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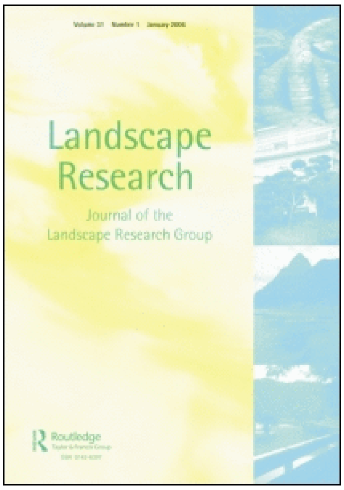

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Relative Elevation Topographic Surface Modelling of a Large Alluvial River Floodplain and Applications for the Study and Management of Riparian Landscapes

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ABSTRACT *This paper presents a novel and useful spatial modelling technique to create a topographic surface that estimates a floodplain's elevation relative to the average low-flow water surface elevation of a river channel. This model was applied to a 121 km study area of the middle Sacramento River, California, USA, where it was tested as a surrogate for observed water table depth and an observed 3.3 year recurrence interval flood inundation surface using independent data sets. The modelled relative elevation topographic surface correlated significantly* ($p < 0.005$) *to observed well water depths suggesting that the modelled surface reflected a reasonable approximation of vertical distance to the water table. Results from a flood inundation pattern analysis indicated an overall accuracy of 79% for correctly predicting inundated and non-inundated zones. The model was then used to measure relative channel bank height and the distribution of riparian plant communities to examine landscape ecological relationships.*

KEY WORDS: Spatial modelling, restoration design, depth to water table, flood inundation, plant community distribution, bank height, channel meander migration, Sacramento River

Introduction

Riparian landscapes are dynamic heterogeneous environments where plant communities are often responding to both surface and sub-surface water patterns (Malanson, 1993; Naiman *et al.*, 2005). For strategic management of riparian resources, managers and scientists frequently use three basic types of physical information to plan and design ecological field studies and/or restoration projects on rivers: 1) detailed land surface topography and channel bathymetry; 2) surface water flooding patterns of various seasonal hydro-periods or recurrence intervals; and 3) groundwater depth (National Research Council, 2002; Gordon *et al.*, 2004). Of these three, land surface topography is probably the most commonly used and most

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readily available data type whereas bathymetric data and the other two data types are usually unavailable and expensive to acquire at site planning spatial scales. Relative elevation modelling of floodplains from topographic maps is a potentially useful tool to gain insight into these variables and therefore the structure and function of riparian landscapes (Poole *et al.*, 2002).

This paper presents an efficient and economical topographic modelling approach to derive coarse surrogate estimations of both surface water inundation patterns and water table depth in large alluvial river systems for the purpose of rapid assessment, field sampling, site planning and riparian plant community restoration design. In essence, we developed a method using a geographic information system (GIS) to convert a conventional topographic map based on a single vertical datum at mean sea level (MSL) to a map based on a series of vertical datums located along the edge of the river's water surface at average low-flow conditions to create a 'relative elevation' topographic map of the floodplains. We then correlated the modelled relative elevation topographic surface with key geomorphic, hydraulic, and ecological attributes of the river. Mapping relative topographic position has many potentially useful applications for studying basic and applied landscape ecology of rivers and floodplains. The method could also contribute towards better defining 'hydrogeologic settings' of river floodplains for resource assessment (Bedford, 1996).

Study Objectives

The objectives of this paper were to: 1) calculate a relative elevation topographic surface model of the floodplains of a large alluvial river using a 50-year average of dry season low-flows as the basis for a series of datums at the edge of the water surface; 2) assess the efficacy of the relative elevation map to predict water table depth and flood inundation patterns; 3) measure the relative elevations of channel bank heights; and 4) derive relative elevation relationships for plant communities as a surrogate for water table depth relations. The modelling methods, error assessments, and ecological relationships provide important information to scientists and managers for assessing and measuring riparian ecological landscape attributes and geomorphic characteristics over wide spatial scales.

Background

Below we discuss some important considerations for each of the three hydro-geo-information types discussed above. Data sources and collection methods for observed and modelled data are presented. General data availability, expense, and common geospatial data structures are also discussed.

Topographic Information. A fundamental planning and analysis tool for land planning is topographic information. It is used to document existing conditions and as a basis for designing or manipulating topography for a particular function. Topographic data are widely available from government agencies and cover geographically extensive areas in both analogue (paper) and digital products. However, the limiting factor in the usefulness of those data to any particular planning application is having adequate vertical and horizontal spatial resolution. Agencies such as the US Geological Survey (USGS) distribute digital elevation models (DEM) as quadrangles at a variety of cell resolutions in the raster GIS data format. Most of these quadrangles have coarse resolution (30 m cell size or 0.09 ha) and therefore have limited site level planning applications. However, 10 m cell resolution (0.01 ha) is now available in many areas and is more suitable for more detailed site planning applications.

Whereas DEMs are topographic data sets distributed in a raster-based format, a regularly spaced grid of points or pixels, topographic data sets can also be constructed from a set of irregularly spaced points, known as a triangulated irregular network (TIN) which uses a vector-based format (ESRI, 1994). A TIN model is an efficient and accurate surface-generation tool and a TIN surface can be converted to raster format for subsequent analysis using cartographic modelling techniques with tools such as the Spatial Analyst extension in ArcGIS (ESRI, 2003).

Surface Water Flood Inundation Patterns. Another critical element in planning riparian restoration projects or field studies is an understanding of flood flow inundation patterns and frequency at the site under investigation. The physical processes of scour and inundation are known to structure riparian plant communities and increase landscape heterogeneity (Malanson, 1993; Naiman *et al.*, 2005). Flooding tolerance is a function of an individual species life history characteristics, thus sites with greater inundation frequency require plants adapted to these conditions.

Flood frequency of river flow is characterised with the use of extreme value statistical analyses using annual flood peak data from a single gauge station, and are commonly characterised by recurrence intervals (RI). The most frequently used and most readily available RI spatial data in the US are the 100-year flood maps, updated and distributed by the Federal Emergency Management Agency (FEMA) in both paper and digital versions. Existing geospatial data of recurrence interval flows *less* than the 100-year flood (e.g. two-year, five-year, or ten-year floods) are very rare for most river systems unless a special effort was made to collect or model those conditions. Unfortunately, the more frequent flows are the most important types of flows to consider in riparian restoration and field studies because they have strong influence on the spatial distribution of plant communities.

As indicated above, flood inundation maps at various recurrence intervals, especially two–five year events, are usually not available at broad spatial scales and they are expensive to acquire for site-level riparian restoration planning and design. However, these data can be acquired through direct observation and through geospatial modelling techniques. Direct observation techniques include: 1) gauge station records that record river stage information at regular time intervals; 2) remote sensing imagery of floods while they are occurring (such as LIDAR, thermal mapping, and traditional aerial photography); and 3) personal observation through ground level photography during a flood event or debris mapping after a flood event.

More commonly, flood flow inundation patterns are modelled using hydraulic analysis software that utilise cross-section data frequently derived from topographic and bathymetric maps. Some examples of popular software packages for computing flood depth and inundation patterns are: HEC-RAS and HEC-GeoRAS developed and distributed by the Hydrologic Engineering Center of the US Army Corps of

Engineers (USACE, 2002b; Ackerman *et al.*, 2000) and MIKE 11 developed and distributed by the Danish Hydraulic Institute. The accuracy of the results can be variable depending on the quality of the input data (e.g. topographic and bathymetric map spatial resolution, and gauge station measurements) and construction of an adequate model with sufficient cross-section density. These software packages require personnel with special training in their use and proper operation. As a result, obtaining these data can be very costly and exceed the budgetary constraints of most typical small-scale river or creek restoration projects.

Groundwater. Riparian obligate plants are dependent on groundwater resources for long-term survival, growth, and reproduction. An important groundwater consideration for studying riparian ecology is the depth to the water table. Many hydrologists and geomorphologists assume that the water table (excluding perched water tables) of an alluvial river system is related to the water surface elevation of the channel (Figure 1a, b). For riparian obligate plants the depth to the water table at base-flow is important (National Research Council, 2002). Base-flow in a natural channel is the fraction of channel flow attributable to groundwater during the dry season (Gordon *et al.*, 2004). The water table level is a dynamic zone responding to surface infiltration and the fluctuations of flow within the channel over time. The zone of aeration from the floodplain land surface down to and including the

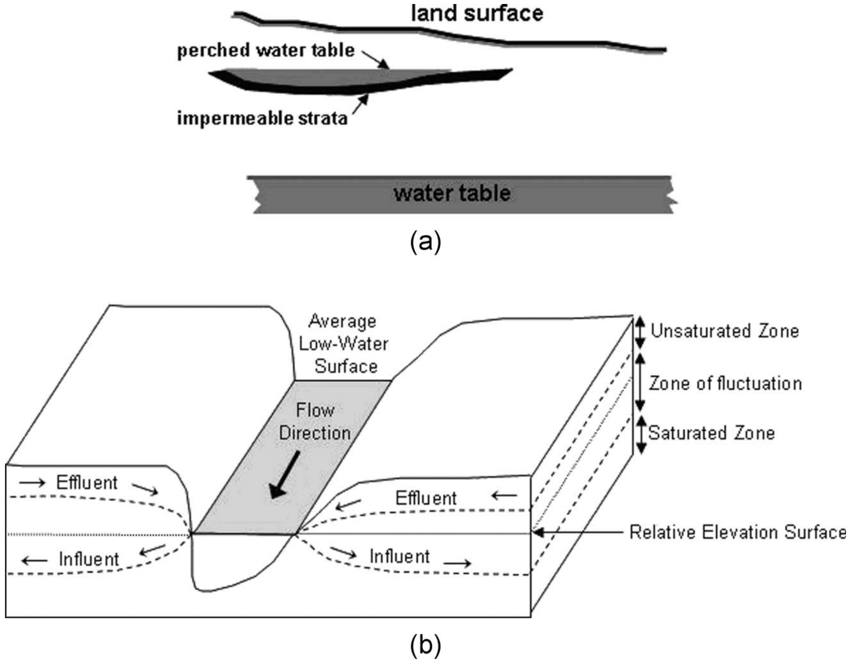

Figure 1. Water table concepts in profile. a) A cross-section showing a perched water table and the main water table (unconfined aquifer). b) The level of a water table is influenced by channel base-flow or low-flow conditions and whether it is located in a gaining (effluent) or losing (influent) reach.

capillary fringe of the water table is known as the vadose zone (Bedient & Huber, 2002). It is also known to fluctuate in response to numerous variables (e.g. rainfall and stream flow). Secular variations of groundwater levels are those observed over long time periods (Todd & Mays, 2005).

This dynamic pattern of change in aerated and saturated zones underground can be further characterised by whether the channel is a gaining reach (i.e. effluent) versus a losing reach (i.e. influent) in relation to the water table (Figure 1b). In the case of a gaining stream segment, the water table depth is expected to be somewhat elevated relative to the base-flow in the channel, and the opposite would be true for a losing stream reach (Todd & Mays, 2005). Generally, flow regulation by dams decreases the peak flow of storm events and increases flows during dry periods. In turn, flow regulation in streams during naturally low-flow conditions in the dry season of the semi-arid western US can affect whether a stream is effluent or influent depending on the stage of the flow released by the dam operators. During periods of large conveyance, a stream channel reach may switch from being an effluent stream to one that is influent. In addition, the presence of perched water tables can further complicate predicting local water table depth. Thus, the water table depth at any one place in the floodplain of a typical alluvial river is highly time-dependent and location-dependent.

Groundwater data can be obtained from direct observation through drilling wells and measuring water levels over time (e.g. using piezometers). Various groundwater modelling approaches have been developed, such as MODFLOW by the US Army Corps of Engineers (Harbaugh *et al.*, 2000), however, they require numerous well sites and observation logs to calibrate and operate the model effectively. Wells are costly to install, maintain, and monitor, especially if the alluvial river system has large and extensive floodplains. Also, attaining the proper spatial resolution of wells (i.e. density) to capture the geological variation would be in most cases prohibitively expensive. A groundwater model is therefore a large investment and beyond the scope of most small-scale project budgets. In the absence of a groundwater model we present a method to model relative elevation that could be used as a general surrogate for water table depth.

The 'Relative Elevation' Concept

Conventional topographic maps are usually created based on a single vertical datum located at mean sea level (MSL). By nature, the MSL elevations of river channels and floodplains generally trend downward (toward the sea) and obscures the relationship between floodplain surface and river channel water level elevations. We developed a method to remove that downward elevation trend by subtracting the floodplain MSL elevation from the nearest channel water MSL elevations (Figure 2). In this study we define the relative elevation of a local floodplain site for a natural (un-dammed) river as the local land MSL elevation minus the weighted average of the nearest dry season base-flow channel water surface MSL elevations, giving greatest weight to water surface MSL elevations closest to the floodplain site in question. However, in the case of flow-regulated rivers by dams that technically do not have a base-flow, we modify the above relative elevation definition and substitute the term 'average *low*-flow' for base-flow. Using either definition the result is that the

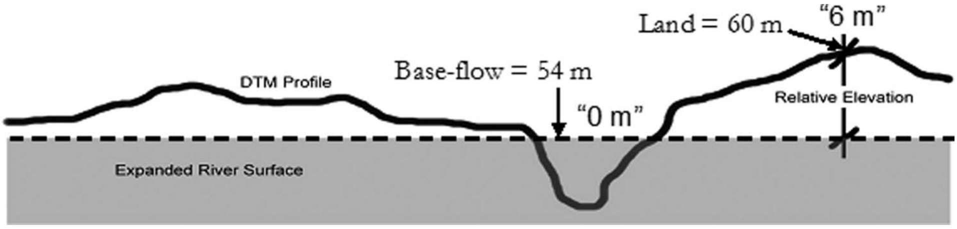

Figure 2. The relative elevation concept. The base-flow or average low-flow conditions water surface elevation of the channel (e.g. 54 m, shown as a dashed line) using mean sea level (MSL) as the datum for the elevation units is used as a local datum to subtract the local land elevation surface value from (e.g. 60 m at MSL, as depicted), in order to derive land elevation values relative to the local datum (e.g. 6 m, as shown in quotes). The relative elevation of the water surface of the main channel has a calculated value of zero (m), as shown in quotes, along its entire length.

water surface elevations are calculated to a value of 'zero' and the floodplain (land) elevations are calculated as positive vertical distance values above the nearest set of local channel water datums (using a weighted average). To summarise, the conventional topographic map is de-trended using a series of datums associated with the surface elevations of low-flow channel water. We believe the long-term average low-flow conditions of a regulated river best represents one of the key physical conditions that woody riparian plant communities have responded to for their establishment.

Relative elevation has been defined in various ways by other investigators. In a study by Turner *et al.* (2004) relative elevation was defined as a floodplain within or outside the 100-year flood recurrence interval. They found that a significant relationship existed between relative elevation and the spatial distribution of several riparian tree species. In a study by Poole *et al.* (2002) relative elevation was defined as "the difference in elevation between any point on the flood plain and any given (though arbitrary) river stage" (p. 335) and they found significant relationships to explain the distribution of several land cover types including vegetation communities. Land surface elevation relative to base-flow is also an important variable in determining the potential for primary succession in rivers as described in the "recruitment box" theory by Mahoney and Rood (1998). This is discussed further in the riparian landscape ecology and discussion sections below.

Fluvial Geomorphology Application

River scientists and restorationists need tools to help them measure and interpret channel and floodplain features and how they change over time (Kondolf & Piegay, 2003). A relative elevation topographic model, using our definition for a natural or regulated river, can be used to measure geomorphic characteristics in meandering rivers, such as local, average, and maximum bank height. Bank height has been shown to be an important factor in simulating bank erosion (Hasegawa, 1989). Bank height is considered an important variable in predicting the rate of plan-form migration of river channels in alluvial systems (Howard, 1992, 1996). There have been no efficient means of measuring and characterising bank height in meandering rivers and researchers have primarily relied on costly field measurements for these data. For these reasons, bank height has been ignored in some numerical meander migration models (i.e. Johannesson & Parker, 1989; Howard, 1996; Larsen *et al.*, 2006). With the relative elevation model presented herein, these data could be readily available for use in modelling bank erosion and channel migration.

Riparian Landscape Ecology

Riparian landscapes are highly heterogeneous land areas that form as a result of a multitude of interacting terrestrial and aquatic (lentic and lotic) processes (Malanson, 1993; Naiman *et al.*, 2005). To survive, obligate riparian plant species utilise groundwater resources in the dry season (especially in the arid western US), however, they must also survive the effects of scour and flood inundation during the wet or rainy seasons. This interaction of processes can produce complex landscape mosaics with high structural diversity that is associated with high vertebrate species richness (Gregory *et al.*, 1991; Knopf & Samson, 1994; Fisher, 1995).

To effectively manage habitat resources in wildlife refuges, managers and scientists often desire the ability to predict changes in vegetation as a result of changes in water table levels (Malanson, 1993; Baird, 1999a). Two relatively new fields integrating water relations and biological systems are 'eco-hydrology' which examines the broad phenomena covering all wetland types (Baird, 1999a, 1999b; Wilby, 1999) and 'hydro-ecology', which specialises in rivers and floodplain systems (Petts *et al.*, 1995; Petts & Bradley, 1997). There has been extensive past work relating water table depth to plant distributions by examining realised niche space in relation to mean water table depth (Pautou & Decamps, 1985) and a good example is a study of the plant distribution on the Upper Rhone River conducted by Bravard *et al.* (1986). The results of these types of studies are often depicted as a chronosequence or idealised toposequence or box plot diagrams showing zonation and distribution patterns.

A review by Wheeler (1999) on the relationships between wetland vegetation and water tables noted that many wetland studies have been conducted to relate water table levels to plant distribution but were unsuccessful because of the nature of the oscillations in water depth over time (both intra- and inter-annually). Large fluctuations in duration can exceed the niche breadth of a plant species and cause significant mortality. Wheeler (1999) suggests these types of studies are best in situations where low water levels are thought to control the distribution of vegetation, as is the case in our study. Wheeler (1999) identified five reasons it is difficult to derive these relationships: 1) correlative procedures assume equilibrium between vegetation and water regime; 2) water table behaviour is complex and difficult to characterise; 3) soil moisture can be more important to describe species distributions than water table depth; 4) most studies examine established plants as opposed to conditions that affect recruitment; and 5) other factors, such as lateral flow, redox potential, and competitive interactions.

These factors are reasonable limitations. Other variables are also important in fluvial systems, such as floodplain age (Greco, 1999; Fremier, 2003; Greco *et al.*, 2007), surface water scour, and inundation (duration and frequency). Timing of establishment criteria for recruitment of species such as *Salix* spp. and *Populus* spp. (the willow – cottonwood floristic association) is especially important to understanding the spatial distribution of those communities (Mahoney & Rood, 1998). Depth to groundwater is a secondary variable since establishment is first determined by geomorphic and flow parameters near the active channel. Then as the floodplain evolves (aggrades or degrades), depth to the water table changes and plants must be able to adapt to those new conditions. Some species such as cottonwood respond to these changes by growing adventitious roots.

Methods

Study Area

The Sacramento River is the largest river in the state of California and is a critically important resource both economically and ecologically (Kelley, 1989). The middle Sacramento River is a large, low-gradient alluvial river that has wide floodplains and a primarily single-thread, meandering channel (Figure 3) (Greco & Plant, 2003). Its flow is regulated by Shasta Dam, the largest dam in California. A major concerted effort to conserve and restore riparian plant communities (see Vaghti & Greco, 2007) in the middle reach between the cities of Red Bluff and Colusa is being undertaken by numerous state, federal and private agencies because it contains the largest remnant forests remaining in the system, and limited hydro-geomorphic processes still operate despite the regulation of flows (CALFED, 2000; California Resources Agency, 2000). It is estimated that 95% of the riparian forests in California's Central Valley have been lost since 1850 (Katibah, 1984; Bay Institute, 1998; GIC, 2003).

A river-mile point marker system for the Sacramento River was created by the Army Corps of Engineers many decades ago. River-mile (RM) zero is located at the confluence of the Sacramento with the San Joaquin River in the San Francisco Bay Delta, and upstream, RM 302 is located at Keswick Dam on the main stem channel north of the city of Redding. Given the constantly migrating nature of the channel in the middle reaches, this point marker system no longer accurately measures the length of the river and presently acts as a widely used geographic place name and reference system by managers, scientists, and engineers.

In this study we used two study area extents. The overall extent of the study reach was from RM 143–218 (121 km) for all the analyses except flood inundation. The flood inundation analysis was limited to RM 182–218 (Figure 3c).

Constructing a Digital Elevation Model (DEM) of the Study Area

The most resolute topographic data of the middle Sacramento River from RM 143 to 218 were obtained from the US Army Corps of Engineers Sacramento/San Joaquin River Basins Comprehensive Study collected in 1997 (USACE, 2002a). The Army Corps map data included two-foot land contours, and also included two-foot contour intervals of the main channel bathymetry that were collected with sonar

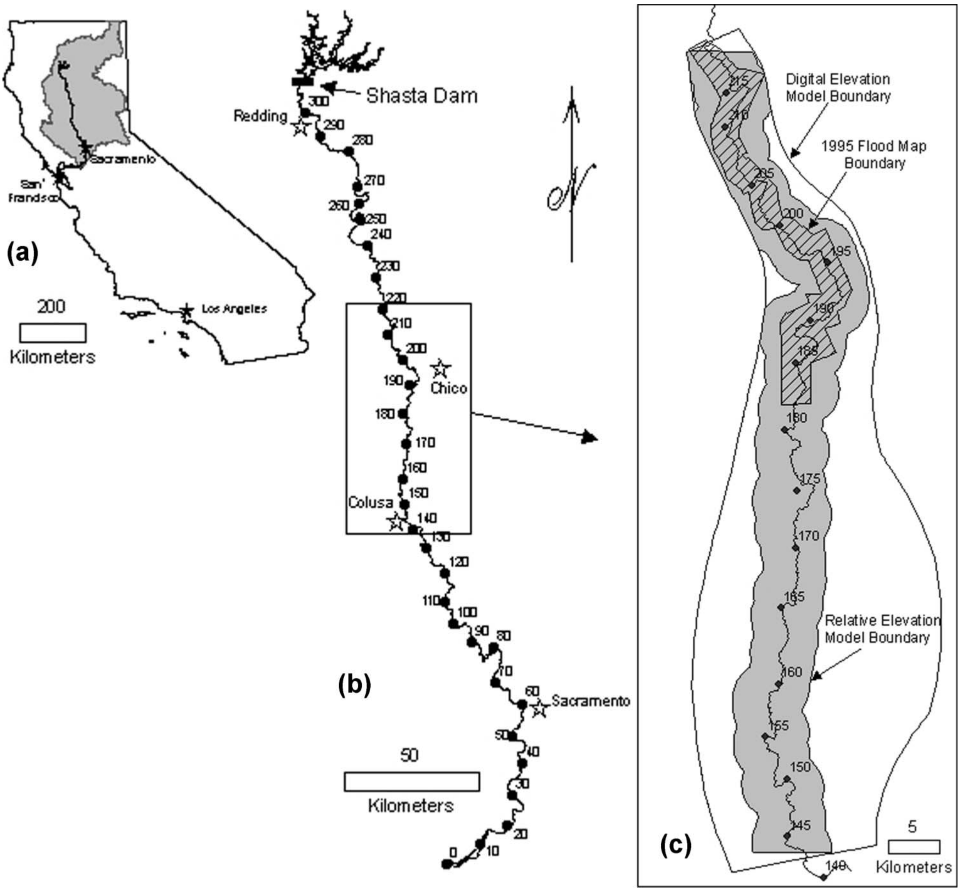

Figure 3. Location maps of the Sacramento River and the study areas. a) The Sacramento River and its watershed (grey tone) within the state of California. b) The Sacramento River is shown in 10-mile increments from river-mile 0 in the San Francisco Bay Delta to river-mile 300 near Shasta Dam. c) Study area boundaries: the raster digital elevation model boundary (no fill), the relative elevation model boundary (grey tone), and the observed 1995 flood map boundary (hatched pattern). River-miles are shown in five-mile increments.

technology and spliced into the traditional land survey. The contour and spot elevation data were interpreted with the TIN module in ArcInfo (version 8; ESRI, 2003) and then converted to a floating-point, 1 m cell spatial resolution (0.0001 ha) raster digital elevation model (DEM). The DEM was converted to integer values with z-values in centimetres to preserve the sub-meter elevation accuracy of the floating point raster data.

To cover floodplain areas outside of the US Army Corps Comprehensive Study boundaries, USGS DEMs were utilised at cell resolutions of 10 and 30 m (1978 source date) and were resampled to 1 meter cell resolution. The DEM was then clipped to exclude the 1997 US Army Corps Comprehensive Study area, leaving a 4 m (4 cell) overlap. The Army Corps DEM raster data were then combined with the

USGS DEM raster data using the MOSAIC command in the ArcInfo GRID module. Using the MOSAIC command allowed for cell-value averaging in the four-cell overlap area between the two DEM data sources.

This process was used to successfully construct a conventional raster digital elevation model of the study reach based on a single datum at mean sea level. The 1 m cell resolution DEM was resampled to 10 m cell resolution for computing the relative elevation surface map (Figure 4).

Relative Elevation Modelling

The geographic boundary for this analysis was defined as a three km buffer around a 1997 main channel centerline of the Sacramento River (river miles 143–218). The 1 m cell resolution DEM of land elevation and river channel bathymetry was sampled for cross-sections at an interval of approximately 200 meters and used as an input to Hydrologic Engineering Centers River Analysis System (HEC-RAS; USACE, 2002b) for modelling water surface elevations. The water surface elevations were modelled at a flow equivalent to the average (mean) summer (June to September) low-flow for the water years 1948–1997, ranging between 292 m^3/sec (10 312 ft^3/sec) upstream at the Vina gauge at RM 218 to 230 m^3/sec (8122 ft^3/sec) downstream at the Colusa gauge near RM 243. A Manning's 'n' value of 0.030 was selected for this

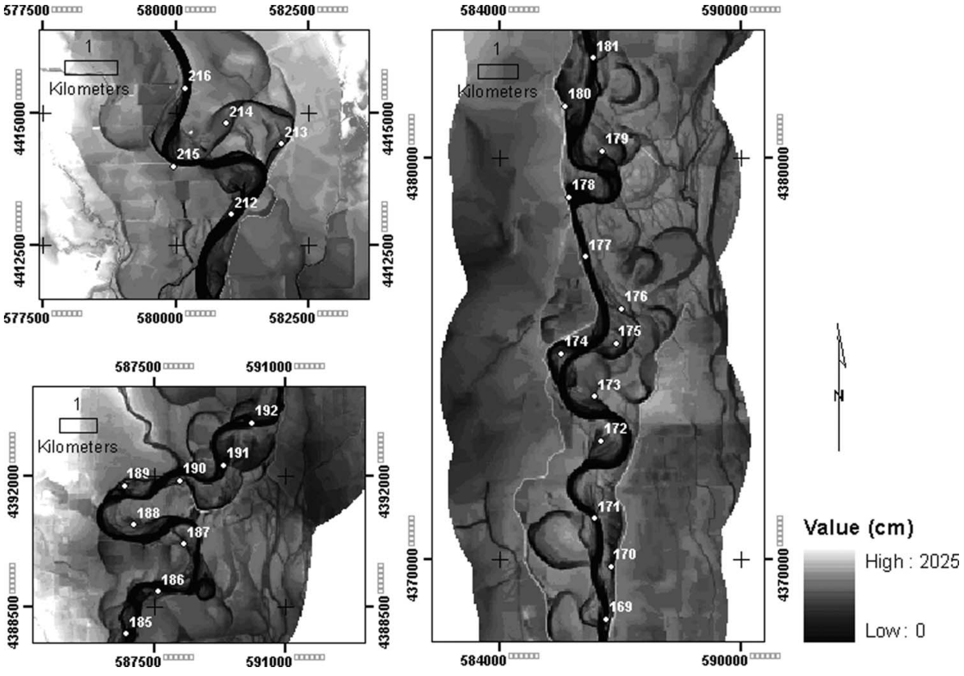

Figure 4. Example relative elevation surface maps of three areas within the study reach of the Sacramento River, USA. River-miles are shown as white points and text. Tick marks show the UTM coordinate system (zone 10, NAD27).

model from calibrating the model at gauge locations with known river flood elevations. River channel water surface elevations at each cross-section were modelled from these input data.

The resulting modelled water surface elevations were input into a GIS based on the known geographic locations of the cross-sections used in the HEC-RAS model. The modelled summer low-flow river surface elevations were joined to the cross-section lines based on the river mile attribute common between the two datasets. An ArcGIS 8.2 Visual Basic for Applications (VBA) macro was used to place a point at the midpoint of each cross-section line. The cross-section lines were then spatially joined to the mid-points, resulting in a set of points along the centre of the river channel spaced approximately 200 meters apart and attributed with the modelled water surface elevation.

These points were then used to interpolate a 10 m cell resolution GIS surface of water surface elevations for all raster cells within 3 km of the river channel using an inverse distance weighting (IDW) algorithm in the Geostatistical Analyst extension of ArcGIS (Johnston *et al.*, 2001). IDW is a deterministic interpolation method that forces the calculated surface to pass exactly through the known data values (Johnston *et al.*, 2001). We set the power variable to '2' which gives greater weight to closer input points when interpolating. After experimenting with several ways to choose channel datums for the purpose of relative elevation mapping, we implemented a weighted average approach using a fixed search radius of 10 km (for the major and minor semiaxes) to the nearest 10 cross-section water surface elevation points (as opposed to using a single datum value). This had the effect of smoothing the relative elevation floodplain surface and prevented abrupt and artificial changes within highly sinuous point bar features (see Poole *et al.*, 2002 for further discussion of this phenomenon). Thus, for this analysis the IDW algorithm calculated the interpolated water surface elevation using the 10 nearest channel elevation points to any given floodplain raster cell within the 3 km buffered area. Ten points were used because it represented the smallest number of points that provided sufficient smoothing of the water surface data for raster cells within the study area. This interpolated surface (i.e. the expanded water surface) was then subtracted from the 10 m (cell resolution) DEM of land surface elevations, resulting in the final relative elevation surface. All GIS procedures were performed in ArcGIS (version 8.2; ESRI, 2003).

Relative Elevation as a Surrogate Water Table Model

The relative elevation model was tested as a surrogate for water table depth using two independent data sets collected by The Nature Conservancy (TNC): 1) soil core data; and 2) well water elevation data. The soil core data were collected between 22 October 2002 and 25 November 2002, and the well data were collected between 23 October and 17 November 2000. The soil cores were taken in three general areas: Deadman's Reach (RM 185–186), Rx Ranch (RM 194–195), and Sunset Ranch (RM 199). Only soil cores that reached saturation were used in the validation, resulting in 43 usable data points: 19 points at Deadman's Reach, 15 points at Rx Ranch, and 9 points at Sunset Ranch. All of the well data points were located between RM 190 and 201 with the exception of one point at RM 214. The modelled relative elevation values were associated with each observed data point using the 'summarise zones' command in ArcGIS 8.2 Spatial Analyst. Simple linear regression was then used to test the fit of the modelled relative elevation to the observed depth to the water table and a p-value of 0.05 was used to assess the significance of the relationship.

Relative Elevation to Approximate Flood Inundation Patterns

The relative elevation map was tested to assess how well it could be used to approximate flood inundation. To conduct this error assessment, an observed flood was mapped using aerial photographs within a 57 km study reach (river miles 181.8–218.3) of the middle Sacramento River. The date of the flood was 17 March 1995, which was very close in time to the 1997 topographic mapping of the channel and floodplains. For more information on the mapping methodology see Greco and Alford (2003). According to a flood frequency analysis by Lowney and Greco (2003) at the Bend gauge (ref. no. 11377100; located at RM 267) the observed flood represented a 3.3-year recurrence interval (RI) flow (2718 m^3/sec) in the time period after construction of Shasta Dam. The Bend gauge was utilised because it has the longest and most complete record of Sacramento River flows.

Two steps were taken to measure the error of the relative elevation map in comparison to the observed flood flow: 1) all relative elevation depth classes ranging from <1 m to <13 m were compared to the observed flood map to assess the total error and the relative proportions of omission error and commission error for each; and 2) from the first step we selected the best model (i.e. a relative elevation depth class) with the lowest total error and conducted a direct map comparison to measure overall agreement and disagreement between the observed flood map and the relative elevation map. All of the analyses were computed using the Spatial Analyst Extension in ArcGIS (version 8.2; ESRI, 2003).

Relative Elevation Class Comparisons. Depth classes of the relative elevation map were created by selecting all cells below a particular depth level and reclassifying it to a binary map (i.e. flooded and not flooded). This was performed for each depth class ranging from <1 m depth to <13 m depth resulting in 13 depth maps. Following this step a conditional statement was used to extract the relative elevation values from the relative elevation map surface of the cells identified as flooded from the respective modelled depth maps and observed flood map. The omission error and commission error for each depth class was measured and summed to calculate total error.

Direct Map Comparison. The relative elevation depth class with the lowest error was determined to be the <4 m depth relative elevation map (see Figure 6) and it was directly compared to the observed flood. A difference map was calculated and summarised to measure the number of cells that: 1) agreed on where flooding occurs, and agreed on where flooding does not occur; 2) disagreed on where flooding occurs (omission error); and 3) disagreed on where flooding does not occur (commission error). Agreement and error rates were calculated.

Relative Bank Heights

Relative bank height was measured using the relative elevation model. The first step was to create an analysis area by generating a 300 m buffer of the main channel centreline that captured all banks near the main channel with slopes greater than 87 degrees. The buffered area was then divided into 62 river channel segments based on homogeneous characteristics for channel curvature (at obvious inflection points) and bank continuity. Statistics were calculated in ArcGIS (version 8.2) for each segment including the length and area; mean bank height; median bank height; and maximum bank height. Summary statistics were also calculated for the whole study reach averaging the results from all 62 zones.

Plant Communities and Other Land Cover as a Function of Relative Elevation

The modelled relative elevation surface was then related to a plant community and land cover map. The land cover map contained classes of vegetation community types and various riverine feature types and was delineated from digitised aerial photography (Geographical Information Centre, 2000). The land cover map included the following categories: gravel, riparian scrub, cottonwood forest, other mixed riparian forest, *Arundo donax* dominated, blackberry bush, grassland, valley oak, cropland, orchard, and disturbed/developed. The land cover map was converted to a 10 m raster map, to match the raster cell-size of the modelled relative elevation surface. The modelled relative elevation surface was then classified into the following categories for this analysis: 0–50 cm, 51–100 cm, 101–200 cm, 201–300 cm, 301–400 cm, 401–500 cm, 501–600 cm, 701–800 cm, >800 cm.

The area of each land cover type in each relative elevation category was calculated using the 'zonal sum' command in ArcGIS 8.2 Spatial Analyst (ESRI, 2003). Proportions of cover for each land cover type in each relative elevation class were calculated by dividing the total land area of the respective land cover category in a particular relative elevation class by the total area for the respective relative elevation class. Likewise, the proportion of each relative elevation class in each plant community type was calculated by dividing the total area of the respective relative elevation class in a particular plant community type by the total area for the respective plant community type.

Results

The modelled relative elevation values for terrestrial areas within 3 km of the main channel ranged from 1 cm to 2213 cm (median = 548, mean = 581). Three examples of the relative elevation map are shown in Figure 4.

Relative Elevation as a Surrogate Water Table Model

The modelled relative elevation at the locations of the 2002 soil core surveys ranged from 228 cm to 494 cm, and the observed depth to the water table ranged from 264 cm to 579 cm. For the 2000 well survey locations modelled relative elevation ranged from 304 cm to 704 cm, and observed depth to water table values ranged from 305 cm to 900 cm.

The results of the linear regression analysis indicated that the modelled elevation positively correlated with the observed depth to the water table for both validation data sets (Figure 5). The fitted regression line for the 2002 soil core survey data set had a slope coefficient of 0.61 that significantly differed from zero ($r^2 = 0.44$, $p < 0.0001$; Figure 5a). The fitted regression line for the 2000 well survey data set had a slope coefficient of 0.95 that significantly differed from zero ($r^2 = 0.29$, $p = 0.0015$; Figure 5b).

Relative Elevation to Approximate Flood Inundation Patterns

The error assessment showed how error is distributed in different ways between the observed flood and the relative elevation depth maps (Figure 6). Many of these differences were expected due to the pronounced nature of the backwater effect during flood events in meandering river systems. The direct map comparison approach illustrated this phenomenon clearly in some areas, such as at RM 216 (Figure 7). Results from the direct map comparison approach show that the <4 m depth relative elevation map had an overall accuracy of 79% for correctly predicting inundation zones and non-inundation zones. This indicates an overall error rate of 21%, of which 9% were commission errors, meaning the relative elevation map predicted inundation when none were observed, and 12% were omission errors, meaning the relative elevation map did not predict inundation when inundation was observed (e.g. backwater effects from flooding). When the elevation classes within the <4 m depth map were individually assessed for error, the 1–100 and 101–200 cm classes achieved 93%–94% accuracy, respectively, while the 201–300 cm class had an accuracy of 80% and the 301–400 cm class had an accuracy of 51%.

Relative Bank Heights

The average reach length of the 62 river channel segments was 1.9 km (SD = 0.8 km); mean relative bank height for all the study reaches was 3.2 m (SD = 0.7 m) and the mean maximum relative bank height was 8.5 m (Table 1).

Plant Communities and Other Land Cover as a Function of Relative Elevation

The results relating plant communities and other land cover types to the relative elevation surface are shown in terms of area (ha) in Figure 8 and proportionally in Figures 9 and 10. The Sacramento River floodplains that we examined are dominated by agricultural land uses such as orchards and croplands in the relative elevation classes between 300 and 800 cm (Figure 8). However, clear distribution patterns of plant communities are evident for natural vegetation types suggesting that relative elevation may be an important riparian landscape variable or surrogate variable to consider for determining potential plant communities (Figure 9). In particular, mixed riparian forest, cottonwood, riparian scrub, and gravel have distinct patterns that separate their respective distributions. When plant community types were looked at proportionally within relative elevation classes a gradient of

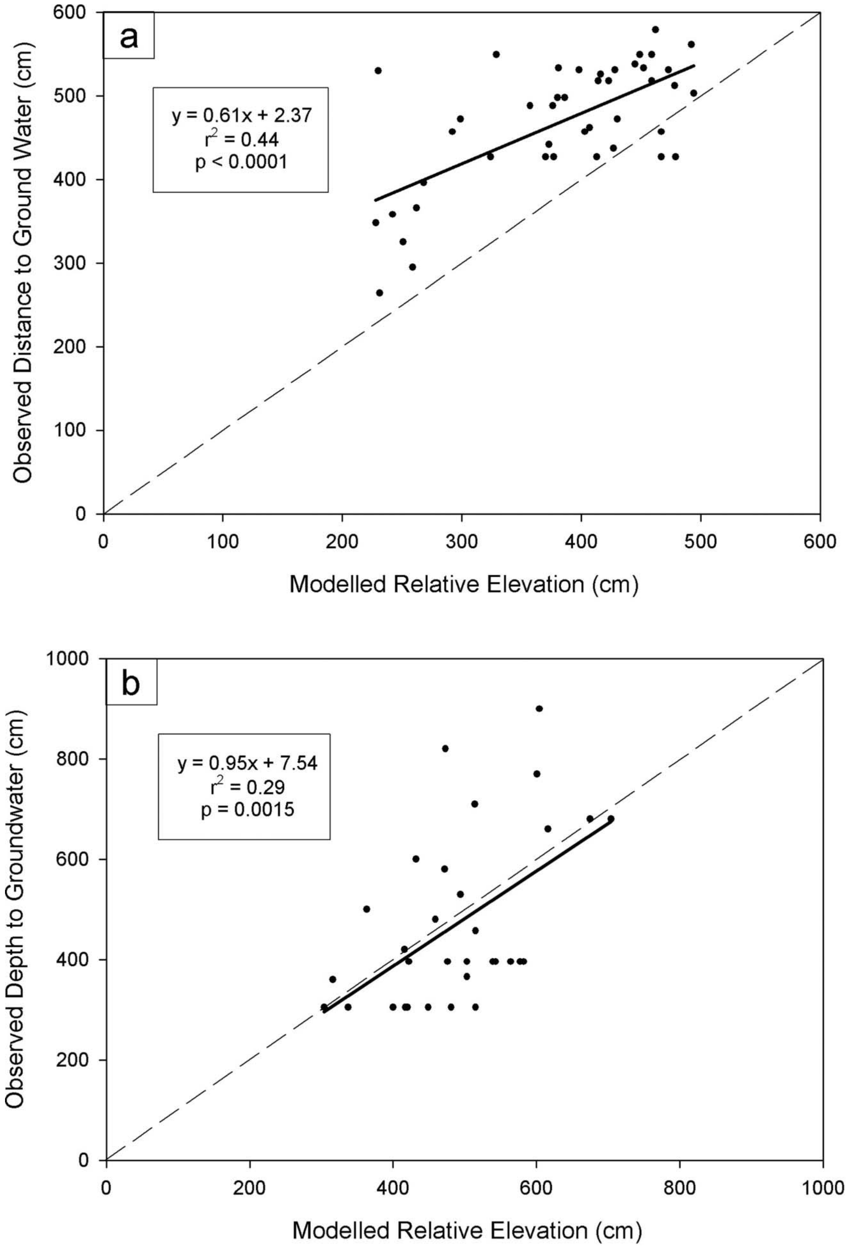

Figure 5. Observed distance to water table regressed against modelled relative elevation (solid line) from a) 2002 soil core surveys and b) 2000 well surveys. The dashed line though $y = x$ represents a perfect one-to-one relationship between the two variables.

affinities became evident from low to high relative elevation as follows: gravel, riparian scrub, cottonwood, mixed riparian forest, *Arundo donax*, blackberry, grassland, valley oak, cropland, orchard, and disturbed (Figure 10).

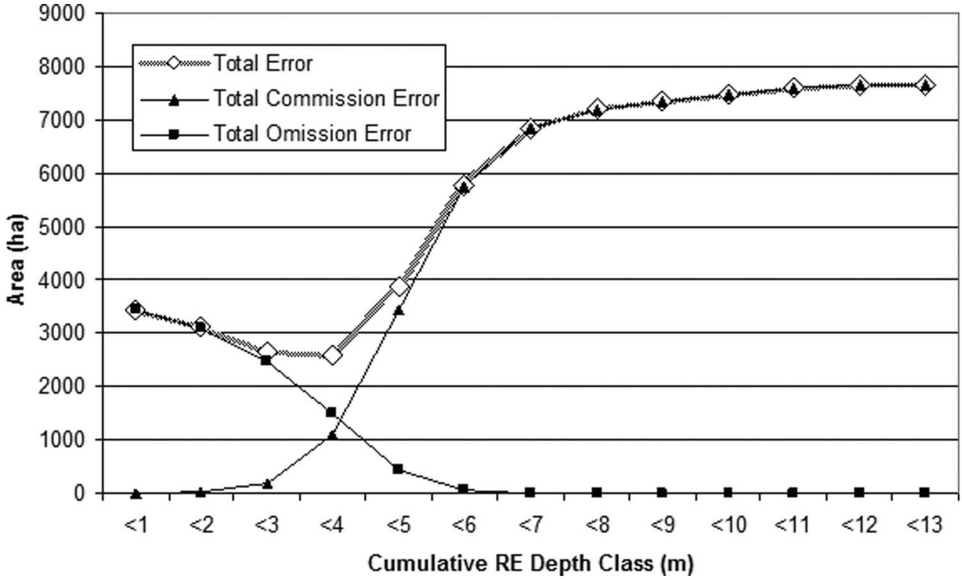

Figure 6. The omission errors, commission errors and their sum (total error) for each cumulative relative elevation (RE) depth class map as compared to an observed 3.3-year recurrence interval flood flow surface water map.

Discussion and Summary

The discipline of landscape ecology mainly focuses on the effects of processes on the structure (pattern and configuration) and function of interacting ecosystems over wide spatial scales (Forman & Godron, 1986; Turner, 1989). The outward expression of vegetation community patterns in riparian landscapes is the result of a combination of allogenic physical processes and autogenic biological processes interacting with the individual life history characteristics (i.e. niche breadth) of the plant species present in the system (Malanson, 1993). Clearly, topographic data in combination with flow records and/or flow modelling (of both surface and groundwater) are critical information for designing scientific field studies, or for planning and design of riparian restoration projects at the landscape scale. However, since there is typically a lack of geospatial flow or groundwater data available for most river systems on wide spatial scales at appropriate resolutions, as for example on the Sacramento River, the necessity of creating map-based flow and water table data presents a challenge. We have demonstrated (by comparing the relative elevation model with independent data of observed water table elevations and observed flood inundation patterns) that a relative elevation map based on a long-term average low-flow water surface elevation in the river channel can act as a surrogate for water table depth and flood inundation patterns, especially in near-channel applications. As such, this model can be a useful planning tool for landscape scale restoration design of riparian vegetation communities or broad-scale site reconnaissance or rapid site assessments. Because it is a simple model with many assumptions it can be considered a 'strategic' modelling approach (Baird, 1999b).

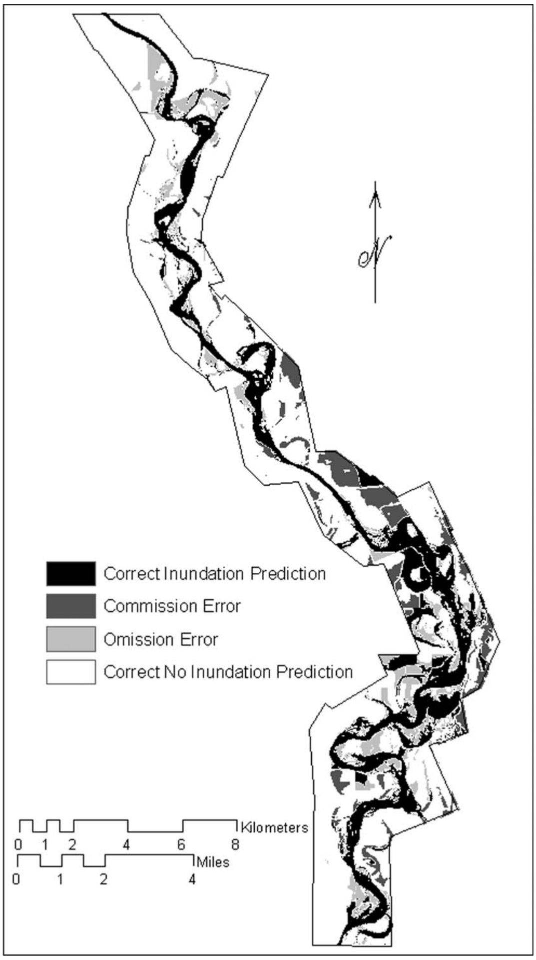

Figure 7. An error map showing agreement (correct predictions are shown in black and white) and disagreement (error is depicted in shades of grey tones) of a flood inundation analysis of a 57 km study reach on the middle Sacramento River (RM 181.8–218.3), USA, comparing an observed 3.3-year recurrence interval flood flow and a modelled relative elevation surface at a 4 m depth from a baseline mean summer low-flow elevation.

The relative elevation mapping approach also has potential useful applications for measuring various geomorphic aspects of alluvial river floodplains, for example, relative bank height, for the purposes of descriptive analysis, modelling future system states, and modelling geomorphic processes related to bank erosion. Site-specific rates of bank erosion have been shown to be related to the river bank-top elevation relative to the adjacent water surface elevation (Hasegawa, 1989; Howard, 1992). Predicting the stream-wise patterns of bank erosion constitutes the foundation of predicting meander migration patterns. Relative bank height information is largely unavailable and, therefore, in some meander migration applications, has been ignored (Howard, 1992; Larsen & Greco, 2002). The relative elevation model

Table 1. Relative bank height measurements on the Sacramento River from RM 143–218

Reach ID	River miles (approx.)	Length (km)	Area (ha)	Max. Bank Height (m)	Mean Bank Height (m)	SD Bank Height (m)	Median Bank Height (m)
1	215.5–218.3	4.65	277.9	11.9	4.2	2.9	5.5
2	214.3–215.5	1.57	93.6	7.4	3.3	2.1	4.0
3	211.8–214.3	2.30	138.1	8.1	3.2	2.4	3.5
4	211.1–211.8	1.55	92.9	6.4	2.7	2.2	3.0
5	210.2–211.1	1.12	67.1	7.2	2.7	2.2	3.3
6	209–210.2	2.22	132.9	7.0	2.5	2.1	2.9
7	207.7–209	2.15	128.9	6.3	3.0	2.1	3.8
8	206.8–207.7	1.27	76.1	9.7	3.6	3.1	3.1
9	204.8–206.8	3.20	192.0	11.4	3.9	3.2	4.3
10	201.7–204.8	2.22	128.2	7.0	2.3	2.2	1.9
11	201.2–201.7	1.08	68.9	7.9	2.7	2.3	3.1
12	198.3–201.2	4.61	275.9	11.0	3.1	2.3	4.2
13	196.6 198.3	2.12	127.6	7.5	2.9	2.0	3.3
14	195.5–196.6	1.50	89.5	6.0	2.1	1.7	2.0
15	194.5–195.5	1.69	101.3	5.3	1.6	1.7	1.1
16	193.8–194.5	1.08	64.6	6.7	2.2	1.9	2.5
17	193.1–193.8	1.27	76.0	6.1	2.4	2.0	2.9
18	191.8–193.1	1.93	115.0	7.1	2.4	2.0	2.9
19	191–191.8	1.78	105.1	8.1	2.5	2.1	3.0
20	190.1–191	1.17	71.7	8.0	2.3	2.0	2.4
21	188.9–190.1	2.10	125.8	6.4	2.8	2.3	3.4
22	188.4–188.9	1.33	79.8	8.2	3.3	2.4	4.1
23	187.6–188.4	1.87	112.1	6.4	2.4	1.9	3.1
24	186.6–187.6	1.69	100.9	6.5	3.1	2.3	3.9
25	186.1–186.6	1.48	88.7	6.0	2.2	1.9	2.2
26	185.4–186.1	1.38	82.9	6.6	2.5	2.3	2.7
27	184.1–185.4	1.85	110.2	10.3	2.5	2.0	2.7
28	183.2–184.1	1.28	77.4	9.7	2.9	2.4	3.4
29	182.8–183.2	1.64	98.4	7.5	2.7	2.4	2.7
30	181–182.8	3.03	177.5	8.7	2.9	2.4	3.3
31	179.8–181	2.00	123.6	6.4	2.5	2.1	2.8
32	179–179.8	1.57	93.9	8.9	2.8	2.4	2.7
33	178.2–179	1.65	98.4	6.9	2.9	2.4	3.0
34	176.1–178.2	3.09	185.2	9.1	3.2	2.5	4.4
35	174.1–176.1	1.67	99.7	8.0	2.3	2.0	2.1
36	173–174.1	2.46	146.7	7.5	2.5	2.2	2.6
37	171.8–173	2.35	139.5	8.9	3.0	2.4	3.7
38	171.1–171.8	1.69	101.3	6.7	3.7	2.5	5.0
39	170–171.1	1.16	71.9	6.3	2.9	2.1	3.3
40	169.6–170	0.86	51.4	6.5	3.4	2.5	4.4
41	166.9–169.6	3.58	214.3	11.0	3.4	2.5	4.4
42	165.8–166.9	1.98	118.3	7.9	2.5	2.1	2.9
43	163.3–165.8	1.13	68.0	8.4	3.0	2.3	3.0
44	162.4–163.3	2.32	139.0	10.7	3.8	2.7	4.9
45	161.7–162.4	1.40	83.9	10.0	3.2	2.4	3.7
46	160.5–161.7	1.21	71.9	10.0	3.2	2.5	3.5
47	159.4–160.5	2.12	127.2	10.6	4.1	2.9	5.3
48	158.4–159.4	1.73	103.6	10.7	4.1	2.4	4.8

(*continued*)

Table 1. (*Continued*)

Reach ID	River miles (approx.)	Length (km)	Area (ha)	Max. Bank Height (m)	Mean Bank Height (m)	SD Bank Height (m)	Median Bank Height (m)
49	157.1–158.4	1.70	101.9	11.0	4.1	2.8	5.2
50	156.5–157.1	1.56	92.8	10.2	3.4	2.8	4.4
51	156–156.5	1.39	81.7	7.6	4.0	2.6	5.1
52	155–156	1.25	67.7	9.8	3.8	2.8	5.1
53	153.8–155	1.66	86.8	9.7	3.7	2.7	4.7
54	152.3–153.8	2.02	130.4	11.4	4.7	2.8	5.5
55	151–152.3	2.56	153.1	10.6	4.6	2.4	5.3
56	148.5–151	2.26	141.1	10.7	4.3	2.4	4.9
57	146.9–148.5	2.78	160.8	9.8	3.7	2.6	4.9
58	146–146.9	1.85	106.8	9.4	3.1	2.4	3.7
59	145.5–146	1.17	71.8	8.5	3.4	2.4	4.3
60	144.2–145.5	1.13	67.5	9.7	4.3	2.6	5.3
61	142.8–144.2	1.70	101.7	9.8	4.4	2.6	5.5
62	142.8–144.2	2.40	137.6	11.7	5.0	2.9	5.9
	Sum	117.5	7016.4	–	–	–	–
	Mean	1.9	113.2	8.5	3.2	–	3.7
	SE	0.1	5.8	0.2	0.1	–	0.1
	Median	1.7	101.5	8.2	3.1	–	3.5
	Mode	–	–	11.4	–	–	3.3
	SD	0.8	45.4	1.8	0.7	–	1.1

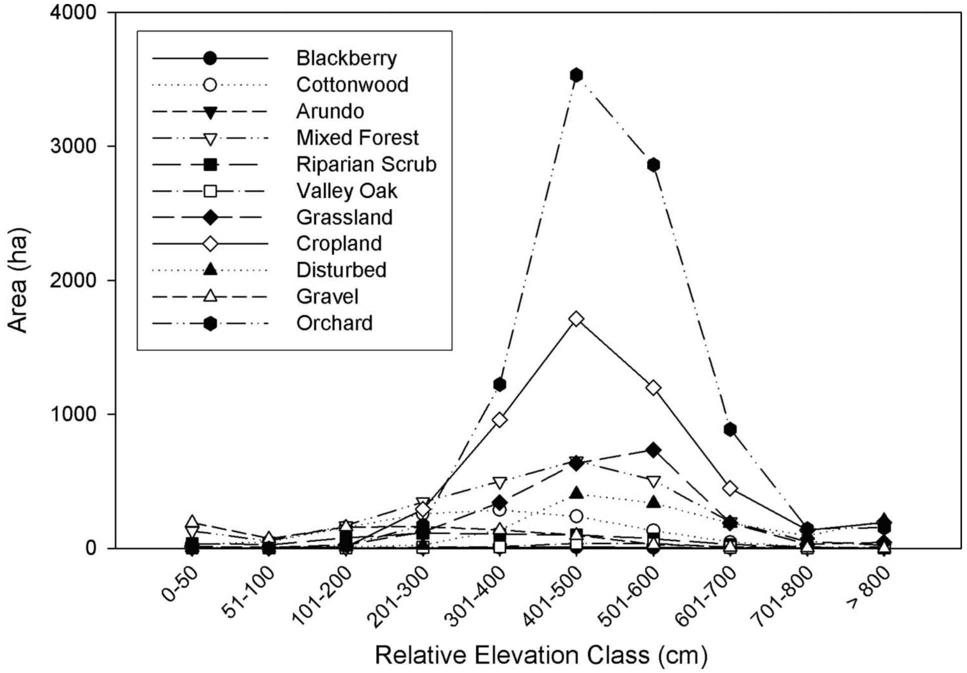

Figure 8. Total area (ha) of each vegetation type in each relative elevation size class.

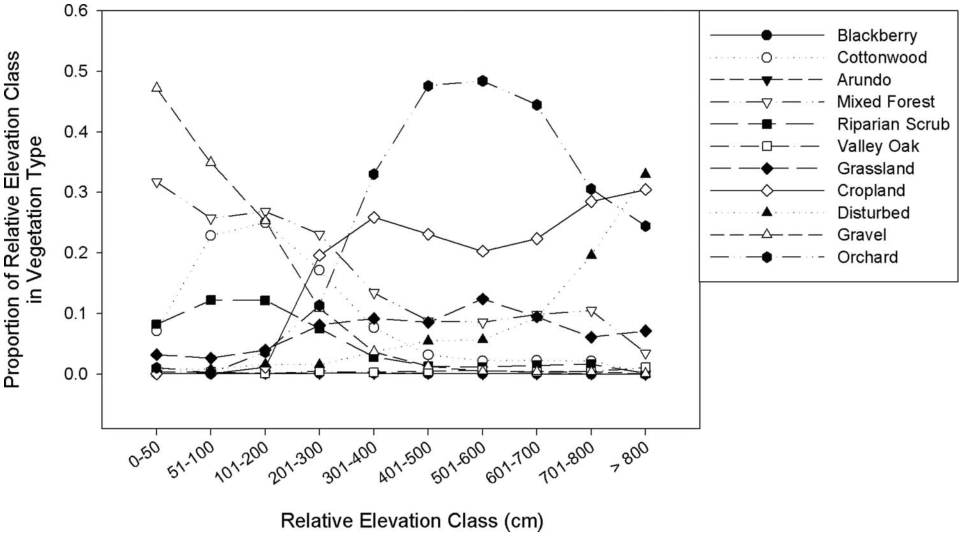

Figure 9. The proportion of the total area of each relative elevation class covered by each vegetation community and land cover type. Note the proportions sum to 1.0 for each relative elevation class.

presented in this paper provides a relatively easy method to obtain such data, and could facilitate more accurate predictions of channel meandering. The model also has potential applications in wildlife habitat relationship modelling for wildlife that utilise river banks. The relative elevation topographic model was recently used in a population viability study by Girvetz (2007) of the California state-listed threatened bird species, the bank swallow (*Riparia riparia*). Bank swallows make their nests by burrowing into eroding banks on the Sacramento River and bank height is an important variable that can determine habitat suitability.

High resolution (i.e. sub-meter) site planning topography is traditionally collected in the field by land surveying methods using a total station in combination with photogrammetric mapping techniques. A modern active-sensor remote sensing technique capable of high resolution topographic mapping is LIDAR (light detection and ranging) which is now gaining more use in ecological field studies. Another active sensor remote sensing technique is sonar technology which is used to map the bathymetry (underwater topography) of channels. All these techniques can yield highly accurate topographic products; however, they can be expensive to acquire.

Our relative elevation spatial modelling approach employed hydrologic modelling to determine the 50-year average low-flow water surface elevations in the channel of the Sacramento River. We believe there may be more economical alternative approaches by eliminating this step if resolute topographic data (e.g. ≤ 10 m cell size and sub-meter vertical resolution for a broad scale site like the middle Sacramento River) were available of average low-flow or base-flow from maps such as USGS DEM quadrangles. The availability in the near future of higher resolution DEMs could provide water surface elevations capable of computing a relative elevation surface in a rapid and economical way.

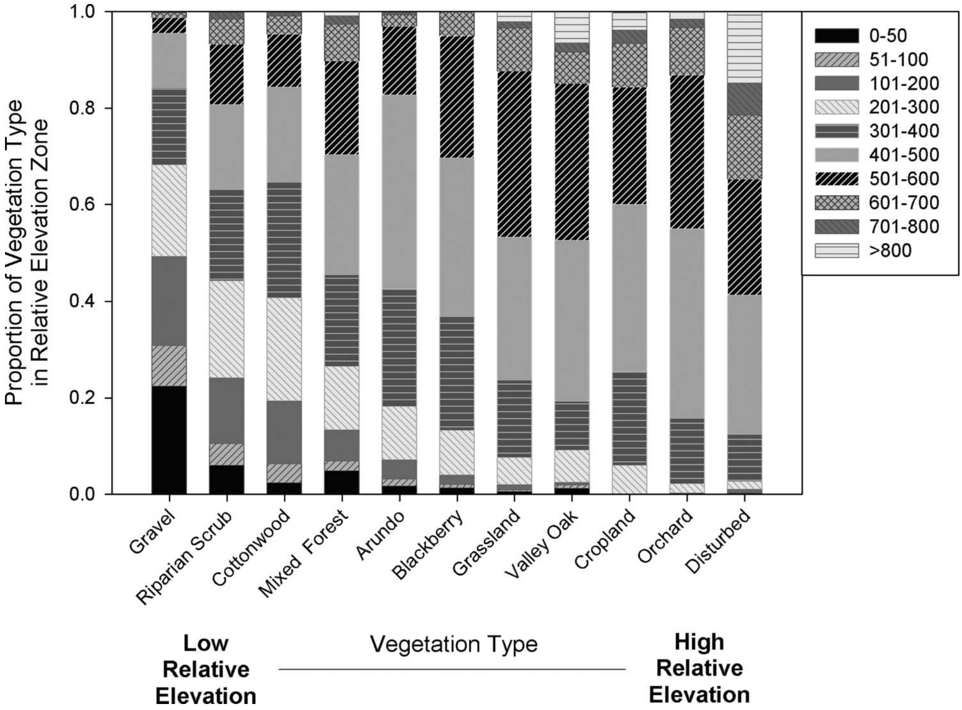

Figure 10. The proportion of the total area (ha) of each vegetation type that is in each relative elevation size class. Note the vegetation and land cover types occupying the lower relative elevation classes are located toward the left side of the graph, and land cover types found more often in higher relative elevation classes are located toward the right.

A cautionary point related to the use of relative elevation mapping as a surrogate for water table depth is error associated with distance and height above the main channel. Relative elevation values close to the main river channel are the most accurate and error generally increases with increasing distance from the main channel. This is an expected result because of the nature of the structure of aquifers in alluvial rivers; some areas are gaining reaches (influent) and some areas are losing reaches (effluent) causing variation in the depth of the water table across large areas of a floodplain. This inherent water table depth variation is not reflected in the relative elevation model and neither are site-specific factors such as site history causing local site-specific depth variations. It must be kept in mind that the relative elevation model is a static, long-term average unlike the temporally dynamic nature of real groundwater systems or formal groundwater models. The results at the soil core validation sites suggest the relative elevation surface under-predicted the depth of the water table in that particular area. However, the well data validation site appears to agree reasonably well with the calculated relative elevation surface. A notable drawback to both of the independent data sets used for the water table model validation was that they were measured in late fall, after rains had started, as opposed to summer, potentially accounting for some of the variability and higher values observed. Overall, there is a dearth of available well data for water table analysis on the Sacramento River. The California Department of Water Resources maintain an extensive database of known wells throughout the state, however, few wells are located near the main channel of the Sacramento River.

The results of estimating flood inundation patterns from the relative elevation surface indicated moderate overall success. It should be noted that the relative elevation class area totals were found to be in greater agreement in the 1–3 m classes than in the 4–6 m classes. This was expected because of well-known and documented backwater effects during high flow events. The result should serve as a good guide and cautionary note in terms of assessing the reliability of the relative elevation map for predicting flood inundation on the upper floodplains and terraces. The relative elevation model is, however, very effective at predicting flood inundation patterns at the lower relative elevation classes near the main river channel. Thus, despite the inherent error in the upper and outer extreme relative elevation classes, the relative elevation surface model has many potential beneficial uses, especially for gaining insight into near-channel ecological processes. For example, the relative elevation model can be used to spatially identify the 'recruitment box' zonation (and volume) patterns of floodplains over broad spatial scales using known topographic parameters for primary succession colonisation of riparian tree species such as cottonwood (*Populus* spp.) (see Mahoney & Rood, 1998).

The spatial analyses relating the relative elevation topographic surface to land cover classes found distinct signals for numerous native plant community types and other land cover types, such as gravel deposits and agricultural crops (Figure 9). The findings for the natural vegetation types are likely the result of the average low water level being one of the primary limiting factors controlling plant species distributions, as previously discussed (*sensu* Wheeler, 1999). With the exception of grasslands, we examined mostly woody perennial plant species and communities (as opposed to herbaceous annuals) and theoretically they are structured by low-water levels (i.e. the lower limits of water tolerance) in years of drought. Another favourable aspect was the lower floodplains (i.e. representing the upper limits of water tolerance; for example cottonwood and riparian scrub including *Salix* spp.) are not converted to agriculture at our study site because of the frequent flooding in these areas. The clear distribution patterns of our findings suggest that relative elevation is a significant variable for predicting the presence of plant communities and specific species in lower floodplains. This is a good example of realised niche space for woody plant species in a floodplain environment. It therefore follows that a relative elevation map can be an important design tool for planting plans in riparian restoration projects by defining the potential depth to the water table and inundation frequency. In conjunction with other information such as soil type and floodplain age (see Greco *et al.*, 2007), a relative elevation map could also be a valuable tool for site stratification in vegetation and other ecological field studies in floodplains (see Vaghti, 2003). For example, a field study designed to monitor the success of an active restoration site in a riparian zone might consider stratifying the site into relative elevation classes to measure plant mortality rates.

The relative elevation concept and technique can be applied most effectively to situations where the basic assumptions of the model hold true. Those assumptions are: the system must be a truly low-gradient alluvial or piedmont river with an unconsolidated river bed and floodplains are present. Many creeks in urban and agricultural areas have been relocated (moved and channellised) away from their original alignments and therefore are no longer underlain with gravel that provide the storage space for groundwater, and therefore may not be a suitable system for this type of modelling. 'Daylighting' creeks in urban areas is a restoration technique to recover creek systems and floodplains within cities that have been placed in culverts (Riley, 1998). Where it can be shown that the original creek bed is intact, a relative elevation map could be a useful tool for creek daylighting restoration planning and design projects.

Another ecological application that relative elevation maps could contribute insight towards is floodplain connectivity analysis. A relative elevation map could determine at what stages or depths the floodplain is optimally flooded for fish habitat. This is an important consideration in fish species population viability assessment, an issue which is increasing in relevance as river systems come under greater demand for utilisation from anthropogenic stressors. Additionally, the use of relative elevation maps to inform or guide property acquisition for river system conservation could contribute to this objective. Public or private agencies seeking to improve riverine functionality and floodplain connectivity could use a relative elevation map to assess the potential contribution of a certain parcel to the whole system. By identifying floodplains of strategic importance, acquisition of valuable conservation lands can be facilitated with the use of a relative elevation map.

It is important to emphasise that we do not view the relative elevation modelling technique presented in this paper as a replacement for detailed groundwater modelling or flood inundation modelling; however, in their absence, we do believe by understanding the limitations of the relative elevation modelling approach it can be an economical and effective technique to estimate flooding frequency and depth to the water table in alluvial river floodplain systems for rapid assessment, field sampling, site planning and riparian forest restoration design.

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