricted to places of saturation or standing water that support indicative wetland vegetation (182), whereas riparian areas can include these places plus associated beaches, tidal flats, point bars, and other non-wetland areas. Riparian areas can also include uplands and terrestrial vegetation that are excluded from wetlands. Riparian areas and wetlands commonly coincide, at least in part, either because the riparian areas encompass the wetlands, as in the case of a riverine riparian forest that encompasses wetlands on a floodplain, or because the riparian vegetation actually overlaps the wetlands, as in the case of a lacustrine riparian forest canopy that hangs over wetlands along the lakeshore (Figure 3A). The exact boundary between riparian areas and wetlands can be difficult to discern in seasonal wetlands with indistinct margins, such as vernal pools (Figure 3B).

A distinction must be made between riparian buffers and riparian areas. Riparian buffers are designated for the protection of adjacent waterbodies. They are not necessarily designated to protect the intrinsic functions of the riparian area per se, or to protect the functional interactions between the riparian area and the adjacent uplands. A buffer might not include all of the riparian area, as defined by the National Research Council. Some of the larger studies and reviews of riparian habitat conditions (e.g., 9, 53, 75, 78, 80) have distinguished between riparian areas necessary to sustain the physical stream environment and those needed to sustain near-channel microclimate and appropriate riparian communities.

For example, studies of California forested streams show that their physical integrity is more likely to be sustained if appropriate tree-fall characteristics are maintained within a buffer that is no wider than the average mature height of the stream-side trees. But much of the woody input from trees growing along the stream bank can result from these trees being struck by other trees naturally falling from farther away (76). Furthermore, the microclimate indicative of forested riparian communities requires a riparian width equal to two or three tree heights (77, 78).

Synonyms for Riparian Area and Buffer

There are many published terms referring to riparian areas or buffers. The following list is not exhaustive, but it contains the most common synonyms found in scientific and policy-related literature written in English:

- riparian areas
- riparian zones
- riparian habitats
- riparian buffers
- buffer strips
- watercourse and lake protection zones
- streamside management zones
- streamside protection zones
- riparian ecosystems
- riparian reserves
- special management zones
- forested riparian zones
- watercourse buffer zones
- areas of concern
- riparian management areas

Permutations of these terms are also evident.

In general, broader riparian buffers result from considering more riparian functions. Strategies to conserve the riparian areas in their entirety, including their interactions with adjacent uplands, will tend to involve broader areas than less comprehensive strategies that focus on a subset of riparian functions, such as stream protection. Simply stated, riparian areas are usually broader and more extensive than riparian buffers. This project is about mapping riparian areas.

Definition of Channel

Given that a map of riparian areas is needed and that some amount of riparian area attends every surface channel that conveys water (57, 58), then a definition of channels that can be used to map riparian areas would be helpful. All the recovered, published definitions of a channel are somewhat circular in reasoning because they rely upon one or more channel synonyms such as creek, river, stream, stream bed, conduit, creek bank, etc. But the literature suggests that, in essence, a channel is a long series of generally u- or v-shaped topographic cross-sections that together confine the gravitational flow of surface water. Natural channels are created and maintained by the flows they convey (183). Unnatural channels are usually designed to convey a predicted flow (174). The following published definition was selected for its agreement with these basic concepts and its overall simplicity.

> *A channel is an open conduit either naturally or artificially created which periodically or continuously contains moving water, or which forms a connecting link between two water bodies (185).*

River, creek, stream, run, branch, anabranch, and tributary are some of the terms used to describe natural channels, which may be single or braided. Canal, ditch, and floodway are some of the terms used to describe artificial channels. A braided or anastomosing channel is characterized by a successive division and rejoining of overland water flow though anabranches, which are diverging and converging secondary channels that together comprise the braided channel as a whole (185).

Definition of Potential Riparian Area

The RHJV recognizes a need to map *existing* riparian habitat for its protection and to map *potential* habitat as a first step toward assessing and prioritizing riparian restoration opportunities. The science advisors to the RHJV have recommended developing separate definitions and mapping methods for existing and potential habitat.

Changes in the distribution of riparian habitat result from changes in the extent or location of a waterbody, especially a lake, lagoon, river, stream, or wetland, or from a change in the location of emergent groundwater that drains to a waterbody (58, 84). The distribution of riparian habitat can be changed by river migration, the rising or falling of water tables, the removal or construction of dams and levees, water diversions, stream channelization, excavations of stream terraces, and the infilling of wetlands and active floodplains. In order to affect riparian functions, these changes have to last long enough to alter the way material and energy tends to be processed between the waterbody and the adjacent uplands. Some concomitant change in the structure of the plant community in the area of hydrological change would be expected. Based on these considerations, the following definition of potential riparian area seems appropriate.

> *Potential riparian areas are uplands or former riparian areas that are likely to become hydrologically connected or re-connected to a waterbody due to its migration, enlargement, realignment, or due to an increase in surface or subsurface runoff to the waterbody.*

Areas that are expected to be permanently exposed by retreating or shrinking waterbodies also represent potential riparian areas. This is an uncommon scenario at this time, but might become more common because of dam decommissions (e.g., 144) or decreased rainfall as affected by global warming (e.g., 106). These potential areas cannot be mapped without knowing the case-specific bathymetry behind the decommissioned dams, or the local effects of global warming on runoff. Efforts to map potential riparian areas due to expanding lakes and reservoirs would also need to be addressed on a case-specific basis. The assessment of potential riparian areas therefore focuses on uplands or former riparian areas that would tend to be flooded in the absence of unnatural channel entrenchment, levees, or other flood control measures (e.g., 143).

This definition of potential riparian areas does not necessarily exclude any land uses or cover types. However, for the purposes of this study, land uses that are not compatible with flooding, saturated soils, or very high water tables are excluded from potential riparian areas. For example, industrial and residential land uses within known or probable flood zones are excluded from potential riparian areas.

Quantitative estimates of potential riparian areas are not common. A literature search using key terms such as riparian potential, riparian prediction, and riparian creation produced numerous references to riparian habitat rehabilitation, restoration, or enhancement (e.g., 98-103), but fewer studies of the full extent of probable riparian response to expected or possible hydrological changes (e.g., 85-88, 143). Site plans for new reservoirs, water-related restoration projects, and land developments seldom consider riparian areas in their entirety; the riparian focus is almost always on the amount of buffer needed to protect associated aquatic resources (e.g., 53, 91-97). This emphasis on riparian buffer design is evident in many land use plans, ordinances, and related reviews (e.g., 14, 41, 55, 80, 81, 90). Forecasts of riparian response to climatic change are necessarily theoretical (e.g., 105, 106), and mostly focus on how floodwaters might be re-distributed across the land.

Scope and Applicability

According to the purpose of this report, the comparison of methods and any resulting recommendations for riparian mapping should pertain to all of California. This means that the methods and related terminology, including the definitions of existing and potential riparian habitat must be broadly applicable across the State's great diversity of climatic, physiographic, and ecological conditions. It also means that the methods must meet the needs of the large community of environmental scientists, regulators, and managers that is concerned with the conservation of riparian resources. The following considerations have guided the selection of methods to compare.

- The definition of riparian provided by the National Research Council (58) does not depend on waterbody type, substrate type, spatial scale, degree of naturalness, geomorphic setting, or plant community composition. It indicates that every length of channel, shoreline, and wetland edge, whether natural or man-made, has some amount of riparian function. A riparian area is essentially defined by the predictable, physical exchanges of material and energy that connect a waterbody to its adjacent uplands. Simply stated, the riparian area *is* the connection. The width of the area varies according to a variety of factors (126-128), and may be almost nil under severely unnatural conditions.
- The methods should not be inherently biased for or against any particular physiographic or climatic setting. They should provide

comparable maps across the full range of riparian conditions well represented in California.

- To be applicable throughout California in a timely way, the methods should be easy to use, inexpensive, and distributable among many work centers, in addition to being scientifically defensible, adequately accurate, and repeatable.
- To remain relevant, the methods must be “up-gradable” to accommodate new mapping technologies, so long as they do not reduce the methods’ broad applicable and cost-effectiveness.

Field-based approaches tend to be more expensive than non-field methods, especially for the remote areas that comprise much of California. Statewide field-based maps of riparian areas are not likely to get completed. This study therefore compares various existing approaches that use remote data, such as Digital Elevation Models (DEMs) and aerial imagery. The comparisons can be spot-checked, however, against field conditions.

The efficacy of approaches to map riparian areas is likely to vary with elevation, aspect, geology, channel order, annual rainfall, land use, vegetation cover, and other factors that influence the extent, composition, and structure of riparian systems (e.g., 14, 145). This study therefore involved selecting test watersheds that encompass broad ranges in environmental factors typical of different environmental settings.

Methods and Results

Selection of Test Watersheds

Criteria were developed to select two test watersheds that represent a broad range of environmental conditions commonly encountered in California. The primary criteria were climate and accessibility; it was decided that one semi-arid and one wetter watershed within which related work was already being conducted should be selected. Based on these primary criteria, a set of candidate watersheds was created. Secondary criteria addressed the budgetary and time limits for the study. The RHJV developed a list of mapping methods or approaches that would be useful to compare, and this lead to discussions about the kinds of data that the candidate methods require. The major datasets include digital elevation models (DEMs), recent high-resolution geo-rectified imagery (1m pixal resolution), stereo aerial photography, vegetation maps showing dominant cover species in riparian settings, and existing or updated maps of the National Wetlands Inventory (NWI). Table 1 of Appendix C shows how the major data types are distributed among the candidate mapping methods. This project could not afford to develop most of the data types that were needed, and therefore depended on available data. Most future efforts to implement any of these methods will also depend on available data. The availability of these data was therefore used to help select the test watersheds. Tables 2 and 3 of Appendix C score the candidate watersheds based on the availability of key datasets, as identified in Table 1 of Appendix C. Based on these criteria, Napa Watershed in northern California and Ventura Watershed in southern California were selected as the test watersheds.

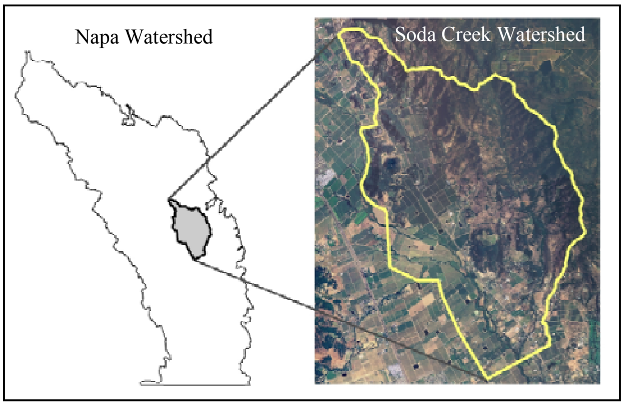


Figure 4: Example index area. Soda Creek Watershed was chosen as one of two similar-sized index areas of the larger Napa Watershed.

Selection of Index Areas within Test Watersheds

As the data for the test watersheds were compiled, their incompleteness became evident. Few of the major datasets covered either test watershed in its entirety. This necessitated the selection of sub-watersheds, termed "index areas," within each watershed for which the major datasets were most complete and could support the broadest comparisons of mapping methods (Figure 4). Two index areas were selected in Napa Watershed to capture its full range of geomorphic and topographic conditions. Only one index area was needed for the Ventura Watershed. The index areas comprise between 5% and 10% of the total surface area of each test watershed. The index areas are classified as Planning Watersheds according to the California watershed classification system (see Table 4 of Appendix C).

Mapping Drainage Networks

Any comprehensive effort to map existing or potential riparian areas must begin with a complete map of all the lakeshores, estuarine shorelines, perennial channels, ephemeral and intermittent channels, and artificial drainage channels that together comprise the drainage network. It can be assumed that every part of the boundary of the network supports some amount of riparian area (see discussion of riparian area beginning on page 2 above). If the map of the drainage network is incomplete, then the map of the riparian areas must also be incomplete.

The most common set of data for depicting the drainage network of any watersheds in the Unites States consists of the "blue lines" of rivers and streams and shorelines from the 1:24000 scale topographic quadrangles produced by the U.S. Geological Survey (USGS). The blue lines comprise part of the standard 1:24000 Digital Line Graph (DLG) dataset commonly available to the public. It has long been known, however, that the blue lines do not represent the complete drainage network for any watershed (45, 46). This is especially true with regard to mapping riparian areas, since they can attend artificial drainage channels as well as natural ephemeral and intermittent streams that are seldom comprehensively included in the DLG (Figure 5 below).

A variety of computer-based methods exists to construct maps of drainage networks based on Digital Terrain Models (DTMs). A DTM is a grid of elevation points. The size of the spaces (i.e., the size of the square cells of the grid) dictates the resolution of the DTM. Cell size is also termed node distance, which is the shortest distance between the intersections of the grid lines. As node distance increases, DTM resolution decreases.

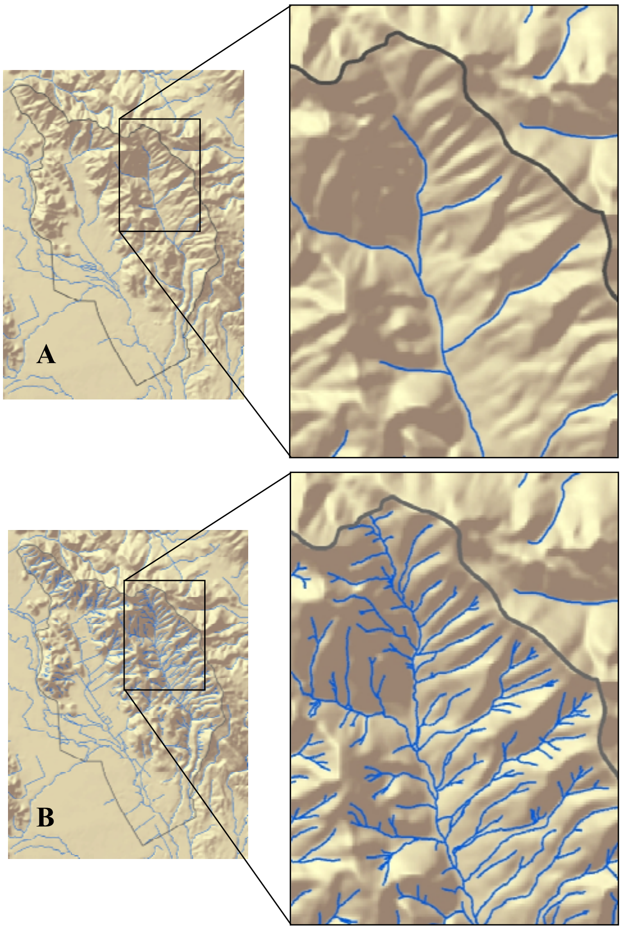


Figure 5: Comparison of drainage networks for the Soda Creek index area of Napa Watershed based on (A) USGS 1:24,000 DLG and (B) heads-up digitizing from 10m DEM plus interpretation of 1m pixel resolution natural color aerial imagery.

Large-node DTMs can only be used to produce relatively coarse, generalized topographic maps (40, 42-45, 110, 111). DTMs can also be used to generate maps of land slope, which can help determine the limits of valley bottoms and flood plains as potential riparian areas (e.g., 46, 88, 100, 143), and to adjust models of riparian buffer width to account for the effects of slope on runoff and tree fall (e.g., 48, 76, 77).

The DTMs produced by the USGS are termed DEMs (Digital Elevation Models). The 30-m DTM and 10-m DTM are commonly available in California. Of these two DTMs, the higher-resolution 10-m DTM is much superior for generating drainage networks (42, 45, 143). The USGS 10-m DTM was used in this study because it is the highest-resolution DTM available throughout California.

LIDAR (i.e., Light Detection and Ranging, or Laser Imaging Detection and Ranging) is a recent technology that can be used to develop detailed DTMs from which topographic maps and drainage networks can be derived. LIDAR determines the distance from a sensor on an airplane or satellite to the ground surface by measuring the time delay between transmission of a laser pulse and detection of the reflected signal. Detailed DTMs with node distances less than 1 meter are routinely produced using LIDAR (112-114). Enough measurements can be taken per unit area to describe the 3-D form of individual trees (e.g., 107-109). Very high resolution DTMs based on LIDAR can be used in some situations to quantify channel cross-sections and longitudinal profiles (115), although most LIDAR does not penetrate water. A 1-m DTM was developed from LIDAR for the Napa Watershed as part of an effort to address sedimentation problems in the Napa River (116). The Napa 1-m DTM was used in this study to help assess the general efficacy of using LIDAR to generate drainage networks for riparian mapping.

After testing the efficacy of the 1-m and 10-m DEMs for the Napa Watershed index areas (see results below), it was decided that the most cost-effective method to comprehensively map drainage networks was to augment the 1:24000 DLG with automated generation of first- and second-order channels using ArcHydro (186) operating on the 10-m DEM, and "heads-up" editing of the Arc Hydro network based on the recent geo-rectified 1-m resolution imagery provided by the National Agricultural Imagery Program (NAIP) (187), existing NWI, vegetation maps (discussed more fully below), and slope maps generated from the 10-m DEM. Using this approach, comprehensive drainage maps were developed for all three index areas.

Mapping Existing Habitat

National Wetlands Inventory

The National Wetland Inventory (NWI) is charged with estimating changes in the amounts of wetlands and riparian areas throughout the United States. It has developed mapping methods that can be fully implemented with the kinds of data, equipment, and expertise most broadly available in California. NWI has published its methods (5) and they are being adopted by the Federal Geographic Data Committee (2). But the NWI methodology is not inflexible. NWI has adjusted its methods for new technologies, and in California NWI has developed partnerships with regional data sources and map developers to improve the relevance of NWI products for local interests. NWI has advised the RHJV and it is interested in this study as a possible source of new methods to improve its capacity to map riparian habitat in California (188).

The current NWI methodology relies mainly on the recognition of vegetation indicative of riparian conditions in the best available stereo aerial photography (5). Every ecological province of California has a flora indicative of riparian conditions (73). These indicator plant species and assemblages, when evident in the kinds of planimetric imagery commonly available for habitat mapping, can be used to help delineate the extent of riparian areas. In some cases, the riparian areas can be delineated by visible differences in plant stature or morphometry along the upland-riparian boundary, rather than plant community composition (58, 76, 80). Not all riparian conditions are represented by indicative vegetation, however.

The NWI method also accounts for some riparian areas that cannot be discerned based on vegetation. This is done by assigning a default constant buffer width of 2.5m to both sides of channels depicted by single blue lines in the 1:24000 scale DLG (5). The mapped riparian areas are then classified according to the NWI riparian scheme. Recent NWI updates have included annotations for water source based on the hydro-geomorphic (HGM) classification system (117).

The resulting map of riparian areas based on current NWI protocol consists of polygons of obvious riparian vegetation plus standard riparian widths applied to both sides of the mid line of small channels and the upland side of lakeshores that are represented by single blue lines on the 1:24000 DLG and lack obvious riparian vegetation. This leaves out channels not shown in the DLG, and the riparian areas of most palustrine (i.e., depressional and slope wetlands according to the HGM system) and estuarine wetlands.

Functional Riparian Width

Knowing how wide riparian areas tend to be is important for mapping areas that lack distinctive vegetation or other indicative features. Not all riparian areas are vegetated (5, 57, 58), and they aren't always clearly distinguishable from adjacent uplands based on vegetation. For example, upland and riparian vegetation assemblages look very similar in aerial imagery for ephemeral or intermittent streams in the headwater reaches of densely forested watersheds and in very arid environments. Also, lakes and streams in urban and farmed areas do not always support distinctive riparian vegetation. All of these examples are common occurrences that in aggregate might represent a significant percentage of the total length of channel and shoreline in California. For the associated riparian areas, criteria other than plant stature or community composition must be used to define the upland boundaries.

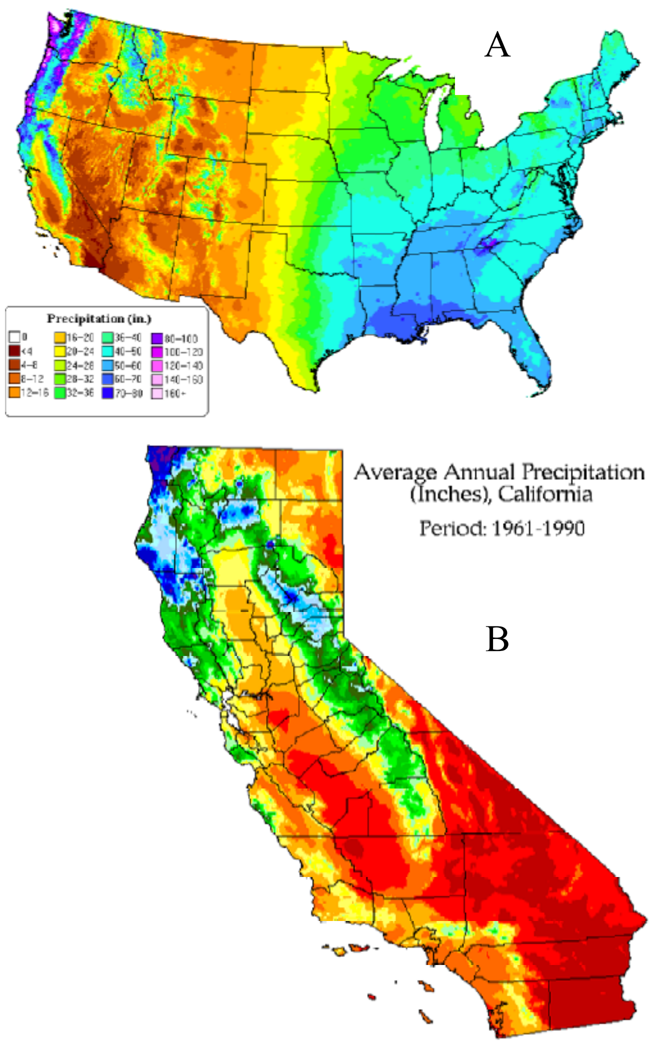


Figure 6: Climatic diversity of (A) the coterminous United States and (B) California (187).

In the absence of indicative vegetation, one alternative approach to mapping riparian areas is to assume a default riparian width based upon relationships between width and riparian function reported in the pertinent literature.

Information about the functional width of riparian areas from throughout the temperate world is applicable to California because of the State's great physiographic and climatic diversity. For example, in terms of average precipitation, which is a controlling factor for the distribution and abundance of vegetation and riparian conditions, California includes all of the climatic zones represented elsewhere in the United States (Figure 5). The same can be said for topographic range.

The search for literature about riparian form, structure, and functional width was therefore geographically broad. The number of technical reports about the nature of riparian areas has been increasing rapidly (58). This has lead to published reviews that summarize much of the pertinent literature. The results of the literature search about riparian functional width are summarized in Appendix D. The findings are further summarized in Table 1 below.

Riparian Function	Average Recommended or Observed Minimum Riparian Width (rounded to the nearest 5m)	Average Recommended or Observed Maximum Riparian Width (rounded to the nearest 5m)
Sediment Entrapment	10	75
Contaminant Filtration or Chemical Transformation	10	115
Large Woody Debris Input to Water Body	40	80
Leaf Litter Input to Water Body	5	25
Flood Hazard Reduction	15	65
Aquatic Wildlife Support	20	60
Bank or Shoreline Stabilization	15	25
Riparian Wildlife Support	40	160
Water Body Cooling	20	40
Riparian Microclimate Control	70	130
When Multiple Functions Are Considered in Conjunction with Riparian Wildlife Support (Part 2 of Appendix D)	30	120

Table 1: Summary of recommended riparian functional widths based on Appendix D.

The literature generally indicates that the total number of functions of a riparian area tends to increase with its overall width and length. The level of any given function also tends to increase with riparian width, but not without limit and not always in a linear way. Most functions increase in level quickly over the first 5m-10m and then level-off within 30m-100m. Some functions, such as bank stabilization and contaminant filtration, can be well supported by relatively narrow riparian areas (e.g., see summaries in references 9 and 129). For protecting the water quality of water bodies (especially regarding nitrogen and phosphorus loading), the average minimum and maximum recommended riparian widths are about 15m and 100m. To protect channel banks and shorelines, the suggested minimum and maximum widths average about 15m and 25m. To provide flood control (i.e., to measurably decrease peak stage of the hydrograph or to increase the residence time of water in a watershed) and to support aquatic resources in adjoining water bodies, most of the recommended riparian widths fall between about 15m and 60m. To sustain natural riparian microclimates, a functional width of about 70m-130m is indicated. Maintaining the intrinsic ecological functions of riparian areas, such as their support of riparian wildlife, require the broadest areas (57, 104). The average minimum and maximum recommended riparian widths to support riparian wildlife are about 40m and 160m, although widths greater than 200m are also suggested (i.e., 51, 52). For studies that reviewed and summarized recommended riparian width for multiple functions, the average minimum and maximum values are about 20m and 80m, with overall averages of about 30m and 120m when riparian wildlife support and other functions are combined (see Part 3 of Appendix D).

A single width can be used to approximately cover all expected riparian functions (e.g., 76, 104), or the width can vary by selected functions (e.g., 139, 53). Functional widths can also vary based on local controlling such water body type, plant community composition, geomorphology, and hydrology (123, 14, 124, 145). Although default widths disregard these local controls (126, 128, 145-147), they are commonly used to map riparian areas. For example, the fixed-width approach is used by the NWI for small streams that lack distinctive riparian vegetation (5), and it is commonly used by different states to design riparian buffers (125).

Most of the studies of riparian width pertain to forested systems and focus on the protection of adjoining rivers and streams. Fewer studies focus on grasslands or shrub systems and most of these are about sediment and nutrient removal by grass strip buffers in agricultural or urban settings. They indicate that 50-90% of suspended sediment and 25-90% of nutrients can be filtered by grass strips 5-10m wide (e.g., 131-140).

Studies of functional width for riparian forests in California are commonly concerned with the beneficial shading and cooling of adjoining streams and the input of large woody debris (LWD) provided by riparian trees. In these regards, the federal agencies tend to assess riparian width in terms of Site Potential Tree Height. SPTH is defined as the average maximum height of the tallest mature tree of the dominant tree species at a given site (53). Several studies indicate that most of the aquatic ecological benefits of riparian vegetation depend on the 5m-30m of riparian areas nearest the adjoining water body. For example, riparian areas that are 30m wide can provide at least 50% of the total riparian benefits to associates streams (e.g., 14). But such "rules of thumb" ignore the effect of tree species on tree height, and the effect of tree height on shading and LWD input. They also neglect the influence of tree species on overall riparian structure and wildlife support. When these factors are taken into consideration, the specifications for riparian areas de-emphasize fixed widths and instead relate width to vegetation structure. Widths ranging from 1-3 SPTH have been recommended (53. 39, 49).

The input of terrestrial or riparian materials into water bodies (i.e., allocthanous input) can be a very important function of riparian areas (53, 156, 158), especially for headwater channels (49, 58, 157, 161). The likelihood of allocthanous input can be affected by the steepness of the terrain (51, 161). Functional widths based on allocthanous input might therefore get narrower as the terrain gets steeper. One way to account for this affect is to reduce the SPTH value as a function of the slope of the riparian areas (157).

Landsliding and other mass-wasting processes, apart from bank erosion, can account for most of the allocthanous input in steep terrain (160, 161). Functional riparian widths might therefore increase in steeper terrain to accommodate hillslope processes. Other studies suggest that, for the purposes of chemical filtration and sediment entrapment, riparian buffers should increase in width as their slope increases (Table 2 below). The rationale is that broader buffers are needed to filter faster runoff in steeper terrain (23, 40, 48, 162). The recommendations generally call for an increase in buffer width per unit increase in percent slope, starting at a minimum buffer width. Some studies also recommend a minimum percent slope below which no adjustments are made. Overall, the recommended minimum functional width averages about 30m, and the minimum slope threshold below which no adjustment is made is about 20%. In other words, the average recommended adjustment is an increase of about 1m in width for every unit increase in

Reference	Recommended Adjustment of Buffer Width (m) for Slope (% as integer)	Slope Threshold (% as integer)	Buffer Width Threshold (m)	Vegetation Type
164	1.25 x slope	None	30.0	NA
163	1.50 x slope	None	30.0	NA
165	1.20 x slope	None	30.0	NA
9	0.60 x slope	None	30.0	NA
166	1.50 x slope	30.0	20.0	Forest
167	0.50 x slope	20.0	20.0	Forest
24	1.33 x slope	15.0	30.0	Forest
Averages	1.12 x slope	18.5	27.1	Mostly Forest

Table 2: Example adjustments in riparian width to account for slope of riparian and adjacent terrain.

slope above a threshold of 20%, starting at a minimum riparian width of 30m. Applying this formula to an area with a 70% slope, which is much steeper than most areas, yields an overall buffer width of 100m, which is comparable to the most commonly recommended maximum default buffer width to accommodate most riparian functions (see Table 1 above and Appendix D).

There are very few studies of the effectiveness of riparian buffers along man-made channels, such as irrigation ditches (137). Most of these buffers are grass strips less than 10m wide. Studies of these buffers have shown that 77-90% of nutrients (137, 138) and 50-90% of the sediments (139, 140) are trapped within grass buffer strips 5m wide along ditches. Grass buffers 12-24m wide can remove 10-40% of herbicides (141), and grass buffers 10m wide can remove 74% of fecal coliform (142).

It should be noted that irrigation and drainage ditches in agricultural and urban settings are not expected to have as much potential for ecological functions as more natural streams of the same size. The literature about riparian areas along ditches is scant, but suggests that relatively narrow areas can provide most of their potential functions.

Vegetation

Maps of dominant plant species or assemblages can help identify the extent of riparian areas. This is because the moisture regimes that characterize riparian areas tend to give rise to indicative riparian flora.

This fact has encouraged the development of remote sensing methods to automate riparian mapping based on the spectral signatures of known riparian plant species. Once a library of signatures has been produced, it can be used to classify the vegetation in multi-spectral imagery. The use of spectral analyses to map riparian areas has been fraught with technical complications, however. First, riparian areas do not necessarily have abundant vegetation (5, 58). Second, spectral analysis does not generally provide accurate classifications of riparian vegetation (148, 149). There can be more spectral variation for a given species than the dictionaries of spectral signatures contain, and the bandwidth of the remote sensors may be too broad to discern differences between species (150, 153, 155). The classification errors can sometimes be corrected by field verification and local expert review, but this adds considerable time and cost to the remote sensing approach. The time required to correct the automated maps can be comparable to original, ground-based mapping. Third, spectral analyses fail to determine the lateral extent of riparian conditions when upland and riparian vegetation is indistinguishable (150), which is not an uncommon situation in California. Some of the more successful remote sensing efforts to map riparian areas have been restricted to valley bottoms where the riparian vegetation tends to be most distinctive (e.g., 147, 154). The approach may one day prove to be more broadly applicable and cost-effective than it is at this time. But given the expense in developing adequate dictionaries of species-specific spectral signatures, and given that adequate dictionaries will not be available for the State in the foreseeable future, remote sensing of riparian areas based on the spectral signatures of riparian plants was not attempted in this study.

Figure 7: Examples of (A) CALVEG mapping and (B) vegetation map based on the California Vegetation Manual.

Two existing vegetation maps were used to help estimate functional riparian width (Figure 7).

CALVEG is a hierarchical classification system designed to assess vegetation-related resources throughout California (119). The system was devised in the late 1970's by the Pacific Southwest Region of the U.S. Forest Service. CALVEG mapping was done between 1979 and 1981 by the U.S. Forest Service based on interpretation of 1:250,000 scale color infrared prints of Landsat Multispectral Scanner (MSS) imagery acquired between 1977 and 1979 (119). The minimum mapping unit (MMU) was 400-800 acres, so the spatial resolution of the resulting map was rather coarse. The California Department of Forestry and Fire Protection had the manuscript maps scanned and converted to ArcInfo coverages. CALVEG maps were acquired for all three index areas for this study. Any obvious problems with classification were resolved before the maps were used.

In addition to the CALVEG maps, the vegetation of Napa Watershed has been mapped through the Information Center for the Environment (ICE) at the University if California at Davis using the California Vegetation Manual (118). The CVM is a newer hierarchical system of vegetation classification and mapping than CALVEG. The CVM maps are more resolute and generally more accurate than the corresponding CALVEG maps (Figure 7). This is because the CVM uses much more resolute imagery that affords a much smaller minimum mapping unit and more accurate classification. The CVM maps are also subjected to randomized field checks (118, 121, 122). The CVM data for Napa Watershed are available at different levels of the CVM hierarchy. The most detailed data were used in this study.

Land Use Maps

The National Land Cover Dataset (NLCD) is a source of statewide land use data (189). The NLCD is a component of the USGS National Land Cover Characterization Program. The NLCD contains 21 categories of land cover suitable for a variety of State and regional applications, including landscape analysis and runoff modeling. The NLCD is distributed as 30m resolution raster images. More detailed land cover datasets are available for some regions of the state, but they are not standardized in terms of resolution, vintage, or land cover classification. They can also be expensive to purchase. The NLCD can help to standardize statewide land use analyses.

Roads

The maps of existing riparian areas exclude the surface area of roads. A standard width was assigned to each road classification in the USGS DLG file based on other studies (177-179). All roads in the DLG file were converted into polygons based on the assigned width values. Overlaps between riparian areas and road areas were then subtracted from the riparian areas.

Watershed	Imagery	Scale or Pixel Size	Vintage
Napa	USGS Digital Orthoquadrangles	1:24,000 scale	1994
	National Agricultural Image Program (NAIP) Color ortho-photos	1m pixel size	2005
	AirPhoto USA true color ortho-photos	0.6m pixel resolution	2002
	NWI Stereo Color IR diapositives	1:58,000 scale	1982
	Napa County true color ortho-photos	0.3m pixel size	2006
Ventura	National Agricultural Image Program (NAIP) Color ortho-photos	1m pixel size	2005
	USGS Digital Orthoquadrangles	1:24,000 scale	1994
	NWI Stereo Color IR diapositives	1:40,000 scale	2002

Table 3: List of imagery used to map riparian areas for this study.

Supportive Imagery

All the methods used in this study to map riparian areas rely on geo-rectified stereo aerial photography and other digital imagery. In general, imagery from different years, seasons, and times of day provide a variety of views that can help identify wetlands, lentic water bodies, drainage networks, and the associated riparian areas. It is helpful to acquire all available imagery for a given watershed. Google Earth© can also be helpful when identifying stream courses by creating oblique views of DEMs with image overlays (151, 152). Being able to see topographic contour lines superimposed on high-resolution photography can be especially helpful in identifying low-order channels in the headwater reaches of watersheds. Table 3 lists the imagery used in this study. The same or comparable imagery is available throughout California.

Selected Mapping Methods

This study evaluates six approaches to mapping existing riparian areas, including a “gold standard” (Method 6) against which the other methods could be objectively compared (Table 4 below). The standard incorporates as much information about site-specific conditions that might affect riparian width as the study could afford, without having to conduct more field work than needed to spot-check the methods. All of these methods, including Method 6, could be applied throughout California using existing software and data that are readily available to the public.

The six alternative methods represent a broad range of readily usable tools for estimating the total amount of fully functional riparian area for any landscape in California. They are not intended to estimate the amount of riparian buffer needed to provide a particular suite of functions, such as protection of adjoining water bodies or support of riparian wildlife; the methods are intended to yield maps of riparian areas as ecosystems in their entirety. There are no significant estimates of riparian area for palustine or depression wetlands, slope wetlands, and estuarine wetlands because these wetland classes were either scarcely represented or entirely absent from the study watersheds and their index areas.

Method 1: *Existing National Wetlands Inventory*

Existing NWI maps of riparian areas were available for the Ventura Watershed but not for the Napa Watershed. The Ventura Watershed riparian NWI maps were produced in 2002-3 and were acquired for this study directly from NWI (Figure 8A). The existing riparian maps for Napa Watershed were produced in 2006 through this study and have not yet been subjected to NWI review. The maps for Napa Watershed cannot be referred to as NIW maps until they have been reviewed and accepted by NWI. However, the NWI riparian maps used to represent existing NWI for the Napa Watershed were developed by experts at the San Francisco Estuary Institute who have previously produced riparian maps for NWI under its direction. For Napa Watershed, the minimum mapping unit (MMU) that was adopted for forested areas is approximately equal to the area covered by the combined canopy of three contiguous riparian trees, or about 0.02 ha (0.05 acres). This is much smaller than the MMU of 0.1 ha (0.25 acres) generally employed by NWI for wetlands and riparian areas (5). The smaller MMU for forested riparian areas was adopted in this study because it is consistent with the natural character of riparian forests in arid parts of California, where a few riparian trees can greatly increase the overall riparian ecological service. For areas of shrubs and non-vegetated areas, the NWI MMU was adopted for this study. This allowed the mapping of point bars, beaches, and other non-vegetated natural features along water bodies as parts of riparian areas.

Method 2: *Single Fixed Riparian Width*

This method simply applies a fixed width of 100m to all water bodies (Figure 8B). The selected width is the most commonly cited riparian width in the literature.

Method	Source of Drainage Network Map	Digitization of Visible Riparian Vegetation and Physiography	Default Functional Riparian Width	Use of Site Potential Tree Height (SPTH)
1. Existing NWI Protocol	1:24,000 DLG plus limited additional channels through photo interpretation; single line "blue lines" from DLG assumed to be 5m wide total.	Yes, based on 1:58,000- or 1:40,000-scale stereo aerial imagery	None	None
2. Single Fixed Functional Width	Comprehensive digitizing of all wetlands, lentic features, and channels	None	100m for all channel banks, shorelines, and wetland margins	None
3. Multiple Fixed Functional Widths	Comprehensive digitizing of all wetlands, lentic features, and channels	None	100m for areas of forest, 30m for areas of shrubs; 10m for grassy areas; 1m for bare ground	None
4. Multiple Fixed Functional Widths Plus SPTH Adjusted for Hillslope to Account for Allocthanous Input	Comprehensive digitizing of all wetlands, lentic features, and channels	None	Twice SPTH for forested areas; 10m for areas of shrub; 5m for grassy areas; 1m for bare ground	Twice SPTH based on tallest dominant tree species
5. Method 4 plus NWI Protocol for Areas Not Included in Method 4	Comprehensive digitizing of all wetlands, lentic features, and channels	Yes, based on geo-rectified 1m pixel resolution color imagery plus slope maps from 10m DEM, existing NWI, Google Earth ™ etc	Same as Method 4	Twice SPTH based on tallest dominant tree species
6. Method 5 Plus Adjustment to Account for Hillslope Process	Comprehensive digitizing of all wetlands, lentic features, and channels	Yes, same as Method 5	Same as Method 4 plus a 1m increase in width for every 1% increase in hillslope for any slope greater than 20%.	Twice SPTH based on tallest dominant tree species

Table 4: Brief descriptions of riparian mapping Methods 1-6 compared in this study.

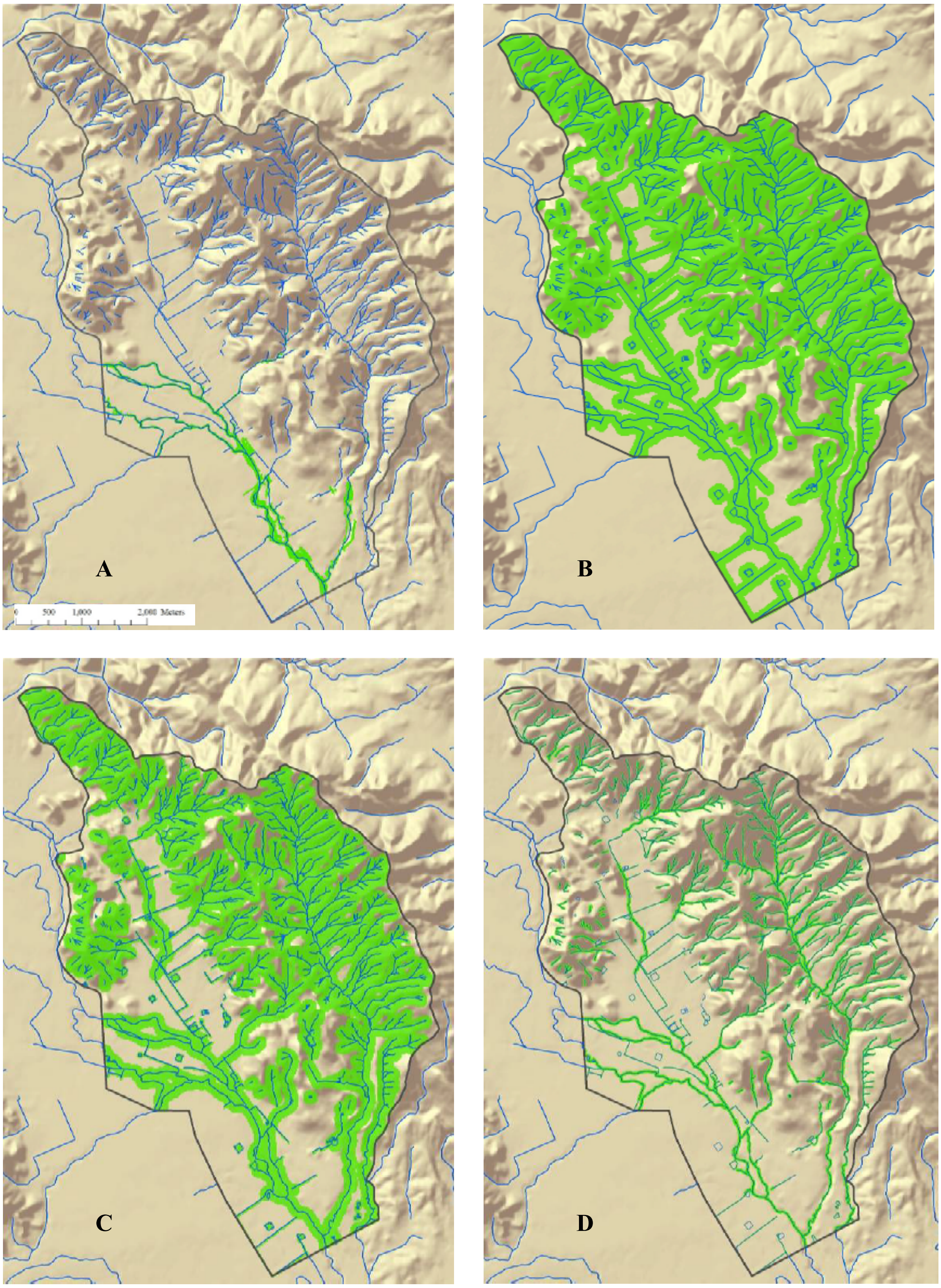


Figure 8 Example results of riparian mapping for Method 1 (A), Method 2 (B), Method 3 (C), and Method 4 (D) for the Soda Creek index area of Napa Watershed.

Method 3: *Multiple Fixed Riparian Widths*

In this approach, different default widths are applied to the drainage network of each index area depending on the dominating major ground cover type (Figure 8C above). The maximum width recommended from the literature was applied in each case. Where trees were dominant, the width was set at 100m, regardless of tree species. Where any species of shrubs was dominant, the width was set at 30m. Where grasses were dominant, the default riparian width was set at 10m. For bare ground the width was set a 1m. The classification of vegetation into trees, shrubs, and grasses was based on species, rather than plant height, and followed the designations of whichever vegetation map was being employed (i.e., either the California Vegetation Manual (73) in Napa Watershed or the CALVEG (119) classification system for the Ventura Watershed).

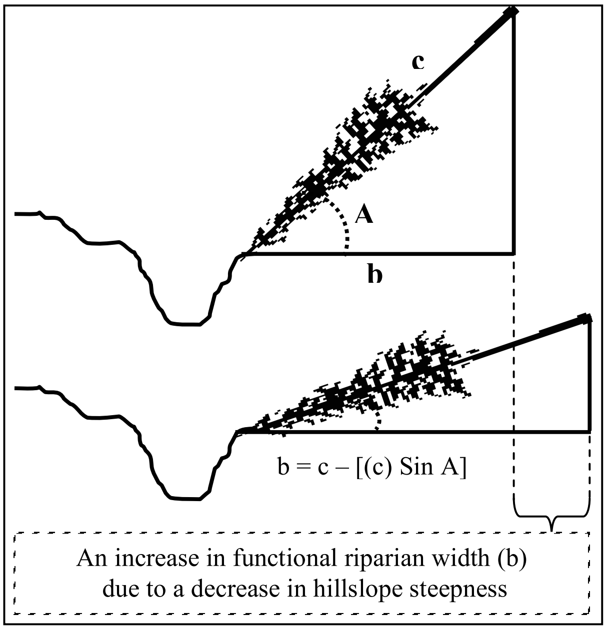


Figure 9: Schematic of method used to adjust SPTH for hillslope steepness; where c = SPTH; A = hillslope in degrees; and b = minimum riparian width for tree top to fall into channel. For any given SPTH, as A increases, b decreases.

Method 4: *Multiple Fixed Riparian Widths plus SPTH*

In this approach, widths are assigned to forested areas based on the SPTH of the dominant tree species, as adjusted for hillside steepness (Figure 8D above). Based on the vegetation maps, and a look-up table of species-specific SPTH, forested areas are assigned a riparian width of 2SPTH. Hillslope steepness, as determined from the 10m DEM, is used to adjust the SPTH values to account for the effect of slope on the minimum distance from a waterbody at which allocthanous input from a tree of height twice SPTH is likely (Figure 9). Default widths for areas dominated by shrubs or grasses are average values from the literature (10m for shrubs, 5m for grasses, 1m for bare ground), rather than the maximum values used in Method 3.

Method 5: *Method 4 Plus NWI Protocol*

A comparison of Methods 1 and 4 revealed that Method 4 can exclude some potentially significant places of distinctive riparian forest along high-order channels, while including other places that appear to lack distinctive riparian vegetation (Figure 10 below). The latter situation was deemed acceptable for the following reasons: (a) some of the indicative vegetation may not be visible in the imagery along the upland boundary (i.e., it may be immature or hidden in shadows); (b) riparian vegetation may be well mixed with upland plant species (81) and therefore misclassified as non-riparian; and (c) some amount of riparian function does not depend on plant cover (58, and see Appendix D), such that the functional riparian area extends further into the terrestrial environment than can be discerned in the imagery. However, the exclusion of obvious riparian vegetation was deemed unacceptable for the following reasons: (a) the excluded areas tend to be portions of the largest obviously riparian areas encountered, and failure to map these areas in their entirety would not help to protect them; (b) larger riparian areas tend to have greater levels and diversity of riparian functions, and a failure to protect them might therefore significantly degrade the riparian functions overall; and (c) the default riparian widths are based on rather conservative average values and their reduction is not clearly justified.

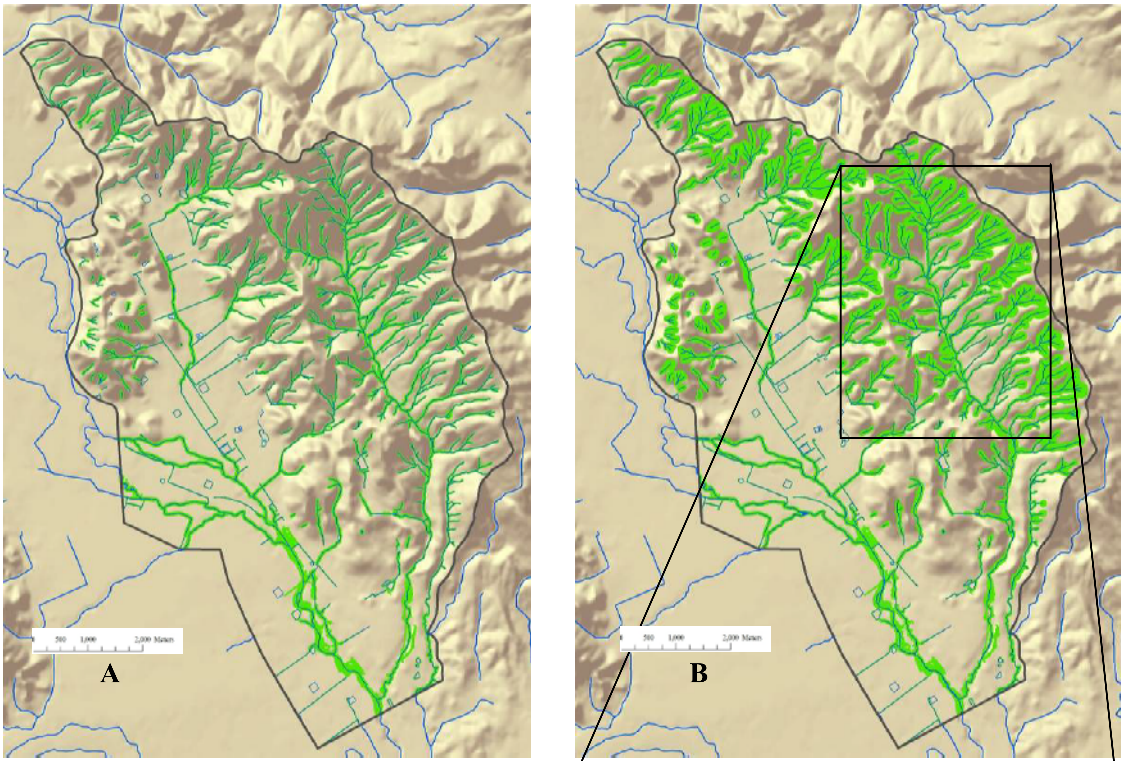
Figure 10: Comparison between results of Methods 1 and 4. Red boxes indicate where Method 1 (green) provides more comprehensive coverage of obvious riparian vegetation than Method 4 (beige). Elsewhere, Method 4 indicates there is more functional riparian area than indicated by Method 1. Blue areas are channels and other water bodies.

Method 5 generally does a good job of encompassing riparian vegetation without grossly overestimating its extent (Figure 10). The rather minor part of the estimated area that exceeds the boundaries of indicative vegetation (i.e., places where beige color surrounds the green color in Figure 10) is not considered a problem because, as stated above, while riparian forests and other riparian vegetation can increase the overall ecological functions of riparian areas, their functions are not entirely eliminated by the absence of such vegetation. Example results from Method 5 are presented in Figure 11A below.

Method 6: *Method 5 plus Hillslope Process*

This method recognizes that some portions of the hillslope processes of low-order channels in the headward reaches of watersheds are riparian in nature (Figure 11B and 11C below) and that they can strongly influence downstream geomorphology, hydrology, and ecology. The headwaters or headward reaches of watersheds are where most water naturally originates within a drainage network (209, 210). They are characterized by interactions among hydrologic, geomorphic, and biological processes that vary from hillslopes to stream channels and from terrestrial to aquatic environments (199, 205, 206, 211). In other words, Headwater areas are riparian in nature.

Headwater areas typically comprise most (70% to 80%) of the total drainage area of watersheds (207, 210). And, since the relative influence of riparian areas on stream ecology tends to increase as stream size decreases (161), headwater areas can be



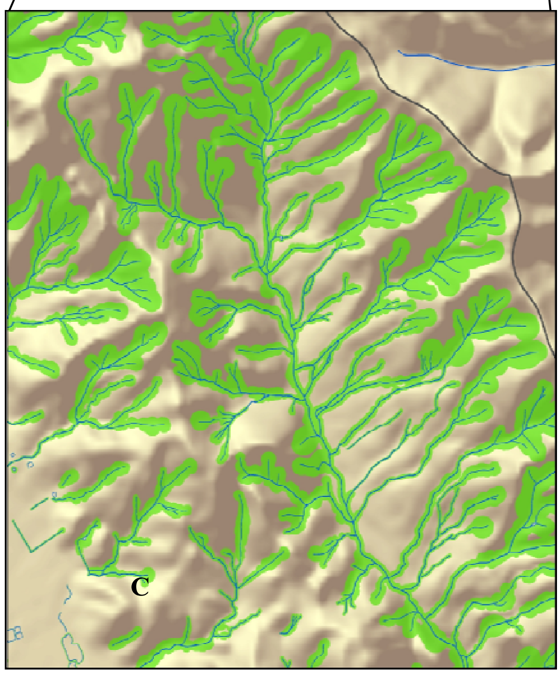


Figure 11: Example results from riparian mapping Method 5 (A) and Method 6 (B), plus details of results for Method 6 in the headwater reaches of the Soda Creek index area of Napa Watershed (C). Blue areas are stream channels.

especially influential on downstream conditions (157, 198). They are important sources of nutrients, sediment, and large woody debris (193, 195-197, 200, 201, 206); they affect downstream channel geometry (183) and landslide probability (206, 210); and the movements of detritus and invertebrates from headwater reaches support downstream food webs (212).

Hillslope erosion processes such as landsliding, dry raveling of soils, and debris avalanches that characterize the headward reaches of watersheds can be dominant sources of allocathanous input of sediment and organic matter (e.g., 194, 213, 214). The magnitude and extent of these mass-wasting processes can greatly increase following wildlife (196, 197).

The immediate drainage areas of first-order channels (i.e., first-order and zero-order basins) are usually “variable source areas” (190). The runoff entering these areas can occur as overland flow (i.e.,

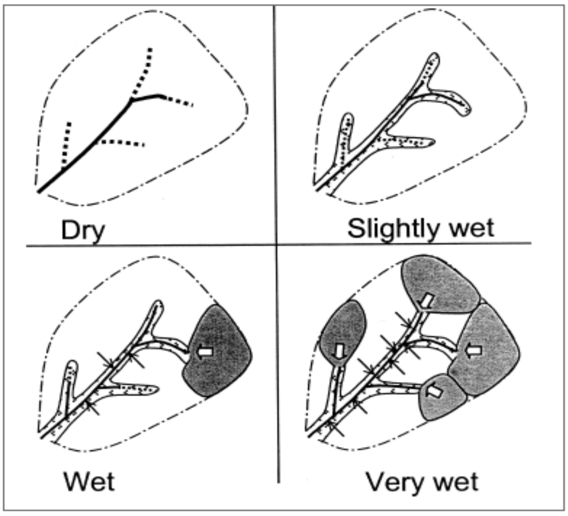


Figure 12. Conceptual model of headwater hydrology. Ephemeral channels mark dry season conditions. Sub-surface flow initiates near the channel as areas get wetter. The preferential flow (thin arrows) and overland flow (broad white arrows) in zero-order basins (shaded areas) increases as conditions become wetter. Figure from reference 205.

precipitation that exceeds infiltration moves downslope as surface sheet flow) (191), lateral subsurface flow (i.e., precipitation that infiltrates and is transported downslope through the soil profile), and preferential flow (i.e., precipitation that moves downslope as flow through rodent tunnels, root channels, etc). This flow by-passes the soil matrix. The variable source areas of zero-order and first-order basins closely resemble the riparian areas generated by Method 6 (Figure 12 cf. Figure 11C).

The various component results of Method 6 can be displayed separately (Figure 13). This can be helpful to understand how the automated riparian widths based on vegetation and hillside slope plus the heads-up digitizing of obvious riparian conditions outside of the automated widths contribute to the results as a whole.

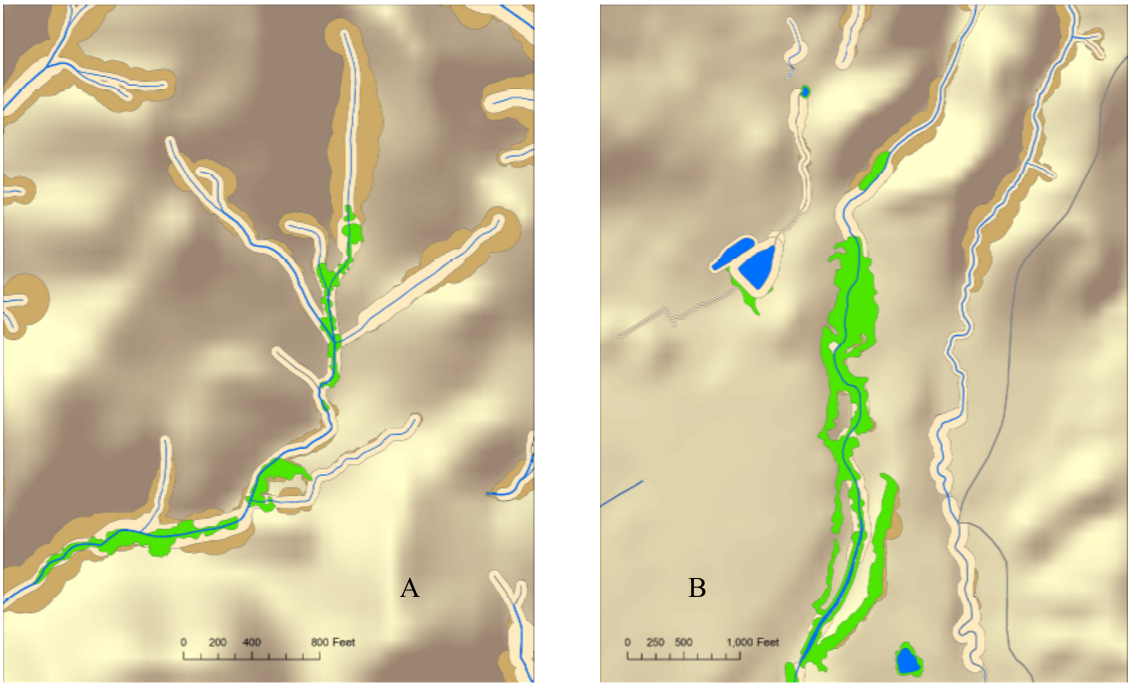


Figure 13: Examples of the drainage network mapping (blue), automated riparian width based on vegetation type (white), automated width based on hillside slope (brown) plus heads-up digitizing of obvious riparian vegetation outside of the automated widths (green for Method 6 in areas were these components overlap (A), and don't overlap (B).

Mapping Potential Riparian Areas

Method 7: *FEMA 100-yr Flood Map*

Given that surface hydrology, especially flooding, is a controlling factor for the distribution of riparian conditions, maps of the expected boundaries for 100-yr floods can be reasonable approximations of potential riparian areas (81). The 100-yr flood is delimited by the elevation contour that has a 1% chance of being wetted or inundated by flood waters each year. The 100-yr flood maps available for the Napa and Ventura watersheds were produced by The Federal Emergency Management Agency (FEMA) under its National Flood Insurance Program (Figure 14A below). These maps were produced in three steps:

1. The streamflow associated with a 100-year flood is estimated using peak flow data from USGS gauging stations and other reputable hydrological data;
2. The flood elevation profile (the elevation of the flood along the length of a waterway) for the 100-year flood flow is determined using a hydraulic model;
3. The inundated areas associated with that profile are mapped. The flood maps for these and other California watersheds need to be updated and modernized in terms of their hydrologic data, topographic data, representation of water control structures, and the models used to simulate flooding. The existing maps must be regarded as approximations of the 100-yr flood zones in the test watersheds.

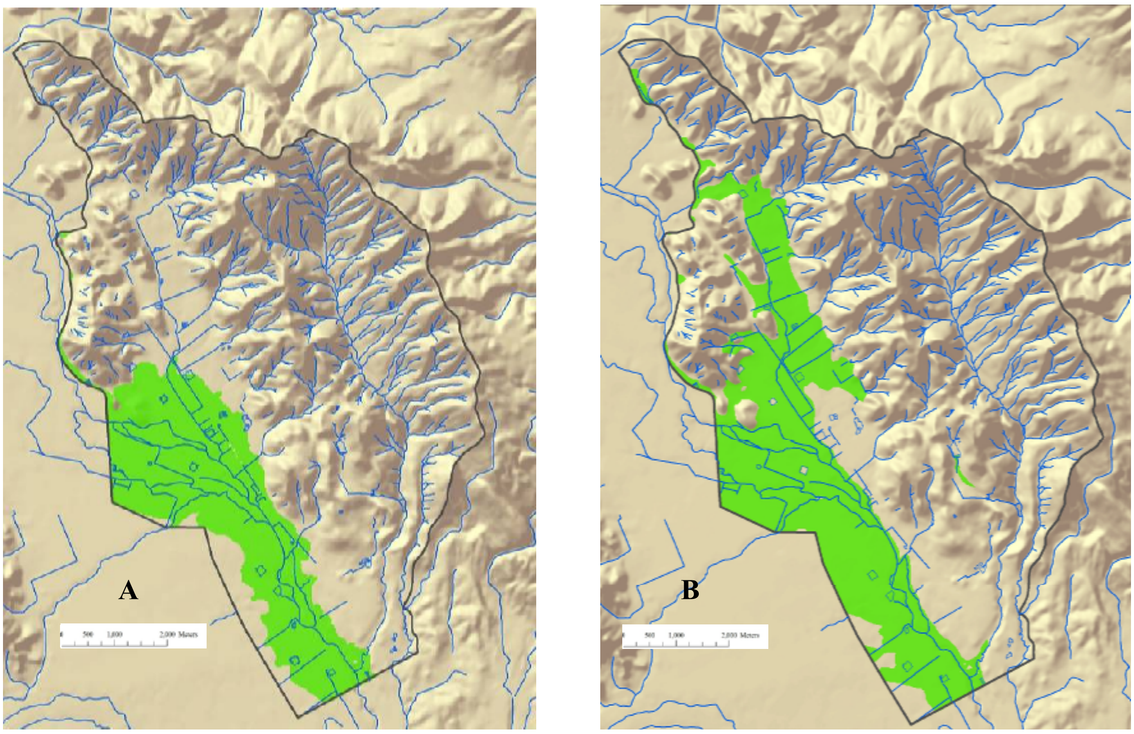


Figure 14: Examples results for mapping potential riparian areas based on (A) FEMA 100-yr flood hazard area, and (B) NRCS soils maps.

Method 8. *Soils Map*

The Natural Resources Conservation Service (NRCS) distributes its soil survey data online from their Soil Data Mart located at http://soildatamart.nrcs.usda.gov/. Their digital soil survey is generally the most detailed level of soil geographic data developed by the National Cooperative Soil Survey. The information was prepared by digitizing existing maps, compiling new information onto a basemap and digitizing the compilations, or by revising digitized maps using remotely sensed data and other information. The soils data used in this project were compiled from the NRCS for Napa Watershed only (Figure 14B); a soils map was not developed for Ventura Watershed County. NRCS staff at the Napa County Resource Conservation District advised the identification of soil types most likely to be associated with riparian conditions. It was noted that riparian soils, per se, are not mapped by the NRCS or anyone else, and that soil types associated with riparian areas are also associated with other, non-riparian areas. The Napa Watershed analysis used the Map Unit Symbol (MuSym) feature of the digital data catalogue and the typical terrain descriptors to select soil types. The selected Map Unit Name and corresponding Map Unit Symbols are Bale clay loam (0 to 2 percent slopes), Bale clay loam (2 to 5 percent slopes, Clear Lake clay drained, Clear Lake clay overwashed, Cole silt loam (0 to 2 percent slopes), Egbert silty clay loam, Reyes silty clay loam, Riverwash, and Yolo loam (0 to 2 percent slopes). Residential and industrial land uses were subtracted from the soils map based on the assumption that such land uses would not be converted into riparian areas.

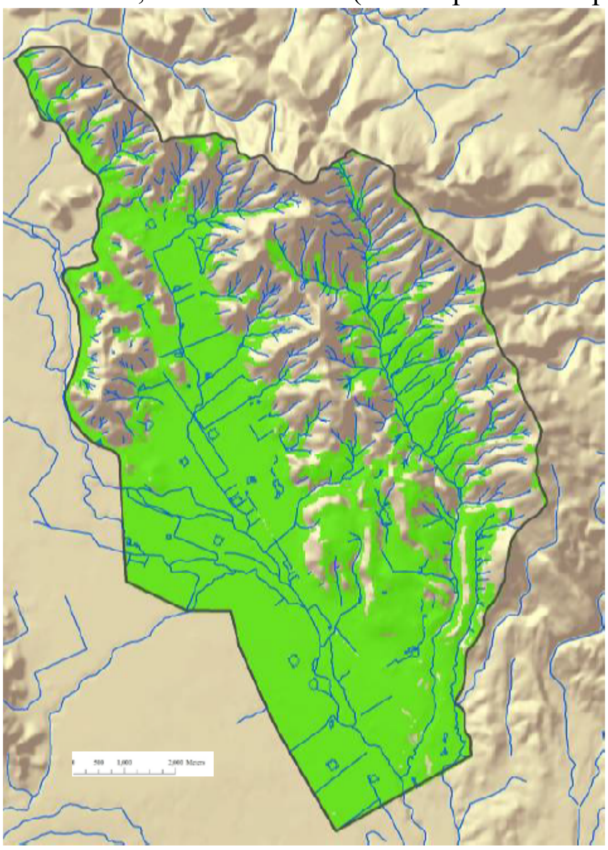


Figure 15: Example results of the GREM model (Method 9) to estimate the potential riparian area for the Soda Creek index area of Napa Watershed.

Method 9. *Geomorphic Model*

The Southern California Coastal Water Research Project (SCCWRP) developed the Geomorphic Riparian Extent Model (GREM) as a method to map potential riparian areas in southern California coastal watersheds (143). The GREM is a GIS-based method that uses topographic data of varying spatial resolutions to map potential riparian boundaries (Figure 15). It can be developed at two resolutions, a more detailed, local watershed-specific version and a more generalized regional version. In essence, a DTM is used to identify steep topographic inclines or breaks in topographic slopes that are expected to significantly block flooding or stream migration. These features are regarded as landward limits to flooding and to riparian conditions. The methodology of the local version involves field work to validate the DEM and to assign thresholds of elevation or slope to bound the draft model output, and to validate the final model. GREM assumes that the potential riparian area is synonymous with the floodplain or valley floor. In this regard, GREM is similar to the method based on FEMA flood mapping, except that GREM does not employ any hydrological data. Although riparian areas also occur along the edges of lakes and estuaries, GREM only applies to riverine riparian habitat (143).

The field work required to develop and validate GREM for the test watersheds or their index areas exceeded the capacity of this study. A more general regional model was therefore used (Figure 15 above). Residential and industrial land uses were subtracted from the maps of potential riparian areas based on the assumption that such land uses would not be converted into riparian areas.

Method 10. *Hydro-geomorphic Model*

This method is designed to provide a coarse estimate of the potential distribution of ecologically significant floodwaters along a drainage network. It differs from the geomorphic model described above by involving basic information about water heights. But it does not involve enough hydrological information to predict the extent of flooding for specific events, such as the 100-yr flood. In this regard it differs from the FEMA effort to map flood hazards. It also differs from the FEMA effort by being readily applicable to small tributaries and other drainages that are not gauged and therefore lack the local hydrological data that FEMA mapping requires.

This hydro-geomorphic model uses regional hydraulic geometry curves (aka "Regional Curves") and the 10m DEM to delimit the area that would tend to be flooded enough to be riparian, assuming that the drainage network is neither entrenched (i.e., the channel bed is not severely incised), or aggraded (i.e., the bed has not filled-in). Regional Curves are log-log plots relating drainage area to channel width, mean depth, and cross-sectional area at 'bankfull discharge" (168, 169). They are based on standard stage-frequency data from gauging stations (168, 172). They can be developed for one watershed (e.g., 171) or for a group of watersheds having similar rainfall (168, 170). Their development is being encouraged by the USDA within California (170) and throughout the country (172).

The regional curves provide estimates of average local bankfull depth, which corresponds to the height of the active floodplain above a stable bed (168). By doubling the bankfull depth, the flood prone height is estimated. The flood-prone height can be used to estimate the height of floodwaters relative to the cross-section of the channel (Figure 16). The flood-prone area probably encompasses moderate floods with recurrence intervals less

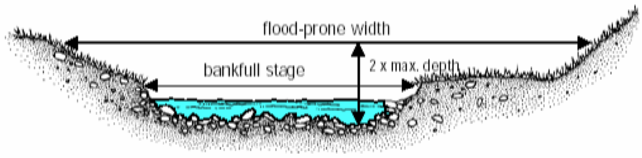


Figure 16: Schematic of a channel cross-section showing the relationships between bankfull and flood-prone depths and widths.

than 50 yrs (175). What role these floods play in creating and maintaining riparian areas is not well known. But they comprise most of the flood events over the typical lifespan of many native riparian tree species, and therefore are likely to strongly influence riparian plant community structure (3). They are also likely to influence aquatic life support in watersheds of the central and northern coast of California (176).

The model uses the 10m DEM to create a three-dimensional map of the drainage network. The model then "walks" upstream along the midline of each channel, stopping approximately every 10m to draw horizontal lines due east and west from the midline of the channel to the land surface (i.e., the lines stop where they intersect the topographic surface represented by the 10m DEM). In doing this, the model first calculates the total drainage area upstream of the stopping point, then uses the drainage area calculation to derive bankfull depth from the regional curve, then doubles the bankfull depth to estimate flood-prone depth, and finally converts the flood-prone depth to flood-prone elevation above the channel bed, based on the DEM. After the model has drawn all the flood-prone contour lines, it attempts to connect their end points to create a polygon as the estimated flood-prone area for any section of channel (Figure 17) or for the drainage network as a whole. Residential and industrial land uses can be subtracted from the maps of potential riparian areas based on the assumption that such land uses would not be converted into riparian areas.

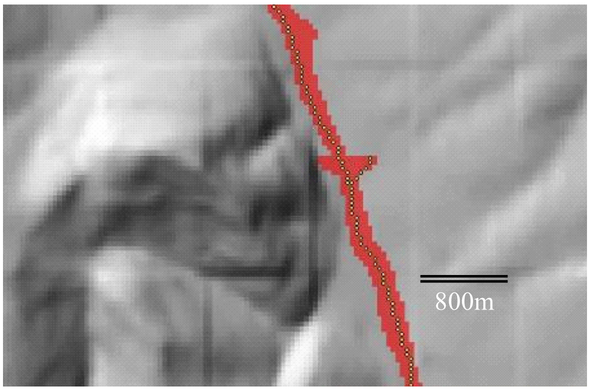


Figure 17: Example results of the hydro-geomorphic model (Method 10) for estimating potential riparian area for a reach of the Soda Creek tributary of the Napa

Standardized Cost Assessments

The approximate costs to apply the methods described above for mapping existing and potential riparian areas were estimated per 1:24,000 scale USGS quadrangle by extrapolation from the selected index areas. The costs were separated into categories for acquiring data, developing drainage networks, mapping riparian areas, running models, and editing the results. The costs for developing models were excluded unless they pertain to each future application of the models. One-time development costs were ignored, even if the models were developed in this study. Costs were estimated in terms of labor hours and materials. The cost estimates are reported below in Table 5.

Estimates of Map Accuracy

The accuracy of each of the nine methods for mapping existing or potential riparian areas was assessed in terms of the total acres mapped relative to Method 6, which is regarded as the most comprehensive and realistic method tested. The estimates of accuracy are reported below in Table 6.

Discussion

Riparian Definition

According to the riparian definition adopted by the RHJV, realistic estimates of the total amount of riparian area in any watershed must reflect the total length of both banks of all ephemeral, intermittent, and perennial natural channels of all orders; plus the banks of unnatural ditches and other engineered channels; plus all uncovered water storage compartments such as lakes, playas, estuaries, lagoons, reservoirs, stock ponds, water traps on golf courses, treatment ponds, etc.; plus the margins of all non-riverine wetlands. In essence, every length of every channel bank, shoreline, and wetland edge has some amount of associated riparian function, and therefore has some amount of riparian area.

This broad riparian definition is well supported in the scientific literature, but it is likely to conflict with some long-standing conventions about what is, and is not, riparian. Most policies and practices to protect and manage riparian areas focus almost exclusively on riparian forests, meaning stands of trees along rivers, streams, and lakeshores. The RHJV will need to undertake a program of outreach and education to vet the broad riparian definition within the government agencies and other institutions that manage and regulate riparian areas. Given the statewide interests of the RHJV, the policies and programs of particular interest at this time include the emerging Stream and Wetland Protection of the Region 1 and Region 2 Water Quality Control Boards, the Dredge and Fill Policy slated for revision by the State Water Resources Control Board, the Forest Practice Rules of the State Board of Forestry, and the National Wetlands Inventory that is updating the statewide wetland and riparian maps through the State Wetland Inventory Program of the California Resources Agency. The riparian definition and mapping protocols of the RHJV may be able to advance these policies and programs over time through their further review, revision, and phased implementation.

Developing Drainage Networks

The most important aspect of mapping riparian areas for any watershed is developing a comprehensive map of the drainage network. As indicated in the paragraph above, this involves mapping all channels, lakes and ponds, and wetlands.

As the availability of high-resolution, geo-rectified imagery and DEMs improves, comprehensive maps of drainage networks become easier to produce. At this time, the most efficient approach to mapping drainage networks involves a combination of heads-up digitizing based on interpretation of 1-m pixel resolution color imagery (e.g., the NAIP imagery), basic drainage network modeling using the 10m DEM, and post-processing the of DEM-derived network to clean up any obvious errors.

While Lidar can be used to generate very detailed DTMs, they often misrepresent the networks of low-gradient terrain that lacks much topographic relief (113). Lidar has been used to generate accurate drainage networks in steep terrain (47), but much of California is not steep. The Lidar-based drainage network for Napa Watershed omitted some low- and medium-order channels that have been diverted from their natural courses, and it tended to include channels that have been buried as storm drains but that follow their historical pathways. In many cases, Lidar produces a DTM that is more resolute than the available imagery, which therefore does not register well on the Lidar-based drainage network. This misalignment between the imagery and the Lidar-based channels can greatly complicate the effort to map riparian areas based on visible riparian vegetation. For example, an unrealistically large amount of indicative riparian vegetation can appear outside of the functional areas derived from the Lidar-based DEM, and adding these areas of vegetation through "heads-up" digitizing as called for in Methods 5 and 6 can inflate the estimates of riparian area. The amount of post-processing to remove erroneous channels on flat lands and to correctly align channels can be daunting and very expensive (see Table 5 below).

Regardless of the dataset used to derive the DTM, the next challenge is to account for the riparian areas of first-order channels. One aspect of the challenge is deciding the minimum size channel to map. In this study, the smallest channels visible in the 1-m pixel resolution NAIP imagery were mapped if they corresponded to swales, draws, or other places where topography indicated a channel would likely form. Standardizing the DTM used to generate the drainage network and standardizing the resolution of supporting imagery will help standardize decisions about minimum mapping units.

Once a decision was made about the minimum size channel to map, the challenge became mapping all the small channels. This part of the study was coordinated with a related effort at the California State University at Northridge. Both studies found that mapping all first-order channels could take an impractical amount of effort. The problem stemmed from the fact that the 10m DEM, while very useful for creating a map of the rest of the drainage network, was too course to generate an adequate map of first-order channels. As a result, many channels generated by the DEM had to be edited, and even more channel has to be added by "heads-up" digitizing.

The following alternative to mapping all first-order channels was developed. It is recommended for use when an estimate of first-order riparian area will suffice without a map of all the associated channels. It is assumed that the total area to be mapped is at least as large as a Planning Watershed as defined by CalWater 2.0, or an 8-digit HUC as defined by the Federal system of watershed classification. The first step is to generate a drainage network from the 10m DEM. The second step is to select a number of fourth- or fifth-order drainage systems as "index areas" that reasonably represent the overall geology and topography of the total area to be mapped, and that together represent 5-10% of that area. All the first-order channels of the index areas are then mapped, using the minimum mapping units and ancillary data sets described in this study. The riparian area of these channels is then determined using whichever of the selected Methods 1-6. A series of tests are then conducted using the 10m DEM to see which threshold value for minimum cell array yields an automated map of first-order channels that most closely approximates the map produced for the index areas. The chosen threshold value is then used to re-generate the larger drainage network for the entire area to be mapped, and to estimate its overall number of first-order channels. This number of first-order channels is then multiplied by the average amount of riparian area per first-order channel in the index areas to estimate the overall amount of first-order riparian area.

Table 5: Acres of existing and potential riparian areas as indicated by different mapping methods, standardized against the method that provides the most accurate maps (Method 6).

Index Area	Method 1		Method 2		Method 3		Method 4		Method 5		Method 6		Method 7		Method 8		Method 9		Method 10	
	Acres	% of no. 6	Acres	% of no. 6	Acres	% of no. 6	Acres,	% of no. 6	Acres	% of no. 6	Acres	% of no. 6	Acres	% of no. 6	Acres	% of no. 6	Acres	% of no. 6	Acres	% of no. 6
Napa 1	248	10	6967	290	5633	235	1133	47	1203	50	2390	100	1824	76	2339	98	5382	225	NA	NA
Napa 2	121	7	4006	230	3821	210	1063	58	1122	62	1817	100	366	20	271	15	2972	163	NA	NA
Ventura	324	20	2314	143	1830	113	319	20	339	21	3824	100	3824	237	3824	236	885	55	NA	NA
Average		12		221		186		42		44	1615	100		111		116		148		NA

Note: Method 10 requires further development.

Table 6: Estimated costs for different methods used in this study to map existing and potential riparian areas.

Task	Method	Data Acquisition	Data Development (Digitizing, Model Running, etc.)		Post Processing (Line Editing.)	Total Costs
Develop Drainage Network Map	Lidar-based DTM	Labor: 2 hrs	Run Model to create DTM Labor: 8 hrs		Labor: 250 hrs	Labor: 260 hrs
	10m DEM	Labor: 2 hrs	Run Model to Create DTM Labor: 8 hrs		Labor:120 hrs	Labor: 130 hrs
Map Existing Riparian Areas	Method 1: Heads-up digitizing of distinct vegetation	Labor: 6 hrs	Labor: 200 hrs		Labor: 20 hrs	Labor: 226 + 130 = 356 hrs
	Method 2: Single Default Width	Labor: 6 hrs	Labor: 1 hrs		Labor: 8 hrs	Labor: 15 + 130 = 145 hrs
	Method 3: Multiple Default Widths	Labor: 6 hrs	Labor: 4 hrs		Labor: 8 hrs	Labor: 18 + 130 = 148 hrs
	Method 4: Method 3 Plus SPTH	Labor: 6 hrs	Set-up SPTH Tables Labor: 16 hrs		Labor: 8 hrs	Labor: 30 + 130 = 160 hrs
	Method 5: Method 4 Plus Method 1 (in part)	Labor: 6 hrs	Run Widths Model Labor: 16hrs	Heads-up Digitizing Labor: 10 hrs	Labor:8 hrs	Labor: 32 + 130 = 162 hrs
	Method 6: Method 5 Plus Hillslope Processes	Labor: 6 hrs	Run Widths Model Labor: 16hrs	Heads-up Digitizing Labor: 10 hrs	Labor: 8 hrs	Labor: 32 + 130 = 162 hrs
Map Potential Riparian Areas	Method 7: FEMA 100-yr Flood Map	Labor: 4 hrs	Extract land use Labor: 2 hrs		Labor: 0 hrs	Labor: 6 hrs
	Method 8: NRCS Soils map (in part)	Labor: 4 hrs	Extract land use Labor: 2 hrs		Labor: 4 hrs	Labor: 8 hrs
	Method 9: Geomorphic Model (GREM)	Labor: 3 hrs	Calibrate Model and Extract Land Use Labor: 100 hrs		Labor: 10 hrs	Labor:113 + 130 = 243 hrs
	Method 10: Hydro-geomorphic Model	Labor: 4hrs	Model Set-up Labor: 16 hrs		Labor: 4 hrs	Labor: 24 + 130 = 154 hrs

The drainage network maps for index areas provide evidence of the characteristic lengths, plan form geometry, and density of first-order channels. The estimates of average riparian area per first-order channel, average length of first-order channels, and the variability of these parameters can be reported with the estimate of overall first-order riparian area. This approach can more than halve the time required to estimate the total amount of riparian area in planning watersheds or 1:24000 scale quadrangles.

The time required to estimate the total first-order riparian area can also be reduced by involving mappers who recognize and understand the field conditions and processes they are mapping. The use of ancillary data, such as a soils map, vegetation maps, the 1:24000 scale DLG, slope maps, and software that allows the mappers to rotate the imagery on-screen can also reduce the mapping time.

Using the DLG road file to subtract areas of roadway from the riparian areas incurs the inaccuracy of the roadway positions relative to the channels (180). Although the drainage network derived from the 10m DEM was edited to fit the imagery, the DLG road file was not so edited. This means that the apparent overlaps between the road areas and the riparian areas are wrong to some degree. The amount of error in the overlaps has not been assessed. It is assumed that the actual overlaps are larger than measured in some cases, smaller in others, and that these differences cancel each other, such that the total amount of overlap is reasonably well represented for each watershed as a whole.

<u>Existing Riparian Areas</u>

Relative Accuracy

The comparative values for acres of riparian areas derived by the various approaches to mapping are summarized in Table 5 above. For each method, the results are standardized relative to Method 6, and the standardized values are averaged across the index areas.

For the three index areas, it can be inferred that the total amount of existing habitat is largely underestimated by only mapping the areas that are evidenced by indicative vegetation (Method 1). This is because much of the riparian areas support vegetation that cannot be distinguished from upland vegetation in the aerial imagery that is commonly available across the State. There are also riparian area that lack vegetation. The underestimates are lower for arid areas where the drainage networks are simpler and the riparian vegetation is more obvious. It is also apparent that the results of Method 1 can vary between mappers. This is exemplified by differences between the two versions of NWI maps recently produced for the Ventura Watershed. This study increased the NWI acreage for the Ventura Watershed index area by more than 20%. Acres of riparian area were added to the existing NWI through the review of the draft maps by local experts. This highlights the importance of involving local experts who know the field conditions and can help interpret the imagery.

The simpler buffering approaches over-correct the underestimates provided by Method 1. Using the high range of default widths from the literature, Methods 2 and 3 result in acreage estimates that are between about 186% and 230% greater that the most realistic estimates provided by Method 6. The application of a single large default width (Method

2) produces the largest over-estimates of all six methods to calculate existing riparian areas. These over-estimates are greater for the Napa Watershed in large part because it has many more agricultural ditches and pond margins that are grossly misrepresented by large default riparian widths. Default widths are probably less applicable to areas with abundant irrigation, unless the selected widths are very narrow.

Methods 4 and 5 both use the same conservative default widths for shrubs and grasslands, and the same species-specific SPTH values for forested areas. Method 5 adds areas of obvious riparian vegetation that appear outside of the default widths. Both methods tend to yield about half the expected riparian area for wetter conditions, and less than a quarter of the expected area for arid conditions. These underestimates are due mainly to the disregard of hillslope processes in steep terrain. They are much greater for Ventura Watershed for a number of reasons: the arid watershed has fewer ditches and other features for which the default riparian widths grossly over-estimate riparian area, and Ventura Watershed has many more channels draining steep terrain with broad areas of riparian hillslope processes that are ignored by Methods 4 and 5.

Although Methods 4 and 5 provide very similar results, the slight differences may be ecologically significant. Method 5 captures the existing riparian areas that are broader than the default riparian widths. These tend to be the larger riparian areas in the watersheds, and might therefore represent the more important areas to protect.

Method 6 mainly differs from the other five methods to map existing riparian areas by accounting for the riparian hillslope processes, such as mass wasting and natural water source area variability, that characterize steep terrain. The result is a map of riparian areas that expand in the upstream limits of the drainage networks. Of all the methods tested, this is perhaps the most radical deviation from conventional riparian mapping. Where the density of first-and second-order channels is especially high, Method 6 can indicate that more than 75% of the area between the upstream limits of the channels and the watershed boundary is riparian.

Relative Costs

The costs of the various approaches to mapping existing riparian areas are summarized in Table 6 above. All costs are in hours of labor for one 1:24000 scale quadrangle. Actual costs could vary greatly due to differences in wages and watershed complexity.

Each method to map existing riparian areas requires a base map of the drainage network. Cost estimates for the base map assume that it will be generated from the 10m DEM, with post-processing to produce detailed maps of first-order channels for two index areas. The index areas account for about half of the total cost for mapping the drainage network. The use of Lidar more than doubles the cost of the drainage network map because of all of the editing required to eliminate spurious channels and to add ditches and other engineered channels that aren't predictable from topography.

Of the six methods for mapping existing riparian areas, heads-up digitizing of riparian vegetation (Method 1) is most expensive. This is due to the time required to examine various datasets, including stereo aerial photography, while making enumerable decisions about the probable extent of faint riparian influences. The bias among mappers and their differences in experience can become very obvious in this method, since it relies on a combination of expert photo-interpretation and knowledge of field conditions. The wages of people with these capabilities tend to be above usual technician scale, which can aso increase the budget for Method 1. The cost estimates provided by NWI for riparian mapping are less that the estimates from this study, which probably reflects NWI's use of the basic DLG as a drainage network, its disregard of ditches, and its application of default widths for small natural channels.

Methods 2-6 are comparable in cost due to their common dependence on automated mapping procedures. Almost 90% of their costs are due to comprehensive mapping of drainage networks. Methods 5 and 6 incur an additional cost for developing look-up tables of default riparian widths and SPTH values.

Potential Riparian Areas

Relative Accuracy

The acres of potential riparian area derived by the various mapping methods are summarized in Table 5 above. All four methods can only provide very coarse estimates of the amount of uplands that could become riparian due to changes in the distribution of alluvial floodwaters. There is no "gold standard" forecast of likely flooding throughout any of the index areas or their encompassing watersheds that can be used to evaluate the efficacy of these methods. They can only be evaluated based on their agreement with general expectations about the possible distribution of riparian functions based on local knowledge of field conditions.

The 100-yr flood hazard map produced by FEMA (Method 7), excluding land uses that tend to be protected from flooding, is based on well-documented procedures, although they need to be modernized to incorporate new technologies and the existing maps need to be updated. The FEMA map includes all of the existing riparian areas within the modeled 100-yr flood boundary. But the flood hazard maps usually only pertain to large valleys and other places where substantial human life and property is threatened by flooding. The maps seldom extend into smaller tributary systems and therefore thee do not usually represent the potential riparian areas in watersheds as a whole.

The soils maps produced by the NRCS (Method 8) can be used to map potential riparian areas throughout most watersheds, but the areas are over-estimates of the extent of actual riparian conditions. The reason is that none of the soil types are specifically riparian, and many of the types that are associated with sedimentary fluvial processes extend far beyond the limits of existing riparian areas. These soil types can represent many millennia of natural channel migration across valley bottoms and alluvial fans. Even the most restrictive criteria for selecting "riparian and flood plain soils" yield a map that can grossly over-estimate the extent of potential riparian areas by including terraces and abandoned fans.

The GREM (Method 9) can provide a better map of potential riparian areas than standard flood hazard mapping (Method 7) because it can be applied to the smaller drainages to which Method 7 is seldom applied, and it does better than standard soils maps because it does not extend as far beyond the likely extent of floodwaters. However, the GREM largely over-estimates the potential riparian areas in low-gradient terrain where the topographic controls for the model are weak. It's less meaningful for these areas than the flood mapping (Method 7) because it does not use hydrological data or actual flood history to delimit flood boundaries. The GREM is best suited for confined channels in steeper terrain, where the valley floor and the maximum flood zone can be more or less synonymous. In these settings, the regionalized version of GREM provides a useful approximation of the potential limits of riparian conditions.

A combination of maps generated with the FEMA Flood Hazard Mapping, which works reasonably well for valley bottoms, and the GREM, which works reasonable well for the steeper tributaries, might be useful for entire watersheds. The problem is that there is no rule for setting the boundary between the two methods. Efforts to draft a rule based on topographic slope were fraught with inconsistent results.

Development of the hydro-geomorphic approach (Method 10) began late in the study, after the other methods had been developed and tested. The intent was to develop a rudimentary model of flooding based on regional correlations between drainage area and flood-prone width that could be used to inscribe flood-prone contours on the 10m DEM. The flood-prone height is conservatively calculated as twice the average bankfull height, as reported on the regional curves, rather than twice the *maximum* bankfull height, which is the convention (173, 174). The potential riparian areas might therefore be larger than what would be indicated by Method 10.

Method 10 assumes that the DEM provides a reasonable elevation for the channel bottom. The likelihood of this assumption being met decreases as the channel gets narrower, since this increase the chance the elevation data from the DEM will fall outside the channel. Variability in the regional correlations between drainage area and flood-prone height also provides some uncertainty in the model, as does any error of the hydrological data employed in the regional correlations. Correcting these deficiencies would require field surveys and flow studies that are not likely to be conducted throughout California in the foreseeable future.

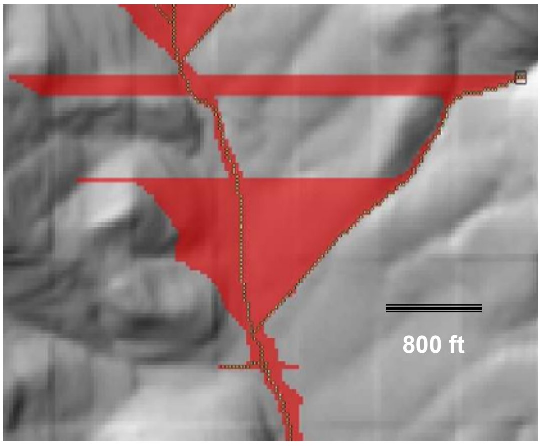


Figure 18: Example results from Method 10 showing places where the GIS and DEM do not adequately constrain flood-prone width.

Development of the hydro-geomorphic approach was halted before it could be adequately tested. A technical problem was encountered that could not be solved with the available funding. The problem has to do with the method used by the GIS software to trace the flood-prone contour on the DEM. The contour consists of a series of points indicated by the intersections of the DEM with horizontal lines drawn by the GIS at the flood-prone elevation from the midline of the channel. The GIS only allows these lines to be drawn to the east and west. Where the channel runs east or west, the lines can lead out of the channel and into space, as the channel runs downhill below the line. There is no limit to possible line length. Lines that leave first-order channels at high elevation can cross whole watersheds (Figure 18). As funds become available, the model will be revised to only run lines perpendicular to the channel. This should largely eliminate the problem of unconfined flooding.

Conclusions

This study compares a variety of methods to map existing and potential riparian areas using commonly available data sources and techniques that could be used by a variety of work centers to inventory the riparian areas throughout California.

The conservation and restoration of riparian resources throughout the State requires that they be defined commonly for all interests, and that the definition be broad enough to include the full range of riparian functions and conditions. The definition provided by the National Research Council (58) and adopted by the Riparian Habitat Joint Venture (RHJV) can satisfy these requirements. This definition is broader than others commonly in use, however. Vetting this broad definition with the large community of riparian interests will require outreach and education. While the RHJV does not intend for this definition and the associated mapping protocols to be used in any regulatory context, it also recognizes that such uses may evolve. This possibility creates a need for broad review of the meaning of the riparian definition in the regulatory context.

Existing riparian areas, potential riparian areas, and riparian buffers are distinct landscape features. Existing areas can be mapped based upon field indicators that are visible in commonly available aerial photography. Areas that are not distinctive can be estimated based on functional widths (i.e., the widths over which riparian functions are expected to occur according to the scientific literature). Buffers are portions of riparian areas that support selected functions, usually to protect adjoining aquatic resources. Potential riparian areas are uplands or historical riparian areas that are likely to be flooded due to management of water supplies or their natural variability.

The most important aspect of mapping existing and potential riparian areas is the development of a comprehensive drainage network that includes all channels, lentic features, and wetlands. The most cost-effective and broadly practicable method to map the channels is to use the USGS 10m DEM to generate a draft network that is then refined based on heads-up digitizing from high-resolution aerial imagery. The cost of estimating the total riparian area associated with first-order channels in a large watershed can be reduced by extrapolation from a sample of sub-watersheds. Remote sensing of riparian areas and the use of Lidar to develop a DEM are not cost-effective at this time because they incur very large costs for post-processing, validation, and editing.

The optimal method for mapping the existing riparian areas is basically a three step process: (1) apply default functional widths to channels, shorelines, and wetland edges based on the associated dominant vegetation; (2) adjust the widths by adding 1m for every 1% slope increase over a 20% slope threshold; and (3) revise the map produced at step 2 to include recognizable riparian areas that are outside the adjusted default functional widths. The default functional width for forested areas should be two SPTH. The default widths for shrubs and grasslands should be 10m and 5m respectively. Orchards should be treated as forests. Croplands should be treated as shrubs. This approach can provide a comprehensive inventory of riparian areas that recognizes their intrinsic ecological functions as well as their support and protection of terrestrial and aquatic resources.

The methods examined in this study to map potential riparian areas can only provide very broad estimates of the amount of uplands (including previous riparian areas) that might become riparian due to existing or possible future changes in the distribution of floodwaters. They provide examples of what can be done to map potential riparian areas throughout the State using easily developed or existing data. Existing FEMA maps of 100-yr flood hazards provide inexpensive, reasonable estimates of potential riparian areas in larger, low-gradient valleys. The GREM model can provide moderately expensive estimates for high-gradient areas. It may be most practical to employ Regional Hydraulic Geometry Curves (i.e., “Regional Curves) to estimate flood-prone contours on the 10m DEM. California is lagging behind other regions of the country in developing Regional Curves. Areas of land use that are not likely to be converted to riparian functions must be subtracted from the maps of potential riparian areas generated by any of these methods. Given the large assumptions and generalities of these models, they might best be used in initial surveys of riparian conservation and restoration opportunities.

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Appendix A: Selected Federal and State Agency Definitions of "Riparian."

Agency (reference)	Definition
National Research Council (57, 58)	*Riparian Areas are transitional between terrestrial and aquatic ecosystems and are distinguished by gradients in biophysical conditions, ecological processes and biota. They are areas through which surface and subsurface hydrology connect water bodies with their adjacent uplands. They include those portions of terrestrial ecosystems that significantly influence exchanges of energy and matter with aquatic ecosystems. Riparian areas are adjacent to perennial, intermittent, and ephemeral streams, lakes and estuarine-marine shorelines*
US Bureau of Land Management (60)	*A riparian area is an area of land directly influenced by permanent water. It has visible vegetation or physical characteristics reflective of permanent water influence. Lake shores and stream banks are typical riparian areas. Excluded are such sites as ephemeral streams or washes that do not exhibit the presence of vegetation dependent upon free water in the soil.*
US Fish and Wildlife Service (61)	*Riparian areas are plant communities contiguous to and affected by surface and sub-surface hydrologic features of perennial or intermittent lotic and lentic water bodies (rivers, streams, lakes, or drainage ways). Riparian areas have one or both of the following characteristics: (1) distinctively different vegetative species than adjacent areas, and (2) species similar to adjacent areas but exhibiting more vigorous or robust growth forms. Riparian areas are usually transitional between wetlands and upland.*
US Forest Service (62)	*Riparian areas are geographically delineated areas, with distinctive resource values and characteristics, that are comprised of the aquatic and riparian ecosystems, floodplains, and wetlands. They include all areas within a horizontal distance of 100 feet from the edge of perennial streams or other water bodies…. A riparian ecosystem is a transition between the aquatic ecosystem and the adjacent terrestrial ecosystem and is identified by soil characteristics and distinctive vegetation communities that require free and unbound water.*
US Forest Service Region 9 (63)	*Riparian areas are composed of aquatic ecosystems, riparian ecosystems and wetlands. They have three dimensions: longitudinal extending up and down streams and along the shores; lateral to the estimated boundary of land with direct land-water interactions; and vertical from below the water table to above the canopy of mature site-potential trees.*
US Department of Agriculture NRCS (64)	*Riparian areas are ecosystems that occur along watercourses and water bodies. They are distinctly different from the surrounding lands because of unique soil and vegetation characteristics that are strongly influenced by free or unbound water in the soil. Riparian ecosystems occupy the transitional area between the terrestrial and aquatic ecosystems. Typical examples would include floodplains, streambanks, and lakeshores.*
US EPA and NOAA Coastal Zone Management Act (65)	*Riparian areas are vegetated ecosystems along a water body through which energy, materials and water pass. Riparian areas characteristically have a high water table and are subject to periodic flooding and influence from the adjacent waterbody. These systems encompass wetlands, uplands, or some combinations of these two land forms. They will not in all cases have all the characteristics necessary for them to be classified as wetlands.*

Appendix A: Selected Federal and State Agency Definitions of "Riparian" (continued)

US EPA (53)	*Riparian Reserves are portions of watersheds where riparian-dependent resources receive primary emphasis and where special standards and guidelines apply to attain Aquatic Conservation Strategy objectives. Riparian Reserves include those portions of a watershed required for maintaining hydrologic, geomorphic, and ecologic processes that directly affect standing and flowing waterbodies such as lakes and ponds, wetlands, and streams.*
Forest Health Monitoring Group, US Forest Service (66)	*Riparian areas are three-dimensional eco-tones of interaction that include terrestrial and aquatic ecosystems that extend 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.*
Ca Wildlife Conservation Board.	*Riparian habitat is composed of the trees and other vegetation and physical features normally found on the stream banks and flood plains associated with streams, lakes, or other bodies of water.*
Ca Fish and Game Code (59)	*Riparian habitat means lands which contain habitat which grows close to and which depends upon soil moisture from a nearby freshwater source.*
US ACE Wetlands Regulatory Assistance Program (56)	*A vegetated upland or wetland area next to rivers, streams, lakes, or other open waters which separates the open water from developed areas, including agricultural land. Vegetated buffers provide a variety of aquatic habitat functions and values (e.g., aquatic habitat for fish and other aquatic organisms, moderation of water temperature changes, and detritus for aquatic food webs) and help improve or maintain local water quality. A vegetated buffer can be established by maintaining an existing vegetated area or planting native trees, shrubs, and herbaceous plants on land next to open waters. Mowed lawns are not considered vegetated buffers because they provide little or no aquatic habitat functions and values. The establishment and maintenance of vegetated buffers is a method of compensatory mitigation that can be used in conjunction with the restoration, creation, enhancement, or preservation of aquatic habitats to ensure that activities authorized by NWPs result in minimal adverse effects to the aquatic environment.*
Forest Ecosystem Management Team (53)	*Riparian Zone refers to those areas where the vegetation complex and microclimate conditions are products of the combined presence and influence of perennial and/or intermittent water, associated high water tables, and soils that exhibit some wetness characteristics." It is the "zone within which plants grow rooted in the water table of these rivers, streams, lakes, ponds, reservoirs, springs, marshes, seeps, bogs and wet meadow.*
Stanislaus National Forest (17)	*"he transition between aquatic and terrestrial ecosystems, characterized by distinctive vegetation which requires free or unbound water.*
Inyo National Forest (17)	*Geographically delineable areas with distinctive resource values and characteristics that are comprised of the aquatic and riparian ecosystems.*

Appendix A: Selected Federal and State Agency Definitions of "Riparian" (continued)

Tahoe National Forest (17)	*As a minimum, riparian areas are defined to be (1) areas a 100-foot horizontal distance from the edge of standing bodies of water; (2) areas a horizontal distance of 100 feet on each side of perennial stream channels; and (3) all wetlands." Riparian-dependent resources include: "those natural, intrinsic resources directly dependent upon the riparian area for their existence, including: water, fish, certain wildlife species, riparian related aesthetics, and riparian related vegetation" Streamside management zones "are administratively designated zones adjacent to perennial, intermittent, and in some cases ephemeral streams, and are designed to call attention to the need for special management practices aimed at the maintenance and/or improvement of watershed resources (e.g. water quality, channel stability). They may include wetlands, flood plains, riparian areas, inner gorges, perennial streams, intermittent streams, ephemeral streams, and the terrestrial ecosystem adjacent to these areas.*
Sequoia National Forest (17)	*Riparian area: includes the aquatic ecosystem, riparian vegetation, 100-year floodplain and Streamside Management Zone. The extent of riparian areas is directly affected by the steepness of stream side slopes, with the steeper slopes having the narrower habitat. Aquatic ecosystem: extends to the normal bank high water mark. Riparian vegetation: defined as vegetation communities that require free or unbound water. 100-year floodplain has a one percent chance of being flooded in any one year. This floodplain provides storage for flood flows, helps reduce the velocity and peak flow, moderates downstream flooding, reduces deposition of sediment in stream channels. The floodplain and the vegetation associated with it help reduce flood intensities.*
Eldorado National Forest (17)	*Riparian areas: consist of streamside ecosystems, aquatic ecosystems, wetlands and flood plains. Riparian encompasses all areas within a horizontal distance of 100 feet from both edges of perennial streams or other water bodies. Wet meadows are included in the riparian zone. Wetlands: included in total riparian area. Defined as: those areas inundated by surface or ground water with a frequency sufficient to support a prevalence of vegetation or aquatic life that requires saturated or seasonally saturated soil conditions for growth and reproduction. Includes marshes, wet meadows, alpine meadows, springs, seeps, potholes, river overflows and natural ponds, and may or may not be associated with Streamside Management Zone.*
National Wetlands Inventory, US Fish and Wildlife Service (5, 6)	*Riparian areas are plant communities contiguous to and affected by surface and subsurface hydrologic features of perennial or intermittent lotic and lentic water bodies (rivers, streams, lakes or drainage ways). Riparian areas have one or both of the following characteristics: 1) distinctively different vegetative species than adjacent areas, and 2) species similar to adjacent areas but exhibiting more vigorous or robust growth forms. Riparian areas are usually transitional between wetland and upland.*

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Appendix B: California Forest Practice Rules Stream Classes

Class I Watercourse: Domestic supplies, including springs, on site and/or within 100 feet downstream of the operations area and/or fish always or seasonally present onsite, including habitat to sustain fish migration and spawning.

Class II Watercourse: Fish always or seasonally present offsite within 1000 feet downstream and/or aquatic habitat for non-fish aquatic species, excluding Class III waters that are tributary to Class I waters.

Class III Watercourse: No aquatic life present, watercourse showing evidence of being capable of sediment transport to Class I and II waters under normal high water flow conditions after completion of timber operations.

Class IV Watercourse: Man-made watercourses, usually downstream, established domestic, agricultural, hydroelectric supply or other beneficial use.

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Appendix C: Data Types and Test Watershed Selection

Table 1: Matrix of mapping approaches and needed data. Mapping approaches were selected for this project by the RHJV Technical Committee. Bold approaches were expected to be most useful. The score for each data type equals its number of cell entries. Scores for bold approaches are doubled. The more important data types are the 10-m DEM and geo-rectified imagery.

Approach	Data Types									
	Historical Soils Maps	Current Soils Maps	Current Vegetation Map	FEMA Flood Zone Map	Current NHD or Digital Streams	Geology	**10-m Node DEM**	**Current 1-3m resolution geo-rectified imaging**	Updated NWI	Regional Bankfull Discharge Curves
Hydro-geomorphic Modeling[1]					X		X			
Vegetation Mapping[2]			X					X		
Flood Mapping				X	X		X	X		X
Soils Mapping	X	X				X		X		
Geology Mapping	X	X			X	X	X	X		
NWI[3]							X	X	X	
Integrated Approach[4]			X		X		X	X	X	
Data Type Score	2	2	3	1	5	2	**7**	**8**	4	1

[1] This refers to an approach developed through SCCWRP based on digital elevation models, and an approach by SFEI using regional hydraulic geometry.
[2] This refers to maps of vegetation based on the California Vegetation Manual.
[3] This refers to the method of riparian mapping published by the National Wetlands Inventory of the USFWS.
[4] This refers to the method developed by SFEI that combines the NWI method with a digital elevation model and vegetation map.

Appendix C: Data Types and Test Watershed Selection

Table 2: Matrix for selecting the Bay Area test watershed. Cell entries are the data type ranks from Table 1. A blank cell means that data type is not available for that watershed. The sum of the entries for each watershed equals its score. Napa Watershed scored the highest and was therefore selected as the Bay Area test watershed.

Criteria	**Candidate Bay Area Watersheds**									
	Coyote Creek	Alameda Creek	Sonoma Creek	Petaluma River	**Napa River**	Corte Madera Creek	Lagunitas Creek	Olema Creek	Wildcat Creek	Guadalupe River
Historical Soils Maps	2	2	2	2	2	2		2	2	2
Current Soils Maps	2	2	2	2	2	2	2	2	2	2
Current Vegetation Map					4		4	4		
FEMA Flood Zone Map	1	1	1	1	1	1	1		1	1
Current NHD or Digital Streams	6	6	6	6	6	6			6	6
Geology	2				2					2
10-m Node DEM	8	8	8	8	8	8	8	8	8	8
Current 1-3m pixel resolution geo-rectified imaging	9	9	9		9	9	9	9	9	9
Updated NWI					4					
Regional Bankfull Discharge Curves	1	1	1	1	1	1	1	1	1	1
Total Score	31	29	29	20	**39**	29	25	26	29	31

Appendix C: Data Types and Test Watershed Selection

Table 3: Matrix for selecting the Southern California test watershed. The criteria are the data types from Table 1. Cell entries are the data type ranks from Table 1. A blank cell means that data type does not apply to that watershed. The sum of the entries for each watershed equals its score. Ventura River watershed scored the highest and was therefore selected as the Southern California test watershed.

Criteria	**Candidate Bay Area Watersheds**				
	San Gabriel River	**Ventura River**	San Diego Creek	Escondido Creek	Carpinteria Creek
Historical Soils Maps	2	2	2	2	2
Current Soils Maps	2	2	2	2	2
Current Vegetation Map		4			
FEMA Flood Zone Map	1	1	1	1	1
Current NHD or Digital Streams	6	6	6	6	6
Geology	2	2	2	2	2
10-m Node DEM	8	8	8		8
Current 1-3m pixel resolution geo-rectified imaging	9	9	9	9	9
Updated NWI		4		4	
Regional Bankfull Discharge Curves	1	1	1	1	1
Total Score	31	**39**	31	27	31

Appendix C: Data Types and Test Watershed Selection

Table 4: The selected watersheds and their index areas correspond to Federal WED Levels 5-7, and California designations Sub-areas, Super Planning Watersheds, and Planning Watersheds, respectively.

Federal WBD Level	Federal Designations	Federal Hydrologic Unit Code	Federal Area (approx.)	State of California Designations	California Area (approx.)
Level 1	Region	2 digit	180,000 sq miles 115,193,577 acres		
Level 2	Sub-region	4 digit	16,844 sq miles 10,779,559 acres	Hydrologic Region	12,735 sq miles 8,150,000 acres
Level 3	Basin	6 digit (formerly "accounting unit")	10,600 sq miles 6,783,622 acres	Hydrologic Units	672 sq miles 430,000 acres
Level 4	Sub-basin	8 digit (formerly "cataloging unit")	703-1,735 sq miles 449,895 ☐ 1,110,338 acres	Hydrologic Areas	244 sq miles 156,000 acres
Level 5	Watershed	10 digit (formerly 11 digit in NRCS)	63-391 sq miles 40,000 to 250,000 acres	Hydrologic Sub-areas	195 sq miles 125,000 acres
Level 6	Sub-watershed	12 digit (formerly 14 digit in NRCS)	16-63 sq miles 10,000 to 40,000 acres	Super Planning Watershed	78 sq miles 50,000 acres
Level 7*	Drainage	14 digit	15 sq miles 10,000 acres	Planning Watersheds	5-16 sq miles 3,000-10,000
Level 8*	Site	16 digit	1 sq mile 650 acres		

* Levels 7 and 8 are extensions of the Federal designations for use at the local watershed level.

Appendix D Part 1

Minimum and Preferred Buffer Widths (m)
in Relation to Riparian Function

Function	Reference	Minimum Width (m)	Average	Maximum or Preferred width (m)	Average
Riparian Sediment Entrapment	7	5	12	45	77
	14	5		25	
	50	10		90	
	51	30		183	
	52	8		91	
	53	NA		1 SPTH (≈30)	
Riparian Chemical. Filtration or Transformer	7	10	12	45	116
	18	8		NA	
	50	4.5		60	
	51	30		262	
	52	4		183	
	54	15		30	
Large Woody Debris Input into Channel	13	8	40	15	78
	14	NA		25	
	39	60 or 1 SPTH (greater of two)		100 or 2 SPTH (greater of two)	
	49	1 SPTH (≈30)		2 SPTH or 90 (greater of two)	
	51	80		100	
	52	30		61	
	53	NA		1 SPTH (≈ 30)	
	76	1 SPTH (≈30)		200	
Leaf Litter Input into Channel	49	0.5	0.5	1 SPTH (≈30)	≈ 23
	53	NA		0.5 SPTH (≈15)	
Flood Control	7	25	16	70	65
	50	7.5		60	
Aquatic Life Support	18	NA	19	30	58
	25	20		110	
	50	18		33.5	
Bank Stabilization	7	5	14	15	25
	50	7.5		17	
	52	30		38	
	53	NA		1 SPTH (≈30)	
Bed Stabilization	7	NA	NA	45	45
Riparian Wildlife Support	7	50	41	150	162
	29	50		100	
	50	7.5		90	
	51	100		200	
	52	8		300	
	53	30		183	
	57	NA		100	
	104	NA		175	

Appendix D Part 1 (cont'd)

Minimum and Preferred Buffer Widths (m)
in Relation to Riparian Function

Function	Reference	Minimum Width (m)	Average	Maximum or Preferred width (m)	Average
Aquatic Habitat Cooling	10, 11	NA	19	15	41
	14	NA		23	
	15	NA		50	
	16	NA		100	
	38	NA		30	
	39	NA		30	
	49	NA		45	
	50	15		33.5	
	51	30		43	
	52	11		46	
	53	NA		1 SPTH (≈30)	
Riparian Climate Maintenance	39	90	70	150	129
	49	NA		45	
	53	1 SPTH (≈30)		3 SPTH (≈90)	
	51	100		200	
	52	61		160	
Overall Averages (m)			24		72

Appendix D Part 2

Minimum and Preferred Buffer Widths (m)
for Multiple Riparian Functions Excluding Wildlife Support

Reference	Minimum Width (m)	Maximum or Preferred Width (m)
10	50	100
19	15	30
20	15	200
21	35	60
24	20	100
25, 26	20	110
27	20	60
28 (cited in 24)	20	30
30, 31	3	30
32	10	20
33, 34	30	90
35, 36	15	100
24	15	90
37	20	100
24	30	90
Average Widths (m)	21	81

Appendix D Part 3

Average Minimum and Preferred Buffer Widths (m)
For Multiple Riparian Functions Including Wildlife Support

Average Recommended *Minimum* Multiple Function buffer width (excluding wildlife support) from Part 2 above	Average Recommended *Minimum* Buffer Width for Wildlife Support from Part 1 above	Average *Minimum* Buffer Width Recommendation for Multiple Functions Including Wildlife Support
21	**41**	**30**
Average Recommended *Preferred* Multiple Function buffer width (excluding wildlife support) from Part 2 above	Average Recommended *Preferred* Buffer Width for Wildlife Support from Part 1 above	Average *Preferred* Buffer Width Recommendation for Multiple Functions Including Wildlife Support
81	**162**	**121**

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Appendix E: Stepwise Instructions for Mapping Existing Riparian Areas

Note: this methodology will evolve through initisl implementation efforts.

I. Summary

For the whole area to be mapped, conduct the following steps.

1. Select 4th order or 5th order sub-watersheds as index areas that together comprise 5-10% of the total area to be mapped.
2. Generate a comprehensive drainage network including all 1st order channels, agricultural ditches, etc., using the 10m DEM.
3. Separate the channel network into two layers: (a) 1st order channels; and (b) all other channels (2nd order and higher-order channels).
4. Align the 2nd order and larger channels with the aerial imagery.
5. For all 2nd order and larger channels represented on the map by a single line, buffer each side of the line by 1.25m.
6. Create hillside slope layers in degree and percent, using 10m DEM.
7. Using existing vegetation data and reference materials, determine Site Potential Tree Height (SPTH) for each dominant tree species in the vegetation data.
8. Attribute the 2nd order and larger channels and other water bodies except natural 1st order channels with vegetation data (vegetation classes, tree heights, and standard buffer widths, accounting for SPTH and hillside slope angle).
9. For all 2nd order and larger channels and other water bodies except natural 1st order channels, calculate the riparian buffer width for forested riparian areas using the assigned SPTH values and hillside slope angle.
10. Use heads-up digitizing to add obvious riparian areas that were not included in the automated widths in Step 9.
11. Convert the riparian polygons created by Step 10 into a line feature (i.e., create outlines of the newly created riparian polygons).
12. Attribute the riparian outlines from Step 11 with hillside slope angle in percent.
13. Increase riparian widths by 1 meter for each increase in slope percent over 20% (e.g., increase the riparian width by 1 meter for 21% slope, 2 meters for 22% slope, 3 meters for 23% slope, etc).
14. Merge the results of Steps 10 and 13.
15. Conduct any additional editing or clean-ups of the GIS layers.
16. Clip to the boundary of the mapping extent. Check topology.
17. Select 4th order or 5th order sub-watersheds as index areas that together comprise 5-10% of the total area to be mapped.
18. For each index area, repeat steps 4-16 for 1st order channels.
19. Multiply the total number of 1st order channels in the whole area to be mapped (from Step 2) by average riparian area per 1st order channel in the index areas.

II. Data

Elevation data

USGS National Elevation Dataset (NED)

Download 10-meter NED for the area to be mapped.
http://seamless.usgs.gov/

Aerial Photography

Main imagery:

- National Agriculture Imagery Program (NAIP) true color imagery (2005) http://archive.casil.ucdavis.edu/casil/remote_sensing/naip_2005/ (As more recent NAIP imagery becomes available, this web site might change.)

Ancillary imagery:

- Color-infrared stereo pair imagery (e.g., National Aerial Photography Program (NAPP) imagery, National High Altitude Photography (NHAP))
- DOQQ
- Locally available imagery

Vegetation Data

- CALVEG (Classification and Assessment with LANDSAT™ of Visible Ecological Groupings) by USDA Forest Service
- Locally/publicly available and reliable vegetation data (Note: The quality of the vegetation data would affect the quality of riparian area buffer.)

III. Data preparation

Slope data (degree and percent)

1. If necessary, "Clip" NED data for the area to be mapped. (Note: "Export" option creates some noise in the output, so "Clip" is preferred for subset.)

2. Project the NED into appropriate projection (e.g., UTM NAD83). The projection to be used is preferably in meter unit (for creating slope data). Select "Bilinear" for Resampling option (Nearest neighbor option adds artificial lines in the output layers.)

3. Create Slope layers in degree and percent, using **Spatial /3D Analyst: Surface Analysis -- Slope...** Select Degree option for creating Slope Degree layer and Percent for creating Slope Percent layer. The output layers will be raster layers with slope values in float.

4. Round the slope degree and percent values, using Raster Calculator (ArcMap - Spatial Analyst – Raster Calculator). Round the slope values for each layer separately.

Use the script below in one line (the script is from ESRI support website):

G2 = INT(CON([FILENAME] > 0,CON(ABS([FILENAME] - INT([FILENAME])) >= 0.5,CEIL([FILENAME]),FLOOR([FILENAME])),CON(ABS([FILENAME] - INT([FILENAME])) >= 0.5,FLOOR([FILENAME]),CEIL([FILENAME]))))

Note: This script does the rounding of slope values and creates the raster layer G2 (in this case).

G2 = This is a temporarily created file, so if several rounds of this process have been done, make sure to change the name, e.g., to G3, G4, SlopeDegRound etc. because G2 may already exists, which will give you an error message.

[FILENAME] = file name (the name of the slope degree and slope percent layers.) If the name of the slope percent layer is "SlopePercent," then it should be [SlopePercent]. In Table of Content in ArcMap, the filenames can also be changed to an alias name.

5. Convert the raster layers with rounded slope degree values and rounded percent values (i.e., G2) into polygon layers. **(Spatial analyst – Convert..)** The output polygon layers should be (1) slope degree polygon layer and (2) slope percent polygon layer.

__**Stream channels with channel orders**__

1. Use Hydrology Tools (under Spatial Analyst Tools, ArcTools) and NED data to create stream channel lines.

   Hydrology tools: Fill, Flow Direction, Flow Accumulation, Stream Order, Stream to Feature

   Use elevation cell value of 114 to create stream lines from the 1st order and larger. (The elevation value 114 was calculated using two index areas in Napa watershed. Thus, this value might not be applicable for different regions. Testing different values would be recommended for different regions in order to obtain the best result for creating stream lines.) The stream line layer will contain channel orders in its attribute.

   (Alternatively, if the area to be mapped is a small area, requiring greater details, then, manually digitizing stream lines would be an option. Heads-up digitize and code the channel segments with appropriate channel orders (e.g., 1, 2, 3, etc) and habitat types (e.g., stream, ditch, etc). This will require a longer time to complete.)

2. Select all the 1st order channels from the stream channel layer and create a layer containing only the 1st order channels. Remove the 1st order channels from the original stream layer. Before removing 1st order channels, it may be a good idea to save an intact version of the entire stream channels as a back-up. The original stream line layer without 1st order channels will be used for Method 5 riparian habitat buffers.

3. Clean/edit both the 1st order channels and 2nd and higher channels for any erroneous lines.

   Note: The stream lines produced with the 10m DEM will not always align with the higher resolution aerial imagery used in "heads-up" digitizing of indicative riparian vegetation. The stream lines will therefore need to be adjusted to fit the imagery. The amount of adjustment will vary within and between watersheds.

Ponds/reservoirs

1. Use the existing pond/reservoir GIS layer (e.g., NWI layer's pond features or locally available data). (If pond/reservoir layer is not available, it might be necessary to allocate the time to digitize ponds/reservoirs.)

2. Create a line layer from ponds/reservoirs polygon layer. (ArcTool: Data Management Tools: Features: Feature To Line). The outlines of the ponds/reservoirs are created by Feature to Line process.

3. At this point, the stream line (2nd order and higher) and ponds/reservoirs could be merged. Streams and ponds/reservoirs should have separate codes (e.g., Channel order field can be added to ponds/reservoirs and assigned as "0" in the field so that pond lines can be separated from stream lines)

Vegetation data

Vegetation maps usually portray land cover types, plant communities, or plant assemblages that can be reclassified into the following basic categories Grass/Forbs, Shrub/Scrub, Woodland/Forest, Agriculture, Bare Soil. A default riparian width is assigned to each category except for Woodland/Forest (Table 1).

Table 1. Default Riparian Widths for Major Vegetation Categories

Category	Default Riparian Width (m)
Barren	1
Grass/Forbs	5
Agriculture	5
Shrub/Scrub	10
Woodland/Forest	SPTH assigned to dominant species
Unknown	Usually a tree species

Woodland/Forest category

Select a dominant tree species for each Woodland/Forest polygon. Based on the pertinent literature, assign a SPTH value (m) to each dominant species (e.g., Table 2 below). An average SPTH can be applied to mixed forests The SPTH values will be used to calculate the widths of forested riparian areas.

Table 2. SPTH values used in this study for Napa Watershed. The plant alliances are provided by the California Vegetation Manual

Map Unit Name	SPTH (m)
Black Oak Alliance	18
Blue Oak Alliance	6
California Bay - Madrone - Coast Live Oak - (Black Oak Big - Leaf Maple) NFD Super Alliance	12
Coast Live Oak - Blue Oak - (Foothill Pine) NFD Association	6
Coast Live Oak Alliance	12
Douglas-fir Alliance	20
Eucalyptus Alliance	20
Mixed Oak Alliance	6
Valley Oak Alliance	12
Winter-Rain Sclerophyll Forests/Woodlands Formation	15

Adding width and tree height in the table

There are two options.

1. A separate table can be created, with the fields containing vegetation classes, tree heights, and standard riparian widths for each plant cover category. For categories not dominated by trees, the value for tree heights is "0." For the categories dominated by trees, the data field for standard riparian width is left blank. This table saved in dbf file format can be joined later to the stream line layer attribute file after stream lines are intersected with the vegetation layer (this process is covered in the later section).

   One problem that might occur with this option is that sometimes the vegetation class names can be very long, and the dbf format file often truncates long names. This causes some vegetation classes to have no tree height assignment, if vegetation class name was to be used as the common field to join tables. To prevent this problem, vegetation class needs to be renamed with some foreshortened code or ID.

2. Create new fields in the existing vegetation data layer for standard riparian widths and SPTH values. Thus, when the stream line layer is intersected with the vegetation data layer, SPTH values and standard riparian widths are automatically transferred to the map.

IV. Details of Method 5 As Required to Conduct Method 6

Adding vegetation and slope degree data to streams and ponds/reservoirs

"Intersect" the line layer containing channel lines and ponds/reservoir shorelines with the vegetation data and slope degree layer in the following order:

1. stream/pond line layer;
2. vegetation layer;
3. slope degree layer

The output line layer will have attributes containing vegetation class names, SPTH values, and the standard riparian widths.

Calculating riparian width for Woodland/Forest type

1. Add new fields in the attribute of the stream line layer from above, with vegetation and slope values. These new fields will be used to input riparian width (e.g., "M5Buf") and actual width to be used (i.e., the width incorporating the width of stream channels. e.g., "M5BufDist").
2. Select the non-Woodland/Forest classes and assign "M5Buf" field with the standard width values. Select the Woodland/Forest classes and assign the riparian width in the "M5Buf" field with the values calculated with the formula below:

   ([TreeHT] * 2) - (([TreeHT] * 2) * Sin ([SlopeDegree] * 0.0174532925))

   Note: when there are many records, the "calculation" using above formula sometimes does not work properly. If the calculated values look just like the tree heights, then break up the formula into 2 sections as follows:

   Part 1: (([TreeHT] * 2) * Sin ([SlopeDegree] * 0.0174532925))

   Part 2: + ([TreeHT] * 2)

   Note: the values calculated from **Part 1** can be temporarily stored in "M5BufDist" and the calculation from **Part 2** should be "M5BufDist" **+ ([TreeHT] * 2),** where the values are calculated and assigned to the field, "M5Buf.")

   Note: the calculated values should be spot-checked for accuracy.

2. After riparian width field (e.g., "M5Buf") is assigned with values (no NULL values in "M5Buf" at this time), then "calculate" the values used for the actual buffering operation – i.e., riparian width + stream channel buffer (1.25m). Assign the values in the second field (e.g., "M5BufDist").

Buffering riparian habitat areas

Buffer the stream line using the values stored in the attribute field, containing riparian width + channel width (e.g., "M5BufDist"). Select the option for merging all the fields. The output polygon is one riparian area.

<u>Heads-up digitizing of additional riparian habitat areas</u>

1. Using NAIP, other aerial photography (stereo pairs), Google Earth, and any other ancillary data, digitize indicative riparian vegetation patches that are not included in the results thus far obtained.
2. Merge all results into one riparian layer. This completes Method 5.

V. Details of Method 6

<u>Adding slope percent data to the Method 5 polygons</u>

1. Create line feature layer from the riparian polygon created in the last stepof Method 5 (use the "Data Management Tool - Feature to Line"). The line will be the outer line of the riparian polygon created by Method 5.
2. Intersect the riparian outline layer with slope percent polygon layer. The riparian outline layer will be attributed with slope percent values.

<u>Buffering riparian areas based on percent slope</u>

1. Add a new field in the riparian outline layer (e.g., "SLPerBuf")
2. Select GRIDCODE < 21. Calculate "SLPerBUF" = 0.

Note: GRIDCODE is most likely the field name containing slope percent values, but this needs to be checked. The line segments containing slope percent values from 0-20. Places with 0 values will not be buffered.

3. Switch Selection (i.e., GRIDCODE > 20).

Note: switch selection can take longer than just re-selecting by GRIDCODE > 20.

While the line segments with the slope percent values more than 20% are selected, Calculate: SLPerBuf = GRIDCODE – 20. SLPerBuf field should not have any NULL values at this time.

4. Buffer the line layer, using the values in the field SLPerBuf. Select the option for merging all the fields. The output polygon is one riparian area polygon created using the slope percent.

<u>Merging Method 5 and 6 riparian buffer polygons</u>

1. Merge the riparian polygon layers from Method 5 and 6 (ArcTool: UPDATE)
2. Update the combined layer with stream and ponds/reservoirs layers and wetland layers (ArcTool: UPDATE)
3. If necessary, "clip" the layer (Method 5 & 6, streams and ponds/reservoirs and wetlands) by the study area boundary.

<u>Additional notes</u>

1. Intersecting polygon or line layers with a large slope degree or percent layers may cause some problems (e.g., ArcMap crash/freeze) or may simply take a

very long time. It may be necessary to do the operations in smaller portions (e.g., in a couple of sub-watersheds at a time), depending on the size of the area to be mapped.

2. Buffering and merging polygons also may or may not take a long time, depending on how complex or large is the area to be mapped.

VI. 1st order riparian area estimation

Mapping 1st order channels can be very time consuming and costly. When mapping all the 1st order channels in the study area is not feasible, then the following approach can be used to estimate the total amount of 1st order riparian area from a sample.

1. Use the stream line layer from containing only the 1st order channels.
2. Select 4th order or 5th order sub-watersheds as index areas that comprise between 5-10% of the area to be mapped.
3. Within the boundaries of the index areas, conduct the same steps described above (from Section **II.** to **V.**) to create Method 5 and Method 6 riparian areas for the 1st order channels of the index areas.
4. For all index areas combined, calculate the average riparian area per 1st order channel.
5. Using the stream line layer containing all the 1st order channels for the entire area to be mapped, obtain the total number of 1st order channels.
6. Multiply the total number of 1st order channels by the average riparian area per 1st order channel calculated for the index areas. The product is an estimate of the total riparian area for the entire area to be mapped.