MIDDLE SACRAMENTO RIVER MEANDER BEND ATTRIBUTES AND ECOSYSTEM HEALTH INDICATOR METRICS

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ABSTRACT

Channel centerlines were mapped on a 160 km meandering alluvial reach of the Middle Sacramento River, California (from Red Bluff to Colusa) from historic topographic maps (1904) and aerial photographs (in 7 time periods between 1937 and 2007). Centerlines were broken into individual segments (between successive inflection points) and analyzed in a GIS for eight different metrics for all segments, and six different metrics for segments that had a sinuosity greater than or equal to 1.1. The whole river had an average sinuosity of 1.26 (calculated as the length-weighted average of the bend sinuosities), and the following average values for sinuous bends (i.e. greater than or equal to 1.1 sinuosity): half wavelength 1039 m, radius of curvature 676 m, and bend entrance angle and exit angles of 65 and 64 degrees respectively.

Temporal changes in channel centerlines and bend geometry were tracked over the 103-year time interval. The river channel length, beginning and ending in the same valley location, tended to decrease from 1904 to 2007. This suggests that river length lost due to cut-off and other processes has not been replaced by channel length gained by migration over the study period. In addition, the formation of high sinuosity bends susceptible to future cut-off has declined. The river sinuosity, the average entrance and exit angle magnitudes, the average migration rate (and floodplain reworked), and the number of high-sinuosity bends – all tended to decrease with time. This suggests that the complexity of the river has decreased over the last century, which has implications for the health of the riparian ecosystem.

Seven different metrics were chosen as indicator metrics of channel complexity in order to provide data for a scorecard of ecosystem health being prepared by The Nature Conservancy: 1) total river length, 2) whole river sinuosity, 3) whole river average meander migration rate, 4) number of bends with sinuosity greater than or equal to 2.0, 5) average bend entrance angle, 6) area of floodplain reworked, and 7) average half-wavelength. In order to develop restoration and environmental health guidelines for the river, ranges corresponding to very good, good, fair, and poor were estimated and preliminary target goals were assigned for each indicator to provide guidelines and goals for ecosystem health.

INTRODUCTION

Large alluvial rivers have a tendency to migrate laterally over time. Meander migration, consisting of bank erosion on the outside bank of curved channels and point bar and flood plain building on the inside bank, is a key process for many important ecosystem functions (e.g. Malanson 1993). Examples include 1) vegetative establishment for the riparian forest, 2) floodplain creation through progressive meander migration, 3) habitat creation (i.e., bank erosion for swallow habitat), and 4) the creation of off-channel habitats (e.g., oxbow lakes, side channels, and sloughs) by progressive migration and cutoff processes.

The meander migration process is a function of flow, channel form, and bank characteristics. All of these have been altered on the Sacramento River, through the construction of Shasta Dam, channel restraints like revetment and levees, and the land-use changes like the transition from riparian forest to agricultural lands. To develop effective strategies for the conservation and restoration of key ecosystem functions, it is important to relate the role that meander migration plays to these ecosystem functions.

Measuring and planning for channel change are some of the most important challenges for managing a meandering river corridor (Golet, Roberts et al. 2004). The dynamic processes related to meander migration benefit ecosystem health (Ward and Stanford 1995; Stanford, Ward et al. 1996). At the same time, conflict between natural river meander dynamics and infrastructure protection has led to the placement of channel riprap and groins to limit channel dynamics. Whether the goal is to promote channel dynamics for ecosystem health or to enhance channel stability, methods to quantify the natural dynamics of river channel migration is critical (Naiman and Decamps 1997; Ward, Tockner et al. 2001). Studying long-term large-scale dynamics on a river over the scale of a century provides an important opportunity to quantify fundamental processes. In this study, maps of roughly 100 years of detailed river channel locations of the Middle Sacramento River were used to analyze river channel changes. Documenting historical patterns provides a better understanding of the forces driving river channel migration and promoting ecosystem health.

Centerline morphology, migration, and metrics

Sequential measurements of river bend planform geometry provide a way to quantify the morphology of a river and to study the changes in channel planform shape over time (e.g. Hickin and Nanson 1984; Hooke 1984; Gurnell, Downward et al. 1994). Channel curvature is related to the spatial distribution and the magnitude of channel migration (Hooke and Harvey 1983; Johannesson and Parker 1989; Furbish 1991; Larsen 1995). Empirically evaluating the channel geometry (Howard and Hemberger 1991) is a means to evaluate environmental characteristics based on channel shape. Research efforts have linked the shape of river meander bends with the movement of bends. Hooke examined the shapes of meander bends and related subsequent movement with characteristic shapes (Hooke 1995). There have been empirical models for predicting rates of meander migration based on bend shape (Lagasse, Zevenbergen et al. 2004). More complex physically-based models use the planform shape in predicting the hydrodynamics (velocity patterns) that are directly related to bank erosion (Ikeda, Parker et al. 1981; Darby and Thorne 1996; Darby, Alabyan et al. 2002). Measurements of channel metrics on alluvial (self-formed) meandering rivers help inform both qualitative geomorphic theories and physically-based models that tend to “scale-up” from micro-scale processes (i.e. sediment transport.) Broad large-scale studies can help to identify thresholds for migration processes (i.e. distinguish between geometries that will evolve by cutoff versus by other processes) (Constantine and Dunne 2008; Constantine, McLean et al. 2010; Micheli and Larsen 2010), but it is likely that these relationships will need to be studied in individual case studies to identify the range of natural variation.

Because river channel dynamism is important to many ecosystem processes, such as vegetation establishment, quantitative indicator metrics that reflect the characteristic dynamism of the channel would be useful. A suite of metrics was measured on the channel centerlines from the Middle Sacramento River study section. In conjunction with The Nature Conservancy and others, seven of the measured metrics were chosen to represent river ecological process health.

Based on the observed trends for the indicator metrics in those time periods, preliminary "scorecard" ratings and desired goals were estimated.

This report first documents the general methods used to analyze the channel geometry and dynamics on the Sacramento River, and presents the results of change over time. Then the chosen indicator metrics are presented one-by-one, describing in detail how each one was determined, and assigning very good-through-poor ratings to the numeric values.

METHODS

Study Area

Location

The Sacramento River (Figure 1) is the largest river in the state of California and drains an area of 2,305,100 ha, more than half of the total drainage area of the San Francisco Bay. Collecting precipitation and snowmelt runoff from the western slopes of the Sierra Nevada, the eastern slopes of the Coast Range, and the southern Trinity and Klamath ranges, the river drains 17 percent of the land in California and flows from north to south with a length of about 483 km, ultimately discharging into the Pacific Ocean by way of San Francisco Bay.

The length of the river has been measured using various reference systems, of which the most common one is a set of "river mile" (RM) markers established by the U.S. Army Corps of Engineers (USACE) in 1964. According to this system, the river extends from the confluence of the Sacramento and San Joaquin Rivers (RM 0) at the San Francisco Bay to near Shasta Dam (about RM 312) (Figure 1). The lower section of the river (from San Francisco Bay to the town of Colusa at RM 143) is limited by artificially installed channel constraints, while the middle section, from Colusa to Red Bluff (RM 143-244), is relatively free to meander, though riprap has been installed on this reach in the second half of this century. Our study was located in this middle section that is relatively free to migrate.

Geologic setting

The Sacramento River flows south through the Sacramento Valley over sedimentary rocks and recent alluvium. The Sacramento Valley is a structurally controlled basin between the Cascade and Sierra Nevada Mountains to the east and the Coast Ranges of California to the west (Harwood and Helley 1987).

The reach between Red Bluff and Colusa (i.e. from RM 244 to RM 143) is primarily a single-thread sinuous channel. The slope, averaged over a minimum of 5 km, ranges from 0.0002 m/m to 0.0007 m/m (Water Engineering and Technology 1988). The riverbed material is primarily sand and pebbly gravel with a median grain size that ranges from 5 to 35 mm in the reach RM 184-201 (Water Engineering and Technology 1988). Between RM 240 and RM 185, the average bank height from thalweg to top of the bank varies from 2 to 8 m with the mean of 4 m (CDWR 1994).

The Pliocene-Pleistocene deposits comprising the banks and floodplain of the Sacramento River are variable in terms of bank "erodibility." Erodibility refers to the relative resistance of bank materials to lateral migration and can be expressed as a coefficient for use in numeric meander models (Johannesson and Parker 1989; Larsen 1995; Micheli, Kirchner et al. 2004). Channel banks are typically composed of sand and gravel with isolated patches of erosion-resistant bedrock of the Modesto or Riverbank formations, terrace deposits typically consisting of 1-3 m of dark gray to red fine sand and silt overlying 1.5-2 m of poorly sorted gravel (CDWR 1994).

The Modesto formation is younger than the Riverbank formation and is usually less than 2.5 m thick and composed of gravel, sand, silt, and clay (CDWR 1994). Where Riverbank and Modesto are exposed, reduced rates of bank erosion and channel migration have been observed (Fischer 1994; Larsen and Greco 2002).

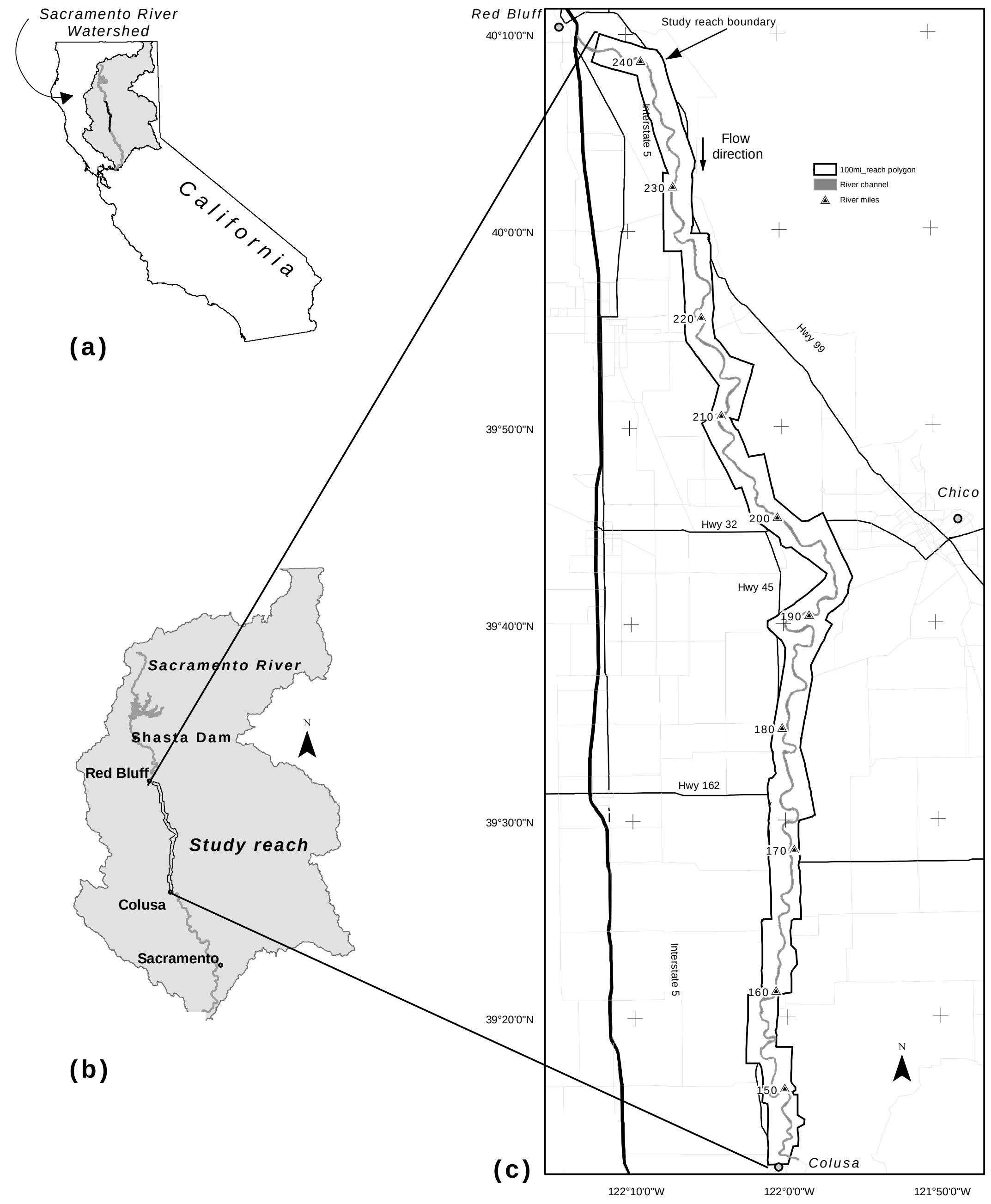


Figure 1 Sacramento River study area

Centerline morphology, migration, and ecosystem processes

Observing changes in temporal series of channel centerline data is a tested method of measuring the lateral movement of a river channel over time and identifying bends that migrate either via progressive migration or cutoff (e. g. Brice 1977; Odgaard 1987; MacDonald, Parker et al. 1991; Lawler 1993; Gurnell, Downward et al. 1994; Dietrich, Day et al. 1999; Micheli, Kirchner et al. 2004; Constantine and Dunne 2008; Micheli and Larsen 2010). Performing these analyses using Geographic Information System (GIS) tools allows for automating measurements, creating repeatable protocols, and sharing results. Channel curvature is assumed to be related to the spatial distribution and the magnitude of channel migration (Hooke and Harvey 1983, Johannesson and Parker 1989, Furbish 1991, Larsen 1995). Research efforts have linked the shape of river meander bends with the movement of bends. Hooke examined the shapes of meander bends and related subsequent movement with characteristic shapes. A recent model for predicting rates of meander migration was based on bend shape (Lagasse et al. 2004). More complex physically-based models use the planform shape in predicting the hydrodynamics (velocity patterns) that are directly related to bank erosion (Ikeda et al. 1981, Darby and Thorne 1996b, Darby et al. 2002). Large scale pattern changes on alluvial (self-formed) meandering rivers help inform both qualitative theories and physically-based models of ecosystem dynamics that tend to “scale-up” from micro-scale processes. Broad large-scale studies can help to identify thresholds for migration processes (i.e. distinguish between geometries that that are best to support ecosystem processes), but it is likely that these relationships will need to be studied in individual case studies to identify the range of natural variation.

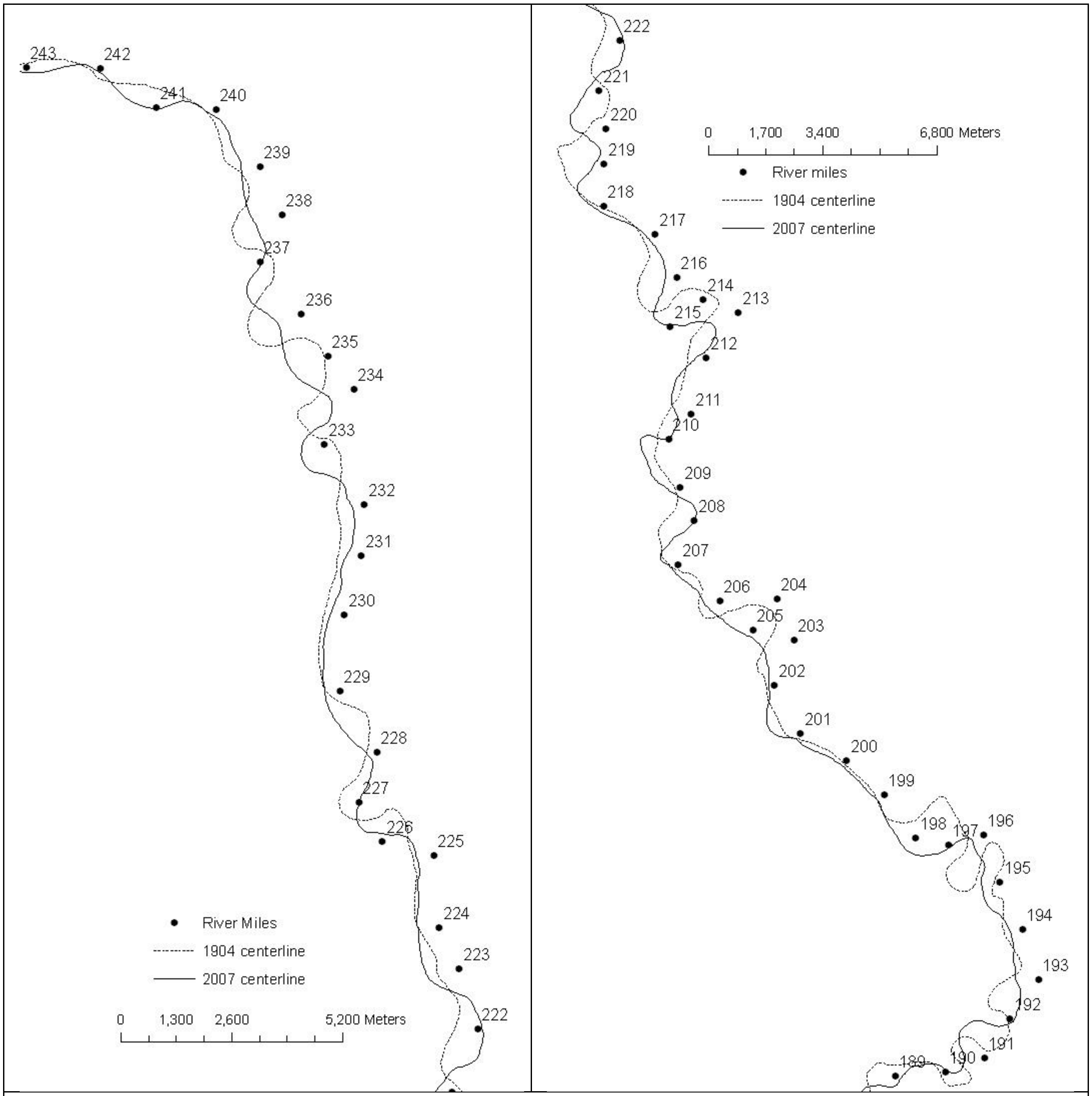


Figure 2 Middle Sacramento River channel migration 1904-2007 upper portion

Channel centerline analysis

Channel centerlines were derived from a 1904 USGS topographic map (1:68,500) and aerial photography spanning 1937 to 2007 (Greco and Alford 2003; Greco and Plant 2003; Nelson 2007) (Figure 2 and Figure 3). Channel planform maps were digitized and stored in a GIS database (e.g. Greco and Plant, 2003). 1937 to 1997 maps were scanned from aerial photographs (displayed at a scale of 1:10,000) taken during low flow (estimated at 60 m^3/s to 85 m^3/s) and were used to trace the channel banks and thalweg location on-screen in ArcView (ESRI 2003). In order to consistently map a single-thread centerline, we defined a protocol for occurrences of mid-channel bars: bars were ignored if their widths were less than the average channel width, but for larger bars the larger of branch of the split channel was assumed dominant. The spatial uncertainty of mapped features using these techniques is ± 10m (Greco and Plant, 2003). Once a channel centerline was digitized and rectified, we defined a set of inflection points to delineate a set of bends. A mathematical algorithm was used to calculate curvature values every 0.25 channel widths (every 62.5 m) along centerlines for each year (Johannesson and Parker, 1989). A preliminary set of inflection points was defined based on nodes where curvature changed sign to segment the centerline into individual arcs. These arcs were then visually inspected and very short segments (less than 2 channel widths in length) were manually merged with their neighbors either upstream or downstream based on the planform to form a final set of segments for analysis. A suite of geometric attributes was then measured for each individual segment, as described below.

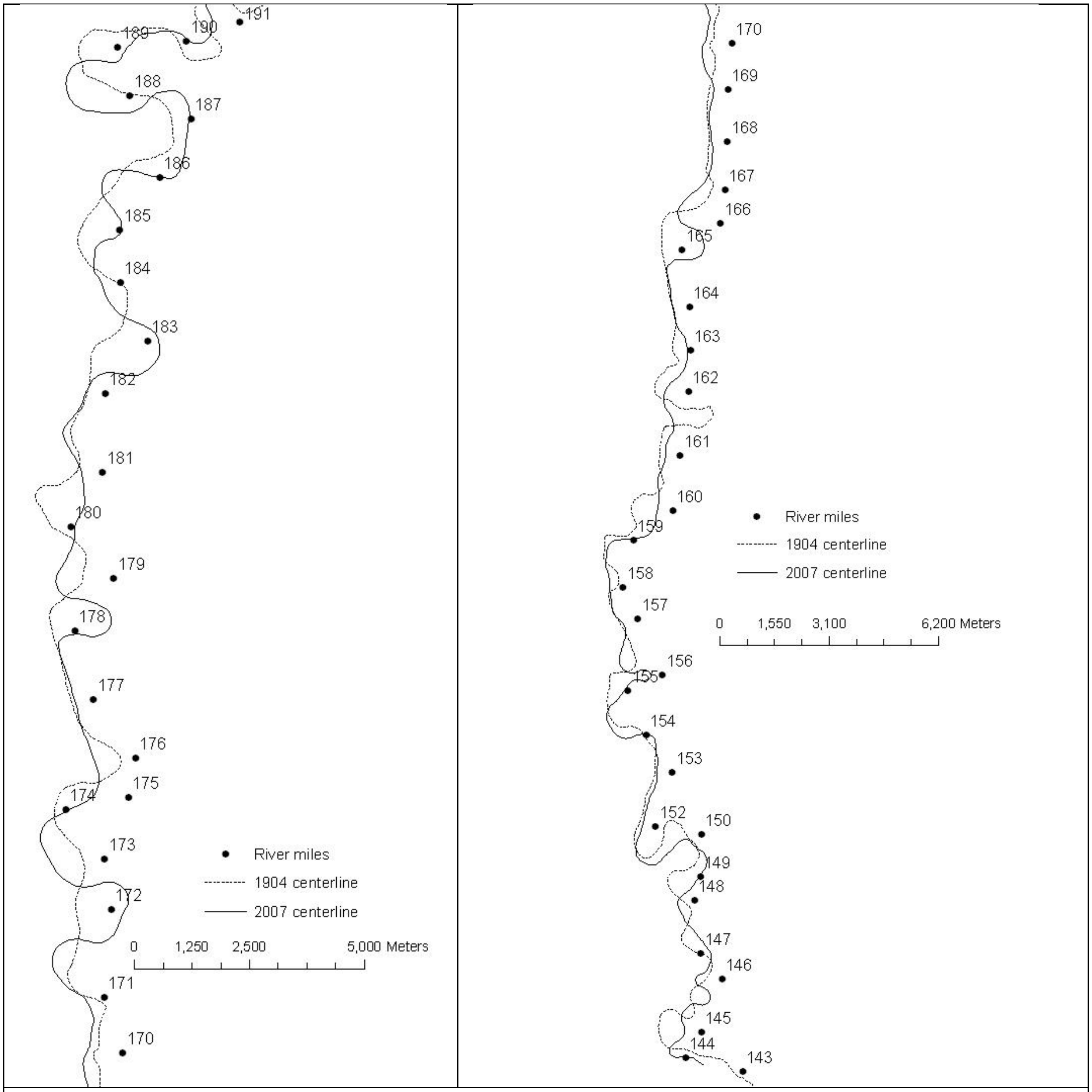


Figure 3 Middle Sacramento River channel migration 1904-2007 lower portion

Area of land reworked

The area of land reworked during a given time period is calculated by intersecting centerlines of channels from the beginning and end of the time period. The area between the two curves is calculated and called the area of land reworked (Figure 4). The migration rate of the channel is the area divided by the average length of the two channels (i.e., one-half the perimeter of the polygon between the curves).

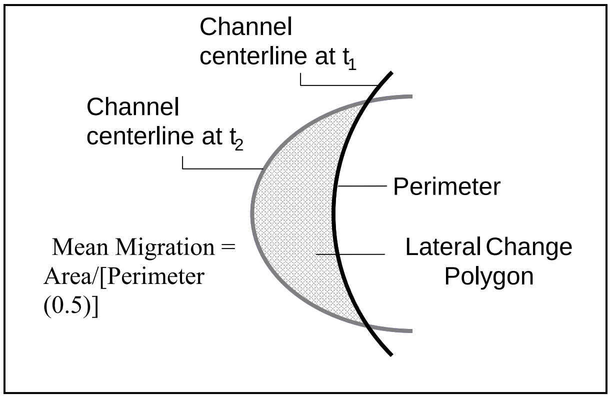


Figure 4 Definition of area reworked polygon

Meander migration rates

Progressive migration is lateral change that occurs via a continual but gradual process of bank erosion. Migration proceeds via erosion of the outside (concave in planform) bank and deposition of eroded material on bars located on the inside (convex in planform) bank (Lewin 1977; Ikeda, Parker et al. 1981; Knighton 1998). Under equilibrium conditions, rates of bank erosion and bar deposition are assumed equal. However in non-equilibrium cases where bar aggradation is accelerated, erosion may also be accelerated on the opposite bank, a hypothesis sometimes termed "bar push". The mechanism of bank retreat when fine-grained floodplain deposits are underlain by a coarser gravel-cobble layer, as is common in this case, is usually the undermining of floodplain materials due to the concentration of shear forces causing erosion at the bank toe (Darby and Thorne 1996; Micheli, Kirchner et al. 2004) Forces acting at the bank toe may be expected to increase with flow depth up to an effective maximum at bankfull.

The rate of progressive migration is generally assumed to increase with centerline curvature up to some threshold (Hickin 1983). Numerical models of progressive migration estimate that the maximum rate of bank erosion will coincide with the location of the peak differential between mean and near-bank velocities, generally lagging somewhat behind the location of peak channel curvature in the latter half of a meander bend (Ikeda, Parker et al. 1981; Furbish 1991) Over time, progressive migration may increase the sinuosity and/or cause the downstream translation of a meander bend, but empirical observations show this is not always the case on the Sacramento River, since in some cases (perhaps due to influences that are outside the channel) progressive migration has been observed to actually straighten the channel over time (Micheli, Kirchner et al. 2004).

The average annual rate of migration is calculated by mapping sequential channel centerlines and then quantifying the change in location of a channel centerline over time (Fremier 2003). Using an ArcGIS 8.3 programming script (ESRI 2003), an eroded-area polygon is created as shown above (Larsen et al. 2002, Micheli et al. 2004). The GIS is used to calculate: 1) the area of the polygon between the two centerlines, 2) the average length of the different centerlines forming the polygon, and 3) the time period between the two centerline locations of the river. The channel migration rate is then calculated as:

$$\frac{A_r}{tL} \qquad [1]$$

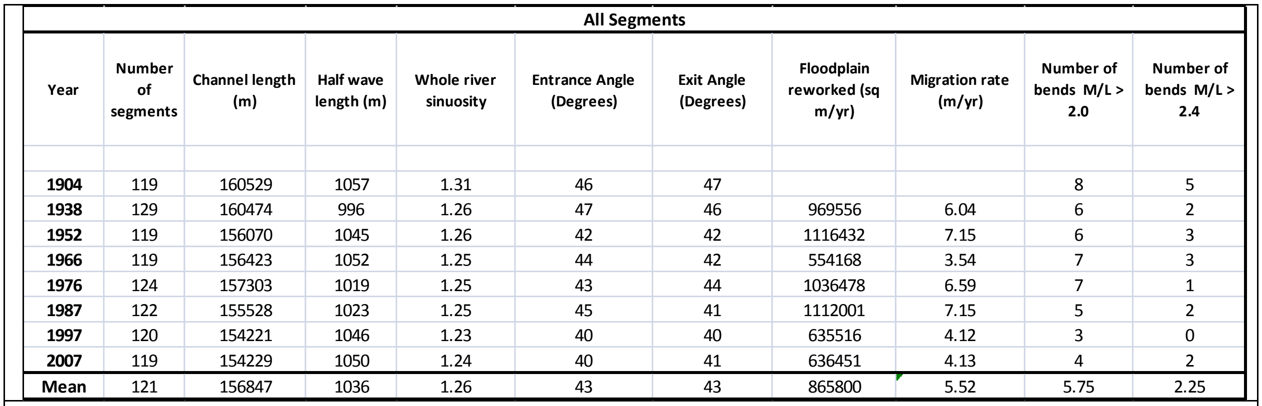
where A_r is the area reworked for a given polygon, as defined above; L is the average channel length of the two centerlines for a given bend; and t is the time in years that had elapsed between the two channel centerlines. The average centerline length is used to standardize the migration rate for variable bend lengths, resulting in the average rate of migration per year per length of channel for a given period of time. Equation 8 calculates the migration rate as a linear distance per time; the rate of land reworked is reported as an area per time, by using Equation 4 without dividing by the length (L).

Graphs of area reworked and migration rate will have identical shapes, but units and scale differ. Because one segment may have a larger length (for example) than another, knowing only the area reworked does not tell you the relative dynamism of two segments. When the channel movement is normalized by length, one can compare the rates at which the two segments move.

RESULTS

Analysis of the “whole river” and all segments

The whole river length was divided into individual segments based on the methods described above. Between 1904 and 2007, the total number of segments was relatively constant ranging from a minimum of 119 **to a maximum of 129 and the total river length varied from a minimum in both 1997 and 2007 to a maximum in 1904 (**Table 1**). Whole river sinuosity varied exactly as channel length, because whole river sinuosity is the length divided by a constant reference valley length.**



All Segments										
Year	**Number of segments**	**Channel length (m)**	**Half wave length (m)**	**Whole river sinuosity**	**Entrance Angle (Degrees)**	**Exit Angle (Degrees)**	**Floodplain reworked (sq m/yr)**	**Migration rate (m/yr)**	**Number of bends M/L > 2.0**	**Number of bends M/L > 2.4**
1904	119	160529	1057	1.31	46	47			8	5
1938	129	160474	996	1.26	47	46	969556	6.04	6	2
1952	119	156070	1045	1.26	42	42	1116432	7.15	6	3
1966	119	156423	1052	1.25	44	42	554168	3.54	7	3
1976	124	157303	1019	1.25	43	44	1036478	6.59	7	1
1987	122	155528	1023	1.25	45	41	1112001	7.15	5	2
1997	120	154221	1046	1.23	40	40	635516	4.12	3	0
2007	119	154229	1050	1.24	40	41	636451	4.13	4	2
Mean	121	156847	1036	1.26	43	43	865800	5.52	5.75	2.25

Table 1 Measured channel geometric values for all segments

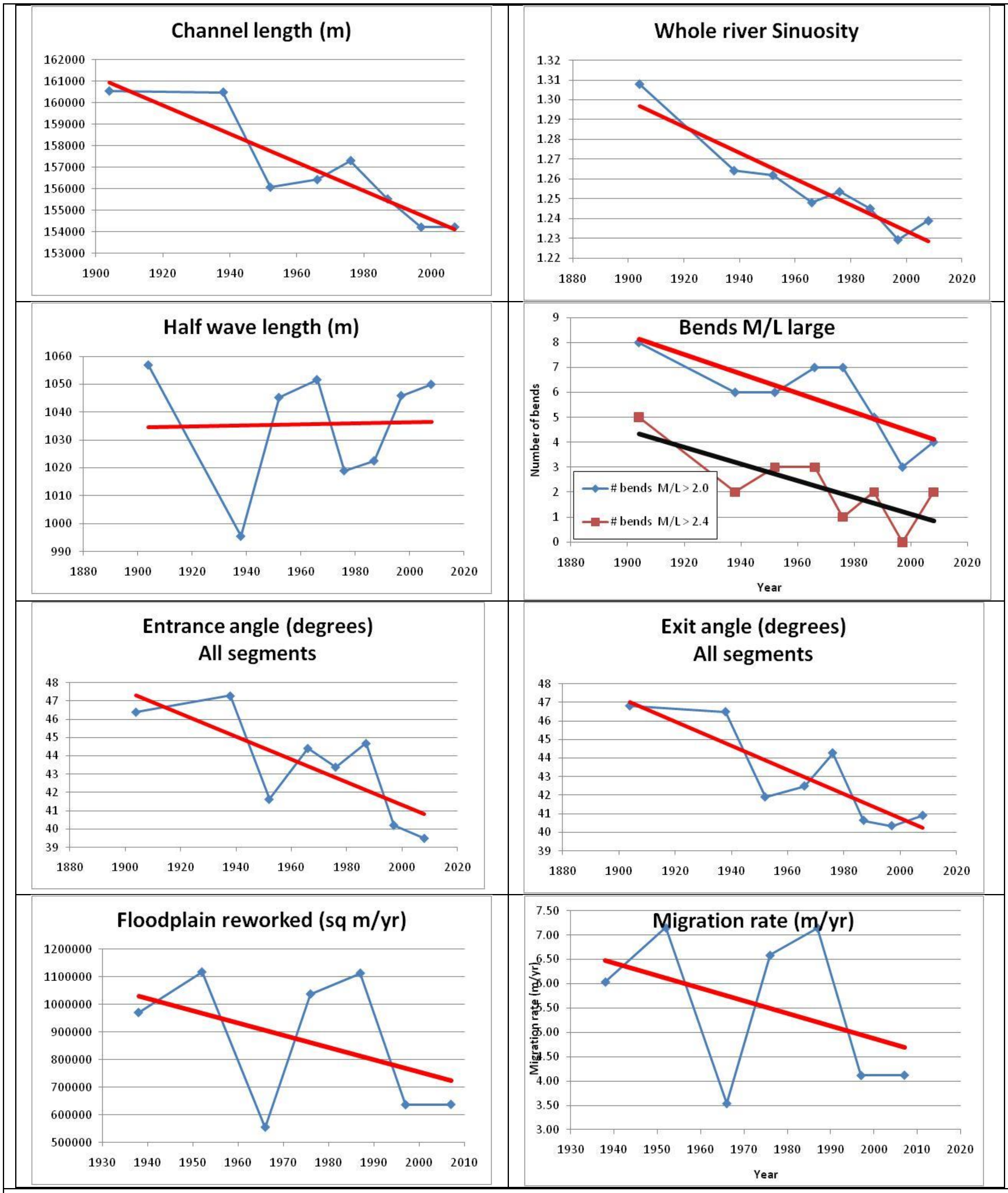


Figure 5 Graphs of measured channel geometric values for all segments

Analysis of sinuous bends

The total number of segments was divided into individual segments with sinuosity less than 1.1 (which are considered to be straight reaches) and segments with sinuosity greater than or equal to 1.1 (which are considered to be sinuous bends). Between 1904 and 2007, the total number of bends decreased, although there was great variation and the pattern of decrease is not significant **(**Table 2 **and** Figure 6**). The percent of channel with sinuous bends remained relatively constant. Bends tended to decrease in sinuosity and in exit and entrance angle magnitudes. The wavelength (twice the half-wavelength) and the radius of curvature tended to increase slightly.**

Bends (segments with sinuosity > 1.1)								
Year	**Number of bends**	**Channel length (m)**	**Half wave length (m)**	**Sinuosity of bends**	**Entrance Angle (Degrees)**	**Exit Angle (Degrees)**	**Radius of curvature of bends (m)**	**Percent (length) meandering**
1904	74	110095	1038	1.48	63	63	709	69%
1938	70	95643	941	1.46	68	67	600	60%
1952	67	99537	1042	1.44	65	63	683	64%
1966	67	101992	1085	1.41	69	64	663	65%
1976	67	92539	957	1.43	65	66	607	59%
1987	70	101699	1043	1.40	67	59	675	65%
1997	70	103813	1099	1.37	59	61	744	67%
2007	64	98155	1106	1.42	62	65	724	64%
Mean	69	100434	1039	1.43	65	64	676	64%

Table 2 Measured channel geometric values for bends

Percent (length) meandering

Sinuosity of bends

Half wavelength of bends (m)

Radius of curvature (m) Bends

Entrance angle of bends (degrees)

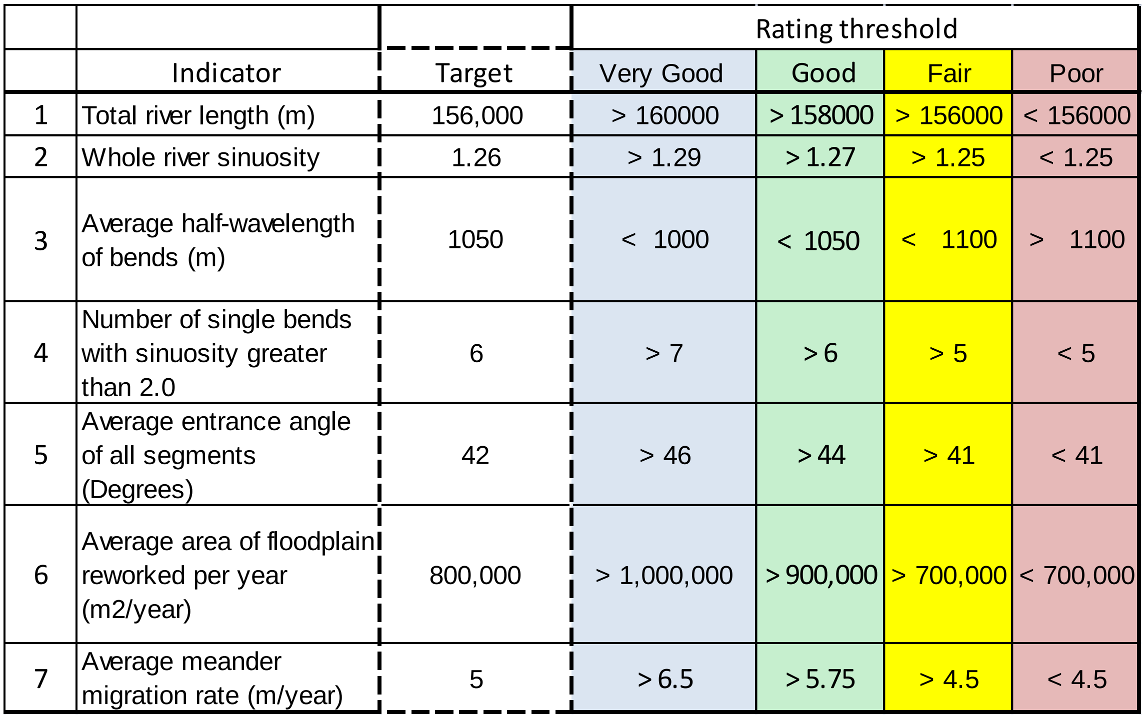
Exit angle of bends (degrees)

Figure 6 Graphs of measured channel geometric values for bends

River health indicator metrics

Each indicator metric is considered, with a description of specifically how it was defined, a rationale for being a meaningful metric, and a description of how the rating thresholds were established. For each indicator, ratings were established in four steps ranging from very good to poor. These rating ranges are shown in Figure 7 and Table 3 in different colors. The blue is very good, green is good, yellow is fair, and red is poor. The target value, which is the value that is targeted for a restoration goal, is show by the heavy dotted line. The data that were analyzed to produce the graphs of indicators over time are the data described above.

Table 3 and Figure 7 show the results of the ratings assigned to the indicator metrics. These metrics and values are explained below. All the indicators are for the same locations and time increments on the Sacramento River. Because all the metrics are related to the channel morphology, some of them are interrelated.



			Rating threshold			
	Indicator	Target	Very Good	Good	Fair	Poor
1	Total river length (m)	156,000	> 160000	> 158000	> 156000	< 156000
2	Whole river sinuosity	1.26	> 1.29	> 1.27	> 1.25	< 1.25
3	Average half-wavelength of bends (m)	1050	< 1000	< 1050	< 1100	> 1100
4	Number of single bends with sinuosity greater than 2.0	6	> 7	> 6	> 5	< 5
5	Average entrance angle of all segments (Degrees)	42	> 46	> 44	> 41	< 41
6	Average area of floodplain reworked per year (m2/year)	800,000	> 1,000,000	> 900,000	> 700,000	< 700,000
7	Average meander migration rate (m/year)	5	> 6.5	> 5.75	> 4.5	< 4.5

Table 3 Indicator metrics rating thresholds

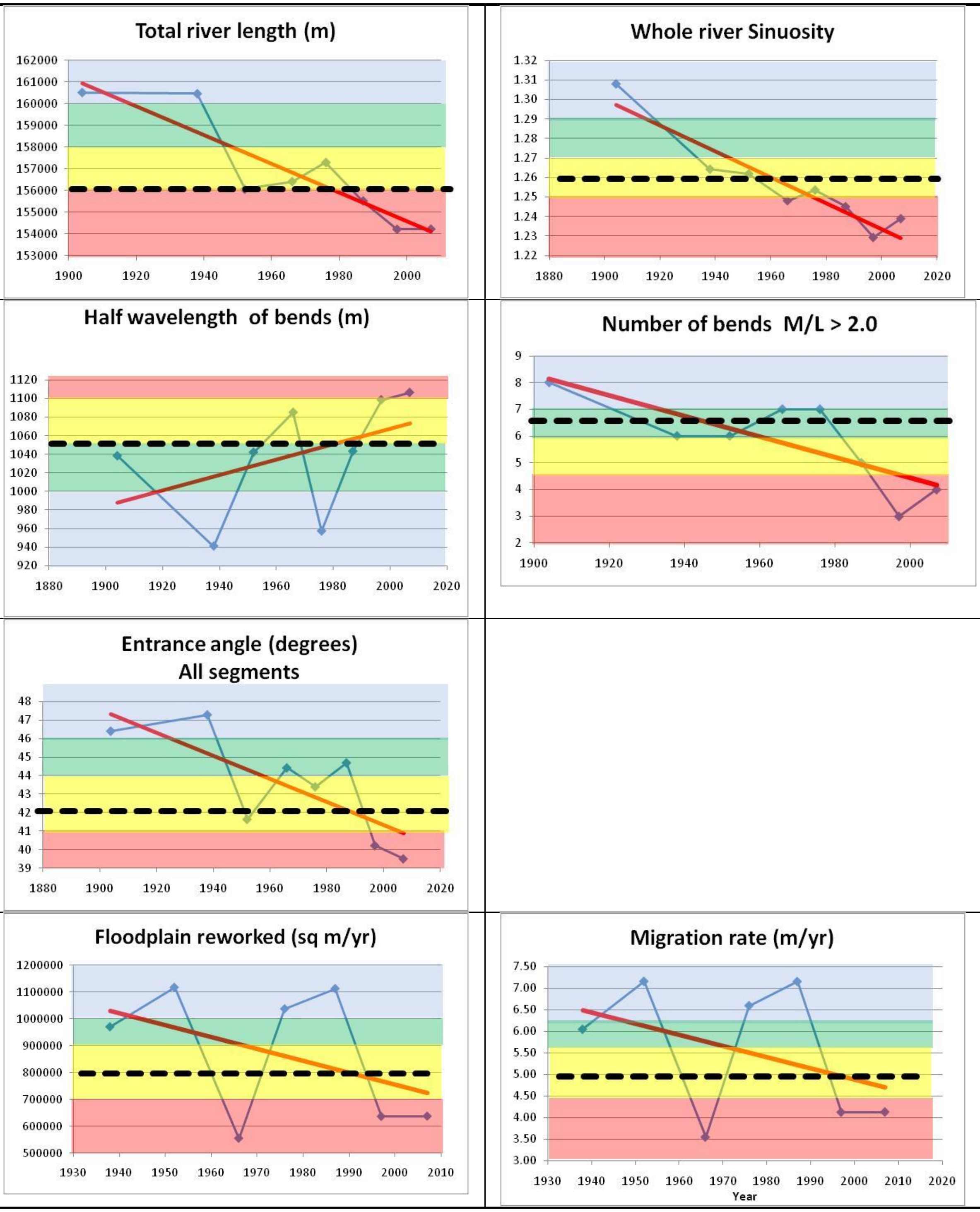


Figure 7 Graphs of channel indicator metrics

The dashed line indicates the value that has been chosen as a target value. This target would be an ecosystem indicator goal for restoration. The colors indicate ranges of the indicator metric that are “very good” (blue); “good (green); fair (yellow); and poor (red).

Total river length

Total river length is defined as the distance along the channel centerline drawn from the Red Bluff Diversion Dam (RM 244) to the Colusa Bridge (RM 143). The total river length was measured by measuring the centerline length of the sinuous channel using GIS tools. Because the river tends to be located in different locations through time, it is important to locate the ends of the channel for each year, and to "trim" the ends so that they start and end in the same location. In order to do this, we drew a reference line that "cuts" the end in the same location, as shown in Figure 8.

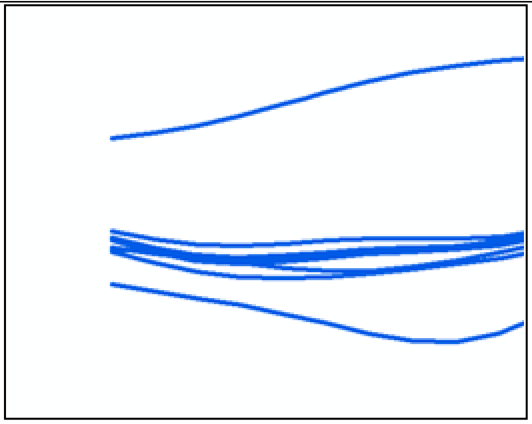


Figure 8 Trimmed ends of channel centerlines

The methodology for drawing a centerline was described above. The total length of river between a starting location and an ending location is a clear and obvious measure of the size of the river. For ecosystem processes related to the areal extent of river channel, or of riparian habitat related to the river bank, a greater total length of river (given fixed end locations) will provide more area, and therefore more ecosystem functions and processes. For example, a longer channel allows there to be more potential area for all riparian forest dynamics. Total river length is by definition a large scale metric that assesses the overall health of the river, although the exact extent must be specified. The same principle may be used for smaller reaches. This indicator was previously used as a metric of river health on the Willamette River in Oregon (IMST 2002).

In order to establish the rating thresholds from the existing data, four evenly spaced categories suggested themselves and were chosen by eye. The desired rating is a value judgment that might best be decided by an expert panel. A reasonable target was chosen to be 156000 m, which is the mid-range of the lengths over the last century.

Whole river sinuosity

The whole river sinuosity (called reach sinuosity in Figure 9) is calculated as the sum of the arc lengths (M's) for all bends divided by the sum of the half wave lengths (L's) (Figure 9). The arc length and half wave length are both measured between successive inflection points of single bends. Whole river sinuosity provides a measure of channel complexity and river dynamism. Descriptions of single bend sinuosity are well documented in fundamental texts on fluvial geomorphology (e.g. Leopold, Wolman et al. 1964; Dunne and Leopold 1978; Richards 1982). The key distinction to note is that a single bend sinuosity as defined above is used as the basis for a cumulative total river sinuosity. The total river sinuosity is the weighted average of the single bend sinuosities. In essence, it is the "along the river" sinuosity of the entire river.

Because our method utilizes the sinuosity of single bends, single bend sinuosity is also an effective site-specific indicator that can be used in comparing sites, at a scale that varies from the entire river to a single bend.

For the purposes of developing new floodplain area in the form of pointbars, a preferred range of sinuosities was estimated. The estimated threshold values (Figure 7 and Table 3) were visual estimates based on the available data. The current whole river sinuosity is 1.24 which is considered "poor". When the overall sinuosity of the river (or average of all the bends) is used as a rating, it is desirable to have a sinuosity (which we correlate with the potential for channel dynamism) that is similar to what was present in the past. This suggests a target average sinuosity in the "fair" range (1.25-1.27).

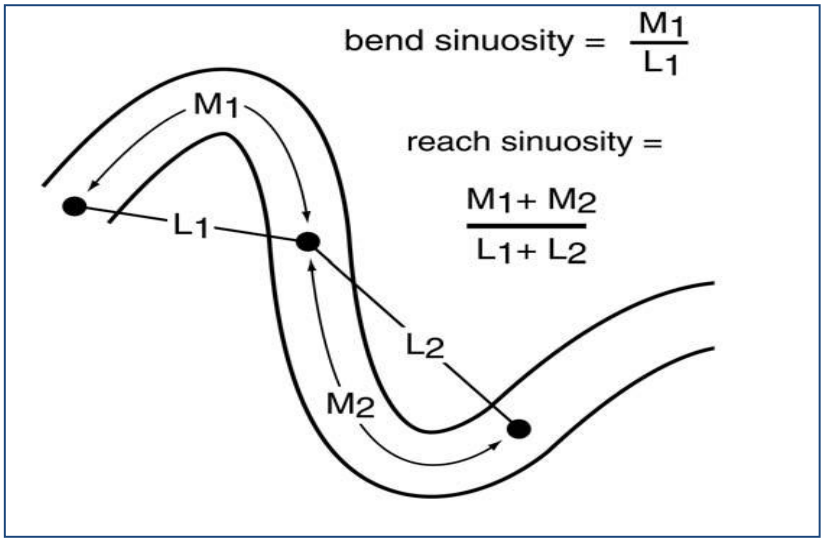


Figure 9 Definition graph of whole river sinuosity

Another method of calculating whole river sinuosity is to consider the channel length versus a down-valley length (Richards 1982). This was not used because this does not capture the dynamism that has occurred in the Sacramento River channel itself as clearly as the weighted average of the individual bends. It is likely that analysis of small geographic scales (less than 10-20 miles) or short time periods (less than 10 years) would not yield meaningful changes in whole river sinuosity.

Average half-wavelength

Average half-wavelength is defined as the length-weighted-average line distance between inflection points all bends between Red Bluff and Colusa. The distance between inflection points is a measure of the wavelength of a meander or a meander bend, where "wavelength" is used to characterize a fundamental measure of the scale or size of a meander. In this study "bends" were defined as any segment that had a sinuosity greater than or equal to 1.10. Wavelength is typically measured as the straight line distance from one point of inflection (through two bends) to the inflection point following the second bend (Figure 10). The distance between successive inflection points is a half-wavelength, which we use as an indicator because we are focusing on individual bends, rather than on pairs of bends. The half-wavelength, or distance between inflection points for individual bends, is determined by measuring the straight-line distance between two adjacent inflection points. The methods for calculating the wavelength are documented in typical texts on river morphology (Leopold, Wolman et al. 1964; Richards 1982; Knighton 1998) and has been previously used in studies on the Sacramento River (Larsen, Anderson et al. 2002; Micheli, Kirchner et al. 2004).

Note that most research and literature simply refer to the "wavelength." Our use of half-wavelength is conceptually the same, only numerically half the value of the standard wavelength. Half-wavelength is easier to measure, less open to interpretation, and clearly represents the hydraulic characteristics of a single bend. Many of the general statements that we make about the half-wavelength apply to the wavelength.

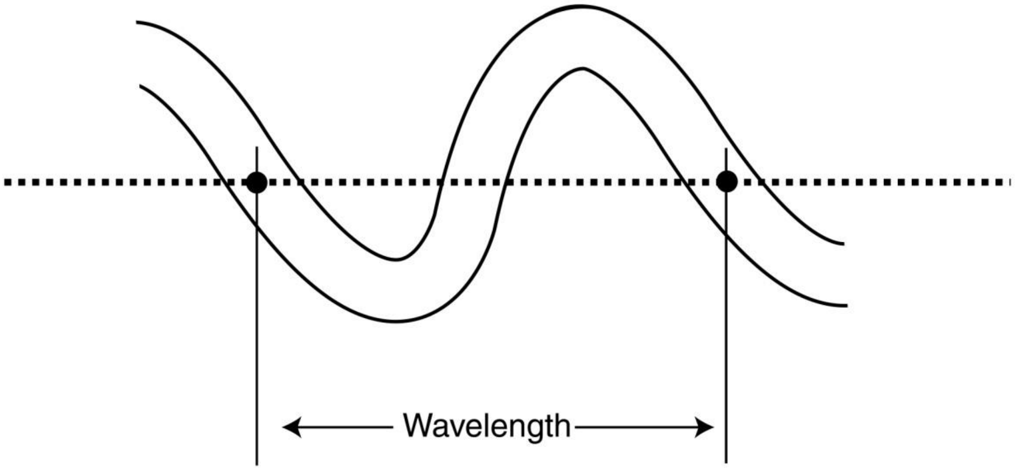


Figure 10 Definition graph of a complete meander wavelength.

The wavelength has been correlated with flow. In what has been called the pivotal first investigation of river morphology, Leopold et al. (1964) show that the dominant discharge ("effective" discharge) and the meander wavelength are empirically related. This is important for river managers who are charged with managing the flow of a river. A team of advisors should decide whether an increase or a decrease in average half-wavelength is beneficial for the given system. Generally, if the characteristic or channel-forming flows of the system increases, the average half-wavelength will increase. Since the construction of Shasta Dam, the hydrology of the Sacramento River has been altered. By looking at wavelength we may assess the response of the study reach to hydrologic and geomorphic changes of the

Sacramento River. We can look at how half-wavelength changes over time to consider temporal changes, and can look at how half-wavelength changes spatially to understand spatial differences in the geomorphology. (Brooks, Gehrke et al. 2004) used wavelength to consider channel dynamics in relationship to woody debris deposition. The use of channel wavelength as an indicator of river channel "health" is an area where active research would be beneficial.

The ratings given above are preliminary estimates based on visual inspection of graphed historical data that require further investigation. These estimates serve to motivate further study. The current indicator value for average half-wavelength is 1110 m (*bends only*). This is within the range of variation of the historical condition. The 2007 indicator value for half-wavelength of all *segments* is 1050 m. The significance of this was discussed above. A desired rating for *bends only* is estimated to be 1050 m. This is open to determination pending further research. The value for 1904 is 1040 m (*bends only*).

Number of single bends with sinuosity (M/L) greater than or equal to 2.0

Single bend sinuosity equals the ratio of the arc (curved) length of a channel bend to the half-wavelength (M/L) (Figure 9). Arc length of a channel bend is defined as the length of the channel centerline between sequential inflection points; half-wavelength is the straight line distance between sequential inflection points.

The sinuosity of a single bend represents the cumulative curvature throughout the bend, and indicates the degree to which the bend is curved. The degree to which a bend is curved correlates directly with the flow velocities and flow patterns in a river channel bend. The flow velocities and flow patterns are then directly related to the spatial pattern and magnitude of bank retreat (migration), which ultimately are related to the renewal and creation of the riparian ecosystem.

Sinuosity provides a measure of channel complexity and river dynamism. In alluvial settings, a sinuous river has more cutbanks and point bars than a straight river. It is also likely to be a more active river in terms of riverine processes of meander migration, erosion and sediment deposition, although such processes may be constrained by the presence of riprap on the river bank. Because sinuous rivers have a greater complexity of habitats and ecological processes associated with them, they are more supportive of natural species (e.g., bank swallows, salmon) and communities (cottonwood forests).

In general, the greater the sinuosity, the more benefit there is for ecosystem processes. One measure of the beneficial complexity of the river curvature is the number of bends with a sinuosity greater than or equal to 2.0. All trends for sinuosities ranging from 2.0 to 2.4 (over eight time periods) show a decrease over time in the number of high-sinuosity bends. The sinuosity of 2.0, which will also include the information for the higher sinuosities, was chosen as a metric to judge river health. The number of bends of sinuosity greater than or equal to 2.0 is by definition an indicator that refers to a length of river at a defined scale greater than a few bends in length. As defined in this case, it is used as an indicator of the river between Red Bluff and Colusa.

The indicator rating thresholds for number of bends with sinuosity greater than or equal to 2.0 were established by visual inspection of the plotted data (Figure 7 and Table 3). In 2007, there were four bends with sinuosity greater than or equal to 2.0, which is considered "poor". Six bends with 2.0 or greater sinuosity in the study reach would result in a rating of "good."

Average entrance angle

The entrance angle equals the angle between the line connecting bend inflection points and a tangent to the channel centerline at the upstream inflection point (Figure 11). This indicator is an average value for all segments in a given time period on the river between Red Bluff and Colusa. The indicator metric is for entrance angles including every mile of river, separated into individual segments by inflection points. There is no lower threshold for entrance angle in this tabulation.

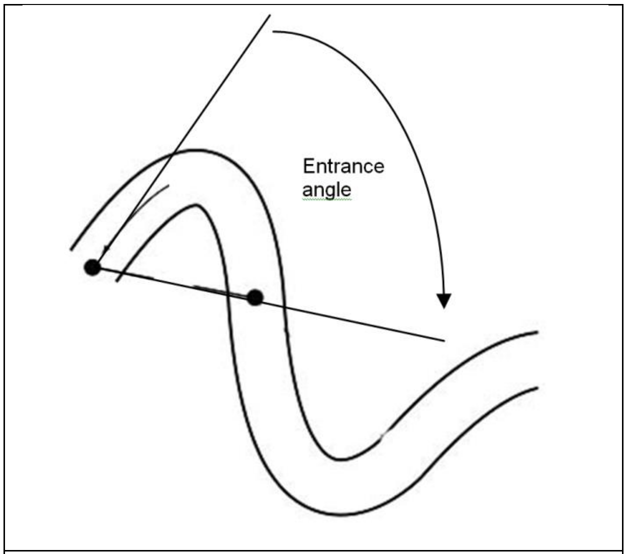


Figure 11 Entrance angle definition sketch

The entrance angle represents the upstream curvature of a bend and can be correlated with a tendency to cutoff (Larsen, Anderson et al. 2002; Avery, Micheli et al. 2003; Constantine and Dunne 2008; Constantine, McLean et al. 2010; Micheli and Larsen 2010). Cutoffs can produce oxbow lakes on the Sacramento River, which are important habitats (Morken and Kondolf 2003).

The entrance angle of a bend is complementary to other indicator metrics that reflect the shape of the river, particularly the degree of curvature. Therefore, it would be expected that as the sinuosity or curvature (inverse of radius of curvature) *decreases*, there would tend to be a decrease in the entrance angle. The measure of the entrance angle itself is important because it is specifically related to the tendency for cutoff occurrence (Larsen, Anderson et al. 2002; Avery, Micheli et al. 2003; Constantine and Dunne 2008; Micheli and Larsen 2010). Like many of the other indicators in this series, the indicator is measured at an individual bend, but the metric that is being used is the average for the entire river. This reflects an overall trend of the whole river, which is a good metric. It can be used at the single bend scale, and would reflect the site-specific evolution of the bend in question, but it would be difficult to assign a rating to that single value.

The rating thresholds were estimated visually by graphical inspection. The current whole river average entrance angle is 40 degrees, which is qualitatively rated as poor. It would be reasonable to aim for a “fair” rating. Qualitatively, that is aiming for a mid-range of return to a condition of more complex (more curved) bends. This avoids the extreme of a “return to pristine”, and, at the same time, recognizes the need for improved river conditions. There is a similar trend for the exit angle, as shown in Figure 5.

Area of floodplain reworked per year

The area of floodplain reworked per year was measured by measuring the area of the “eroded area polygon” (Figure 4) that is formed when two channel centerlines from two different time periods are intersected. The area that results is then divided by the number of years in the time interval between the two time periods. The area of floodplain reworked measured in this way is an estimate of “new floodplain created” (Larsen, Girvetz et al. 2006).

For ecosystem processes related to the areal extent of river channel or of riparian habitat related to the river bank, the reworking of land and creation of floodplain is critical for ecosystem functions and processes (Malanson 1993; Naiman, H. et al. 2005; Greco, Fremier et al. 2007). For example, Freemont cottonwood development depends on point bars that are created. As cottonwoods mature, they depend on the time-sequence of land reworked or floodplain creation. Other riparian species also require a heterogeneity of floodplain age, which is produced by land being reworked (van Coller, Rogers et al. 2000; Dixon, Turner et al. 2002; Steiger, Tabacchi et al. 2005). The “per year” measurement of land reworked is a metric of the rate that such land is being produced. A related metric is floodplain age (Fremier 2003).

The area of floodplain reworked per year is by definition a metric that averages rates over a time interval. It is best used to compare different sites during the same time period. It is somewhat duplicative of migration rate, but in this case gives an actual area. It is also a useful metric to compare river reaches. In order to assesses the overall health of the river, the rate of area reworked per year for the whole river can be calculated to see if there is a trend over time (for example, is the rate continuously decreasing?) The same principle may be used for smaller reaches.

As with other geomorphic indicators, the original value from 1904 of area reworked was used to define a “historic” or “very good” condition. Using visual inspection of the graphed data the rating thresholds were established. The desired rating would best be decided in an expert panel. A reasonable target might be the mid-range of the rates over the last century. As with other indicators, just the idea of a “target” value promotes the important question “what would it take to move in the direction of the target?”

The rationale for setting a target value that would increase the current rate of floodplain created is that there are areas that are constrained that could possibly be allowed to change, which would increase the rate of floodplain reworked.

The area reworked in any given measurement will depend on the length scale over which the metric is measured. For example, suppose two sites were chosen to measure the metric: one a mile long and the other 1/10 of a mile long. Obviously, the longer one would tend to have a greater area of floodplain reworked than the smaller one, regardless of the relative dynamism of the areas. This is an important consideration when comparing different sites. A possible way to compare different sites is to choose similar lengths. Another way is to non-dimensionalize by length. This would then be the same as the channel migration rate because area (m^2) per year (yr) divided by length (m) becomes the migration rate in (m/yr).

Meander migration rate

Channel meander migration rates are calculated by dividing the polygon area of each segment by the average stream length, and then establishing a yearly rate by dividing by the number of years between the initial and final times (Larsen, Anderson et al. 2002; Micheli, Kirchner et al. 2004). It is a simple, reproducible measure of the magnitude of shift in channel location perpendicular to the original channel centerline. Dividing area by length results in a length. When this is divided by time, it results in a rate expressed in length/year.

Channel meander migration, also known as lateral migration, is measured by mapping sequential channel centerlines and by quantifying the change in location of a channel centerline over time using the eroded-area polygon. An eroded-area polygon is created as described above. ArcInfo calculates the area and perimeter of the eroded polygon, from which the average distance migrated perpendicular to the channel centerline is calculated. The lateral migration distance is equal to the polygon area divided by the average stream length for the polygon (with average stream length equal to one-half of the polygon perimeter). Finally the rate is normalized by the number of years of migration so that the final metric is m/yr.

The meander migration rate of the entire channel indicates the degree to which the river is dynamic . The related measure, area reworked, includes information about the patch size under consideration. Taking area reworked per year and “normalizing” by the average length of the patch, gives a dimensionless quantity that can compared across all patch sizes. In the case of whole-river, the graphs for change over time (for floodplain area reworked and for meander migration rate) have precisely the same pattern because the area of the patch in each case is the same - the sum of all the patches in the entire study reach. Meander migration rates are more appropriate measures in order to compare values across river systems, and would tend to be scaled by the size of the river. The degree to which a bend is dynamic provides a characterization of the river’s ability to create new floodplains. Dynamic river processes (e.g., erosion, sediment deposition) revitalize riverine habitats and are beneficial to native flora and fauna (e.g. Shankman 1993; Naiman, Bilby et al. 2000). Cottonwood and willow forests naturally regenerate on freshly deposited floodplain surfaces, and salmon and other aquatic species benefit from fresh gravel inputs.

In addition to a whole-river measure, the meander migration rate is an effective site-specific indicator to be used in comparing sites. If considered for single bends, which was not done here, the definition of good or poor meander migration rates is not a simple question. There are “healthy” sections of the river in all migration rate categories, because migration rate is strongly related to the curvature of the river. The meander migration rate of the whole river, which is a “lumping” needs to be qualified, because it is a complex measure that incorporates many processes such as channel revetment and changing erosion rates due to conversion to agriculture. Given this caveat, it seems to be a useful indicator that reflects the overall dynamism of the river. A useful procedure, which is beyond the scope of this study, is that the migration rate be computed and then averaged for all non-constrained bends between Red Bluff and Colusa.

If the evaluation of the migration rate is considered in terms of floodplain creation, the greater the migration, the better. In establishing a threshold for the ratings, one procedure would be to using a standard deviation (or plus or minus 25% from the mean) as an increment. The rating thresholds that were used were selected to parallel those of the floodplain reworked. Because both area of floodplain reworked and migration rate derive from the same data, these thresholds would logically be the same.

Note that historically, there have been two clustering's of migration rates, the higher ones, and the lower ones. Aiming to restore the rates in the upper zone might also a reasonable goal. The rating of "good" for meander migration rates might be shifted up between 6.0 and 7.0 m/yr. When assigning values for the desired rating, we want to pick a migration rate (which we correlate with the potential for channel dynamism and creation of floodplain area) that is attainable. A thorough investigation of the potential for channel migration in this study reach would have to be performed in order to see if the chosen desired rating is achievable. One good reason to use this desired rating is to set an estimated goal that will encourage research and study to see if it is achievable. As with other indicators, one important question to answer would be "what would you have to do to achieve this goal?"

SUMMARY AND DISCUSSION

From 1904 to 2007, the geometric complexity and meander migration dynamics of the Middle Sacramento River have decreased, which has implications for the health of the riparian ecosystem. The river channel length tended to decrease, suggesting that the river length lost to cut-off and other processes has not been replaced by an increase in length due to channel migration over that time period. In addition, the formation of high sinuosity bends susceptible to future cut-off has declined. The river sinuosity, the average entrance and exit angle magnitudes, and the average migration rate (and floodplain reworked) – all tended to decrease with time.

In order to provide quantitative metrics that can indicate the health of the river system, especially over time, seven of the measured metrics were chosen specifically as ecosystem health "indicator metrics." Radius of curvature was not used because bend sinuosity gives similar information, and it is easier to accurately measure. The exit angle was not used because the entrance angle captured much of the same information. The percent meandering is currently the same as the long-term average, and was considered to not be an informative indicator.

Two different kinds of river classifications were represented in the final indicator metrics. "All segments" represent metrics measured over the entire river channel length, which is separated into discreet segments between successive inflection points. "Bends" represent sinuous meander bends and are defined as those segments with sinuosity greater than or equal to 1.1. Metrics from both categories have their own strengths in representing the dynamic health of the river system. The segment category captures a view of the entire river; the bend category more clearly specifies the changes in geometry of the sinuous portion of the river. A useful link between the two categories is the percent of river that consists of sinuous bends, which has remained close to the average value from 1904 to 2007.

Establishing ratings for the river health indicator metrics provides a first estimate in defining metrics of ecosystem health that can be used to evaluate, enhance, and restore ecosystem functioning related to the riparian ecosystem of the Middle Sacramento River. The ratings established here were qualitative estimates based on expert knowledge of the river system. The "desired" or "target" rating was also a qualitative estimate based on expert knowledge. Both the "very good-through-poor" rating and the desired target rating are subject to more analyses.

A theoretical approach to the concept of a target value is to pose the questions: 1) what would be an optimum condition (for example: is a longer or a shorter river better); 2) and what could be done to return to a better or an optimal condition. Even if a complete return to the optimal condition were not practically possible, attempting to answer these questions would reveal important information about the current state of the river and the possibilities and limitations for restoration.

We assume that a longer, more sinuous river is better for the ecosystem (e.g. Brookes 1987; James and Henderson 2005). In alluvial river settings, a sinuous river has more cutbanks and point bars than a straight river. It is also likely to be a more active river in terms of riverine processes of meander migration, erosion and sediment deposition, although such processes may be constrained by the presence of riprap on the river bank. Because sinuous rivers have a greater complexity of habitats and ecological processes associated with them (e.g. Boano, Camporeale et al. 2006), they are more supportive of natural species (e.g., bank swallows, salmon) and communities (cottonwood forests) (e.g. Jungwirth, Moog et al. 1993; Brunke and Gonser 1997).

The rationale for many of the desired target ratings is that there are areas on the river that have been constrained that could possibly be allowed to migrate. Such changes would increase the length, sinuosity, and entrance angle, and would also increase the migration rate and area reworked. A return to aspects of the geometry and dynamic rate of change of the river as it was at some time in the past is not aiming at "a return to pristine," but sets a goal that can be used to monitor change.

Some of the indicators that we chose to use are measured at the individual bend scale, and their accumulation or whole-river averages are used as an indicator of total river health. This is true in the case of sinuosity, where the sinuosity of single bend can also be a meaningful indicator at a small scale. In this case, a metric that is useful for single bend sinuosity monitoring is the "rate of change of sinuosity". Research on single-bend "rate of change of sinuosity" would be useful.

A careful look at some of the changes in time of the indicator values show that some of the changes in the river have causes and conditions that conflict with each other. For example, there are at least two restoration projects that are currently in the planning stages that would initially decrease some indicator metrics, yet would have over-all benefit to ecosystem processes. These projects are the Kopta Slough project near RM 212 (Larsen and Greco 2002) and the Llano Seco / Princeton, Codora, Glenn pumping plant project near RM 178 (Larsen, Girvetz et al. 2007). Although these would, in the short-term, lead to reducing some of the geometric indicator metrics (length, sinuosity, entrance angle) they would confer other benefits (e.g. reduction in riprap, revitalization of natural processes of erosion and sediment deposition, creation of off-channel habitat, and an increase in migration rate and area reworked). Thus, as with other management actions, it is desirable to consider their effects from the perspective of multiple indicators.

Another example of complicated relationships is the whole river sinuosity and migration rate. The changes in sinuosity and migration rate on the Middle Sacramento River are the result of multiple (sometimes conflicting) causes. For example, sinuosity and migration rate have decreased due to bank protection; whereas sinuosity and migration rate have increased due to replacement of native riparian vegetation with agriculture (Micheli, Kirchner et al. 2004). Further studies should include examining the changing erosion rates due to the patterns of channel revetment and conversion to agriculture.

The wavelength is another indicator that would benefit from further research. As discussed above, the wavelength is related to the flow rate in a self-forming river. Changing wavelength, particularly if in trends over a number of time increments, indicates a fundamental change in the way a river is self-forming. As with the other geomorphic indicators, we might use the wavelength (average over all the bends in the river) in 1904 to define a “historic” or “very good” condition, but this is an area where some active research would help us determine how the indicator is related to ecological processes. What the data show is that the average wave length of all *segments* in 2007 is roughly the same as it was in 1904. In slight contrast, if the wavelength of only the *bends* is examined, there is a trend of increasing wavelength. This may – or may not – reflect a change in hydrologic conditions. More research needs to be done to determine what these data can tell us to help inform management decisions on the Sacramento River.

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