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ANALYSIS OF LATERAL CHANNEL ACTIVITY OF THE SACRAMENTO RIVER FROM AERIAL PHOTOS

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Analysis of lateral channel activity of the Sacramento River from aerial photos.
The technique of photogrammetry permits the study of contemporary river channel changes if the river is large enough and characterized by active evolution of geomorphic pattern. Results presented in the study confirm the dynamic and continual change of the Sacramento River channel and floodplain. The results also showed the channel narrowing along the active channel and straightening of the channel. This specific evolution of the river channel may be generally attributed to local geological conditions, discharge, the occurrence of floods, sediment transport, resistance to erosion and type, presence and density of vegetation. All these causes, except geological conditions, can be influenced by human activities. Analysis of the data set, enhanced by a wide range of field measurements and observations, have demonstrated a successive diminishing of the active floodplain and also higher occurrence of the river cutoff lakes.
Key words: lateral movement, active channel, floodplain, aerial photos, Sacramento River

INTRODUCTION

The aerial photo allows us to go back to the late 1940's with the scale usually ranging from 1:15 000 to 1:30 000 (Gurnell et al. 2003). The technique of photogrammetry opened a high potential for the study of the contemporary changes if the river is large enough and characterized by lateral movement, an active evolution of its geomorphic pattern so that it can be seen from interannual photo analysis.

The effect of cutoffs and oxbow lake formation in meanders was recognized on the Mississippi and other rivers in the first half of 20th century. It was the first use of photogrammetry in evaluation of fluvial geomorphology. Fisk (1947), already noted that the oxbow lakes gradually become filled with sediment and eventually form more resistant clay plugs in the floodplain, which cause variation in the rates of bend migration. Photogrammetry has been used to study channel movement and to document the processes of erosion and sedimentation. The classification system of alluvial rivers developed by Brice (1977) was defined with the use of aerial photographs and topographic maps. He also defined the methodology of comparative analysis of channel movement from aerial photos. Wiliams (1978) documented the channel width reductions by the use of photos of the Platte River. The reduction was the result of river regulation. Hooke (1977 and 1984) used the aerial photos and maps in her studies of lateral mobility.

The aerial photos are also used for diachronic analysis to cense wood and link wood with floodplain contribution, lake evolution (Citterio and Piégay

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2000), but also, the most popular, river landscape evolution (Lehotský et al. 2008) or channel movement (Gurnell 1997a, 1997b and 2003, Grešková 2003, Holubová and Hey 2005 and Piégay et al. 2005). Georeferenced and rectified aerial photos and maps are, therefore, the most desirable for the use in the analysis of meander migration, but often they can be expensive to obtain (Lagasse et al. 2003).

The Sacramento River is a good area for this approach. A long reach with channel movement (Constantine 2006), tedious work done to cense the existing photo (Greco and Plant 2003) and key-questions unresolved: can we expect any channel changes upstream to downstream because of the Shasta dam built in 1943?

The aim of this study is to describe and understand the temporal evolution of channel planimetry in relation to the geometry of the channel and active floodplain. This has been carried out on the Sacramento, an almost free meandering river between RM 243-143, with regards to active channel processes of erosion and deposition along the floodplain.

STUDY AREA

The Sacramento River is the largest river in California with a drainage area of 68,000 km^2. The influence of the geological features on bank erosion in this reach of the Sacramento was subsequently shown by Constantine (2006), who described three zones of active meander migration that exhibit different channel sinuosity and mobility. The basin of the Sacramento River consists of four principal geological units: (1) the Great Valley sedimentary sequence, located in the Coast Range, (2) the Franciscan formation, also part of the Coast Range, (3) the Klamath Mountains, to the north and northwest, which form an island arc terrane composed of marine sediments and granitic plutons, and (4) areas of Pliocene-Recent extrusive volcanic activity, located to the northeast of the river. The basin of the Sacramento River receives most of its water from January to March in the form of rain and snowmelt. The low discharge of the Sacramento River is about 85 cm during the summer.

The discharge of the Sacramento River has been regulated by the construction of the Shasta (1943) and Keswick dams. River regulation has reduced the magnitude and frequency of high flow events and has increased low flow discharges during the summer and autumn irrigation seasons (Buer et al. 1989). At a streamflow gauge (USGS 11377100), the pre-dam 2 and 10-year flood peaks are 3 310 and 5 840 m^3/s and the same post-dam peaks are 2 170 and 3 790 m^3/s (Constantine 2006). This information is important because the high flow events can cause large deposits on the margins of pointbars or can initiate meander bend cutoff events to create oxbow lakes (Hooke 2008). The bankfull channel width decreases with distance downstream, ranging from 500 to 120 m and averaging about 300 m (Constantine 2006).

Larsen and Greco (2002) noted that river locations along the Sacramento River are commonly referred to in river miles (RM) and the river mile designations were fixed in 1964. Due to subsequent channel migration, river mile designations are now essentially place names and no longer accurately indicate distance along the channel centerline.

The study reach (Fig. 1), from Red Bluff (rkm 230, RM 243) to Colusa (Rkm 370, RM 143), is free to migrate approximately along 52% of its length. Along the remaining 48% of the study reach, artificial levees or riprap confine the channel.

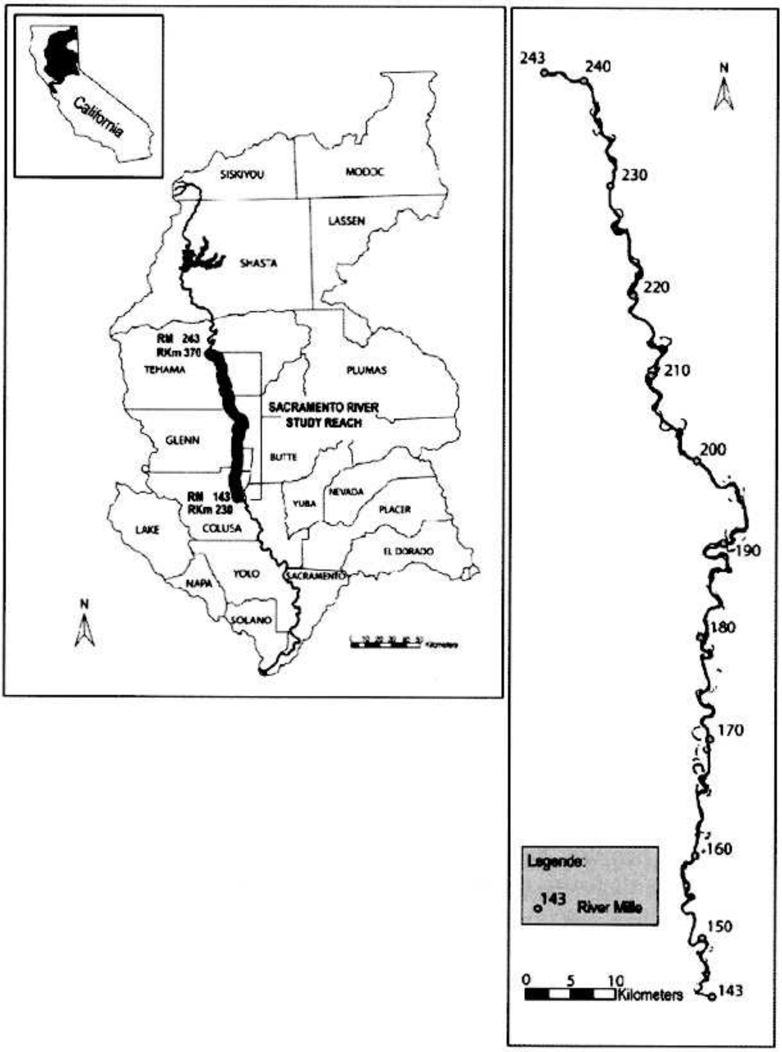


Fig. 1. Sacramento River Basin and study reach with active and former channels from Red Bluff to Colusa (modified by Greco and Alford 2003)

Greco et al. (2007) note that private landowners and irrigation districts have sought federal and state assistance to prevent erosion of their riverfront properties by installation of rock revetment (riprap). Riprap prevents lateral expansion of pointbars and reduces or eliminates the production of new land and thus impacts the regenerative capacity of primary succession processes and has a negative effect on riparian habitat. Buer et al. (1989) note that the channel riprap can cause incision to the bed of the river. The system of levees was completed in the 1920s. The Sacramento River was canalized from RM 0 to RM 144, from RM 145 to RM 176 the levees are set back from the river and from RM 176 to RM 244 levees are intermittently distributed and most are set back from the main channel of the river (Greco et al. 2007). Without channel migration, nursery sites of forest riparian ecosystems would be lost and existing communities would progress into late-seral upland communities. South of Chico Landing (RM 181), artificial levees flank both sides of the river and the width between levees ranges from 0.4-1.6 km (Larsen and Greco 2002). Setback levees favour the sustainability of connection between the active channel and the floodplain. The contiguous bank riprap levees limit the channel migration and the associated bend cutoff process (Larsen and Greco 2002).

The channel evolution and migration rates are functions of the local tectonic flow magnitude, sediment characteristics and bank properties (Johanneson and Parker 1989, Larsen et al. 2006). Annual migration rates observed on the Sacramento River varied between 0 and 39 m/year (Larssen et al. in press). The river influenced by the regulation of the flow and bend erosion by riprap construction generally predicts the reduction of the channel migration rates, but the determination of the simple causality can be difficult to achieve (Piégay and Schumm 2003). Micheli et al. (2004) compared the migration rates of the Sacramento River channel before and after the installation of the Shasta dam. The result was that the mean migration rates are 50% higher for the 1946 to 1997 interval than for the 1896 to 1946 interval. The bank erodibility was about 56% higher during the later time period. The results show that the study reach of the Sacramento River tends to migrate more quickly through agricultural land (the bank erodibility increases here by 80 to 150%) than through riparian forest. The riparian forests are highly productive and host great biological diversity, however, it is estimated that 95% of the forests in the Sacramento River system have been lost to agricultural land conversion, flood control projects and urbanization since the settlement of the valley in the mid-1980s (Larsen et al. 2006). Riparian vegetation on the inside of the meander loop also inhibits downstream migration of the meander loop and helps prevent cutoffs (Brice 1977). McGill (1987) studied changes in spatial distribution of riparian vegetation on the Sacramento River on the same study reach and noted a decreasing trend from approximately 1950 to 1972 and an increasing trend that began in the early 1980s. Greco and Plant (2003) noted that the meander bend cut-off events are expected to be episodic, with a 10-50-year or longer recurrence interval, meaning that potentially just one to six cut-off cycles may have been observed. Bank revetment and channel confinement by levees combined with the regulation of discharge from dam releases, have created several visually apparent geomorphic effects. This form was described by Brice (1977) as "deformed" meander bends.

METHODS

Methodological background

An approach to quantifying of the spatial patterns of channel migration that takes geomorphologic processes into account is the mapping of the low flow channels at various time intervals (Gilvear and Bravard 1996). The source of the spatio-temporal information is the map or an aerial photograph. The long data sets must be treated in a suitable environment proposed by using the GIS. The method used here in the sense of Thomlin (1990), Lo and Young (2002) is cartographic modeling as a map overlay process that uses functions to combine features and attributes of multiple map layers into a single map layer. The first thing to evaluate the methodology is the availability of the aerial photographs for comparable discharge conditions. Conformed to Greco's studies, the low flow is defined as discharge on the Sacramento River between 83 and 351 m^3/s as measured at the Bend gage (USGS gage ref. no. 11377100). These flows typically occur in the dry season (May-October). The definition of lake age is the moment of transformation of water to land in low flow conditions. Greco et al. (2007) confirmed that floodplain water bodies such as oxbow lakes and sloughs can vary significantly in their water levels inter-annually and intra-annually and thus they can confound land age calculations in those areas. The results of his study indicate that the rates of the new land production on the Sacramento River since about 1900 have been altered by the combination of at least four effects: the bank hardening effects of channel bank revetment that prevent erosion, impoundment of water due to storage, flow-regulation effects of the Shasta Dam, and conversion of natural vegetation to agriculture.

Recently, observable earth surface forms emerged as the primary source of ideas in nonlinear geomorphology (Philips 2003). The fluvial processes involved in the lakes' development are very complicated and the variables of importance are difficult to isolate. The major factors affecting the alluvial stream channel forms are: discharge, sediment load, longitudinal valley slope, bank and bed resistance to erosion, vegetation, geological conditions and human activities. Up to the present time, the problem has been more amenable to an empirical solution than an analytical one. Lagasse et al. (2003) noted while mathematical complexity of the analytical solution may be justified for research purposes, empirical approaches might produce results of greater utility to practicing engineers. The empirical approaches are more likely than the deterministic approaches to yield a practical methodology that will be useful to practicing engineers.

The synergic effects of physical, biological and cultural factors have continuously created and destroyed terrestrial and aquatic habitat complexes over long periods, making it difficult to perceive the cumulative effects of these changes over wide spatial scales and long temporal scales and GIS tools have made the analysis of landscape change more approachable (Greco and Plant 2003). The historical aerial photos have been used in studies determining trends in movements and planform behaviour. Many authors used them to measure the changes of channel width (Beschta 1998, Winterbottom and Gilvear 2000), the lateral movement rates (Hickin 1974, Mosley 1975, Hooke 1977, Brice 1982, Xu 1997, Micheli et al. 2004) bank and floodplain vegetation (Beschta 1998, Larsen and Greco 2002), chute cutoffs and avulsions (Beschta 1998), bar development (Macklin et al. 1998).

Data acquisition

Historical photographs were obtained from the University of California, Davis. The coverages included the data sets for the years: 1942, 1962, 1985 and 1999 (Tab. 1). The procedure involved first tracking of the four individual base active channels onto separate overlays, then digitizing, editing, georeferencing and quality checking the data.

Tab. 1. Characteristics of aerial photos (BOR – Bureau of Reclamation, ACOE – U.S. Army Corps of Engineers, DWR – Department of Water Resources, USGS – U.S. Geolgical Survey)

Year	Scale	Type	Coverage rkm	Date of flight	Sources
1942	1: 15 840	B&W Transparencies, B&W Print	230-312	5, 6 and 7 Jun 1942	BOR
1942	1: 10 000	B&W Print	312-369	24 Jun 1942	ACOE
1962	1: 24 000	B&W Print	230-268	19 October 1962	DWR
1962	1: 20 000	B&W Print	268-338	25 Jun 1962	Cartwright
1962	1: 20 000	B&W Print	338-369	21 July 1962	Cartwright
1985	1: 19 200	Color Prints	230-369	5 and 6 August 1985	BOR
1999	1: 7 200	Color Prints	230-369	14 Jun 1999	USGS

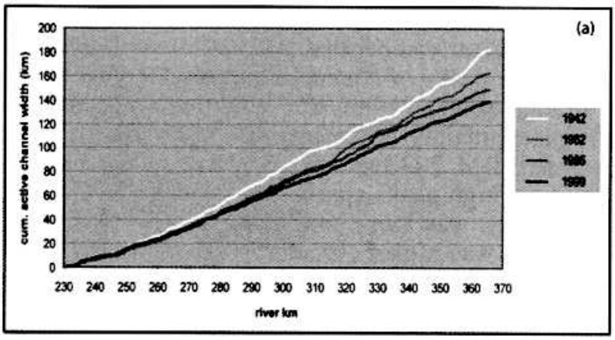
Following Greco and Plant (2003), the field verification study of the 2006 interpretive mapping techniques was done. The same photogrammetric and cartographic methodological process was applied to each historical aerial photograph set selected for temporal analysis. The polygon coverage was transformed to geographic co-ordinates applying a Universal Transverse Mercator (UTM) Zone 10 projection. The resampling method by the nearest neighbour interpolation was applied. Following the field study, interpretive mapping techniques and methodological process were applied to each historical aerial photograph set selected for the temporal analysis. The primary selection criteria were: (1) aerial photos taken during low flow conditions, and (2) a time interval of approximately once per two decades.

The error associated with the present study can be related to the quality of the aerial photographs and the accuracy of digitizing of the planitetric information. The contours were digitized in 1:2 000 scale and were checked by the following manual measurements. The data sources (aerial photographs) were limited by the quality and quantity of information (GIS layers). The raster cell size can be adjusted to provide finer resolution with regard to the spatial unit of channel change within the study area. A smaller raster size could give a better probability because it covers a smaller area, the larger the raster cell, the more generalized the probability.

Thalweg centrelines for 1942, 1962, 1985 and 1999 were digitized and intersected to define polygons that represent areas of floodplain eroded over the 57-years period. Centrelines were drawn through small mid-channel bars and, in multi-threaded segments of the river, were drawn around larger bars and islands, tracing the path of the widest (main) channel. An eroded/sedimented area polygon is created by the intersecting two active floodplain areas mapped at the two moments of time. A similar approach was presented by Micheli et al. (2004). The data were analysed by the use of CPCA (Constrained Principal Component Analysis). This method provided an average ordination of the sampling plots, and this averaged ordination then made it possible to delineate the floodplain with the different morphological characteristics.

RESULTS

The total active channel area was 3 464.80 ha in 1999 against 4 561.72 ha in 1942. It decreased significantly between 1942 and 1999 at a rate, which is fairly constant: 3.51 m/yr between 1999 and 1985, 4.05 m/yr between 1985 and 1962 and 3.34 m/yr between 1942 and 1962. (Fig. 2a).



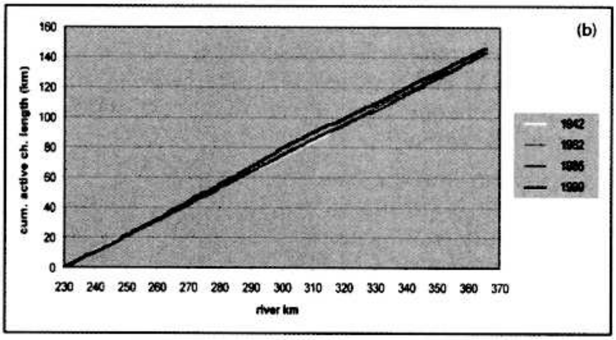


Fig. 2. Longitudinal evolution from river km 230 (RM 143) to km 370 (RM 243) of (a) the cumulated active channel width in 1942, 1962, 1985, 1999, (b) the cumulated low flow channel width in 1942, 1962, 1985, 1999

The decrease of active channel area (in period of years 1942-1999) varies from one reach to another. The most important decrease is on the upstream part of the river 363 ha between the RM 233-243 (i.e. 0.45 ha per km per yr), 155 ha between the RM 223-232 (i.e. 0,19 ha per km per yr), 107 ha between the RM 183-192 (i.e. 0.03 ha per km per yr) and 165 ha between the RM 173-182 (i.e. 0.21 ha per km per yr). The change has been more reduced in downstream reaches, RM 143-152, RM 153-162, RM 163-172, respectively 0.04, 0.03 and 0.05 ha per km per yr between 1942 and 1999.

Three clear reaches occur in terms of chronology of change:

– RM 143 – RM 163: only a very subtle change mainly between 1942 and 1962 and then no other modifications => possibly adjustment to peak flow changes,

– RM 163 – RM 203: again change only occured between 1942 and 1962 but it is much more significant with a constant decrease of 0,0388 m/km/yr,

– RM 203 – RM 243: chronology is different (almost constant reduction during the three periods: 0.0330, 0.0444, and 0.0339 m/km/yr during the periods 1942-1962, 1962-1985 and 1985-1999).

In such context the longitudinal evolution differs from one year to another: constant to downstream in the case of 1999 and 1985 (small inflexion RM 193), clear inflexion in 1962 RM 203.

The basic data also clearly show that the width variability changed in the period of 1942: numerous peaks of channel widening (in average 1 every 2 725 m in length) with a range of 600-959 m. In 1962 peaks were higher in intensity but much more infrequent, mainly upstream from RM 203. Their range was typically 363 m upstream RM 203 but 259 m downstream. The situation in 1985 was close to 1962 with high peaks again less frequency even upstream from RM 203. In 1999, the pattern was more similar to 1942 in term of intensity but the distance between them was higher (in average 1 every 12 636 m in length). As shown on Fig. 2a, no clearer trend appears of narrowing downstream as it is clearly shown in 1942 and 1962.

Fig. 2b affirms the downstream narrowing. The total active channel length is in net diminution from 1942 to 1999. The centerline distance of the active channel was 142 947 m in 1942, 147 503 m in 1962, 146 588 m in 1962 and 150 084 m in 1999. The active channel was divided by the study into 10 reaches of 10 RM. From RM 153 to RM 203 the length is diminutive from year 1942 to 1999. The length in the part between RM 203 to RM 233 is moving up. Fig. 3 proposes another view of the same fact.

The eroded floodplain surface has been estimated as 48.8 ha/yr during the 1985-1999 period, which is similar to the 1942-1962 period (Fig. 4). Band erosion has been significantly more intensive during 1962-1985, reaching 56.4 ha/yr, the peak being observed near RM 178, RM 203 and RM 214. The difference has been mainly observed between RM 205 and RM 234.

In comparison of three graphics of longitudinal evolution of the bank erosion the period 1985-1962 is characterized by the most irregular evolution with the peaks near RM 177 and 214.

Bank revetment and channel confinement by levees combined with the regulation of flows from dam releases have created several apparent geomorphic effects. This form was described by Brice (1977) as "deformed" meander bends.

A flow analysis of several gage locations conducted by the California Department of Water Resources found extensive alteration to the volume and timing of flows using the indicators of the hydrological alteration (IHA) method (Richter et al. 1996) on the Sacramento River. The pre-Shasta Dam 2-year recurrence interval (RI) discharge ($Q2$ = 3 300 m^3/s) was greater than the post-Shasta Dam 5-year RI discharge ($Q5$ = 3 256 m^3/s). And furthermore, the pre-

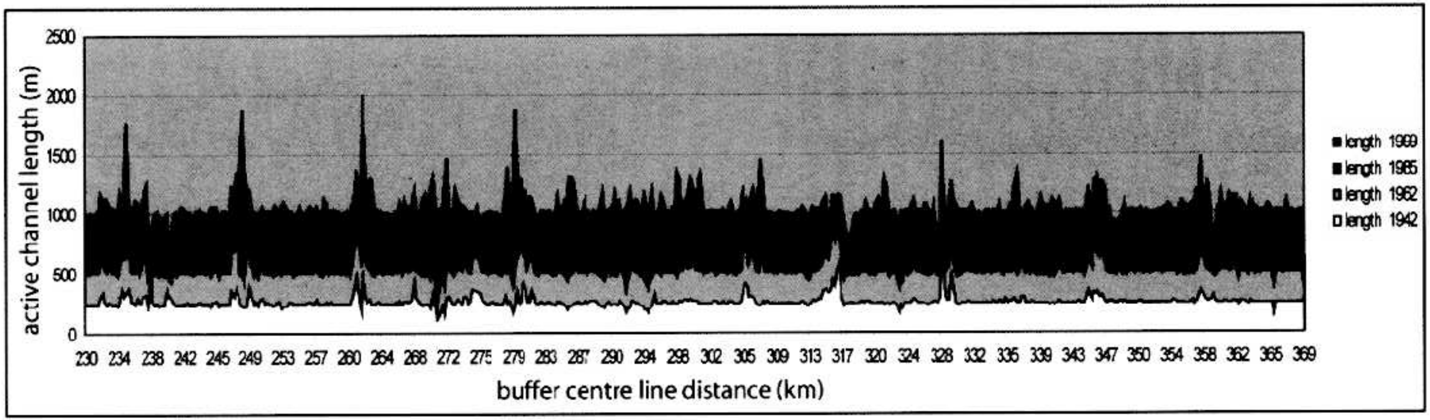


Fig. 3. Longitudinal evolution from river km 230 (RM 143) to km 370 (RM 243) of the cumulated bank retreat between 1962/1942, 1985/1962 and 1999/1985

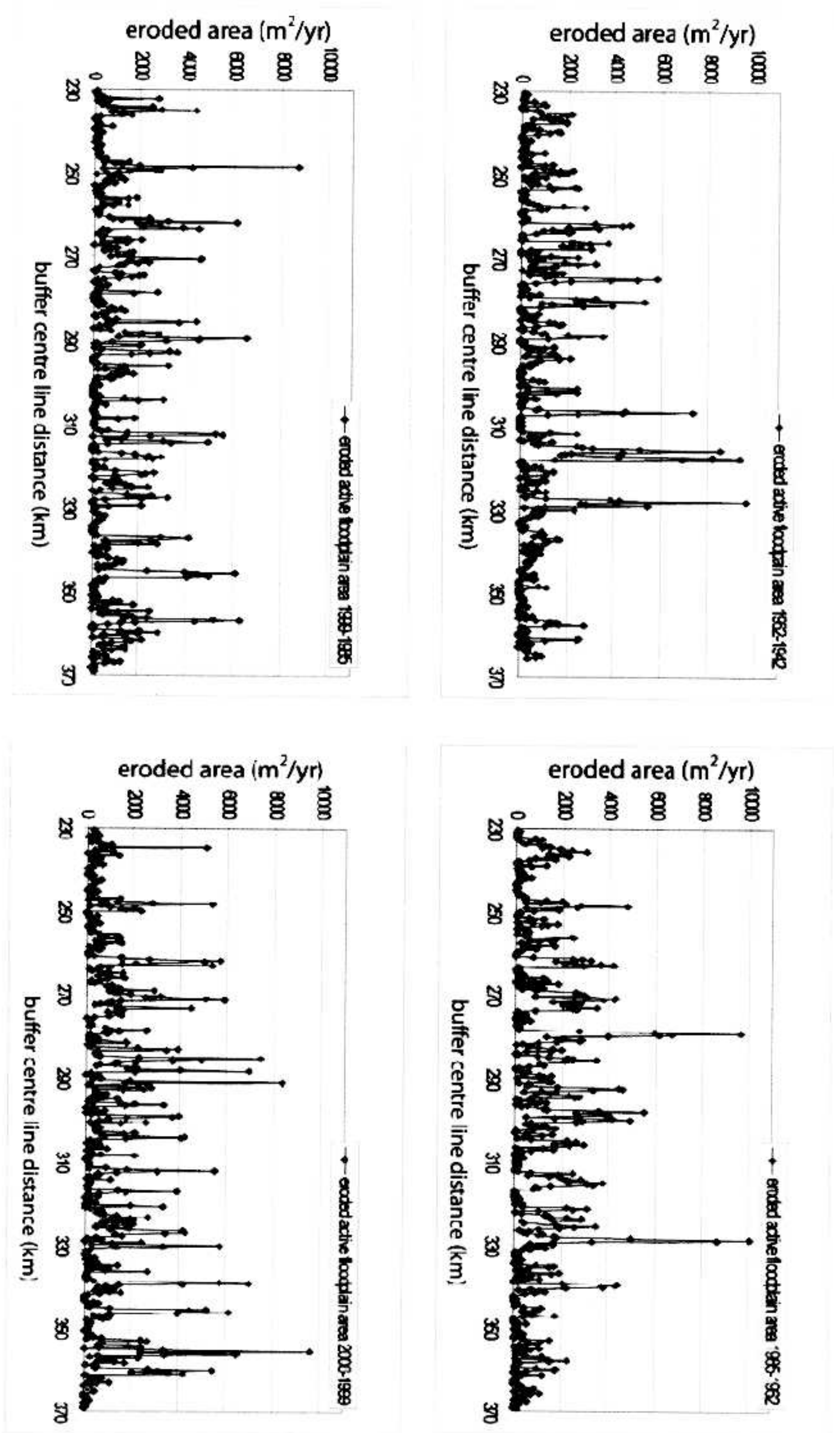


Fig. 4. Longitudinal evolution from river km 230 (RM 143) to river km 370 (RM 243) of the eroded floodplain area between 1942 and 1962, 1962 and 1985, 1985 and 1999 and 1999 and 2006

Shasta Dam 5-year RI discharge ($Q5$ = 4 446 m^3/s) was nearly equal in magnitude to the post-Shasta Dam 20-year RI discharge ($Q20$ = 4 417 m^3/s).

CONCLUSION

The total active channel area was 3,470 ha in 1999 but 4,560 ha in 1942. It decreased significantly between 1942 and 1999 at a rate, which is fairly constant. Micheli et al. (2004) compared the migration rates of Sacramento River channel before and after the installation of the Shasta dam. The result was that mean migration rates are 50% higher for the 1946 to 1997 interval than for the 1896 to 1946 interval. The bank erodibility was about 56% higher during the later time period. Their results show that the study reach of the Sacramento River tends to migrate more quickly through agricultural land (the bank erodibility increased here by 80 to 150%) than through riparian forest. The riparian forests are highly productive and host great biological diversity, however, it is estimated that 95% of the forests in the Sacramento River system have been lost to agricultural land conversion, flood control projects and urbanization since the settlement of the valley (Larsen et al. 2007). Riparian vegetation on the inside of the meander loop also inhibits downstream migration of the meander loop and helps prevent cutoffs (Brice 1977). The results also proved the channel narrowing in active channel width and the straightening in channel length. The active channel has become narrower and longer. The total active channel length was in net diminution from 1942 to 1999. The centerline distance of active channel was 143 km in 1942, 148 km in 1962, 147 m in 1962 and 150 m in 1999. Greco et al. (2007) in results from the floodplain age model of buffered channel centrelines note, that channel length was 154 km in 1942, 155.6 in 1966 and 153.3 km in 1987. The lengths introduced in Greco et al. (2007) are overestimated. The difference in results is caused by the different method applied. Our channel length is measured from aerial photos. Active channel width decreases significantly between 1942 and 1999 at a rate, which is fairly constant: 3.51 m/yr between 1999 and 1985, 4.05 m/yr between 1985 and 1962 and 3.34 m/yr between 1942 and 1962. Constantine (2006) noted values of the mean reach migration rate 1946-1997 between 4.0 and 5.3 m/yr. But these values had been calculated only for active reaches, without including the stable reaches.

The eroded floodplain surface have been estimated as 48.8 ha/yr during the 1985-1999 period, which is similar to the 1942-1962 period. Band erosion was significantly more intensive during 1962-1985, reaching 56.4 ha/yr, the peak being observed near RM 178, RM 203 and RM 214. The difference has been mainly observed between RM 205 to RM 234. The tendency in erosion rate is approval to Greco et al. (2007). However, the rates estimated by Greco et al. (2007) are higher.

According to Greco et al. (2007), the results of this study proved the dynamic and continual change in the Sacramento River landscape. The specific evolution of the river channel has generally these causes: geological conditions, discharge conditions, flood occurrence, sediment transport, erosion resistance, type, presence and density of vegetation. All these causes, except of geological conditions, can be influenced by human activities. Discharge conditions and flood occurrence by the construction of the Shasta Dam and by the river bypass on the downstream part. Erosion resistance downstream is due to the channel bank revetment. The type of vegetation had been changed completely along the study reach. Riparian vegetation had been replaced by agricultural land, mainly by orchards. Its propagation has become more intensive. In 1962, the orchards can be seen also inside meander loops, without surface access. The natural vegetation had been conserved only in the lower floodplain. Micheli et al. (2004) showed a comparison of the migration rates and bank erodibility for reaches bordered by the agricultural land versus reaches bordered by the riparian forest with the result of a consistent trend of more rapid channel migration through agricultural land. These changes in land use, river training connected with changes in flow dynamics and sediment transport have caused (resulted in progressive disappearance of active floodplain area) significant changes in the lateral activity of many meandering rivers like the Sacramento River, creating the system of cut-offs and oxbow lakes. Knowledge about the morphological processes – erosion/deposition under the existing constraints, creates the necessary background for the better understanding of river behaviour in the given time scale. Quantification and analyses enhanced by a wide range of field measurements and observations have proved successive diminishing of the active floodplain and also higher occurrence of the river cutoff lakes. A major-part of these changes during the period were associated with the strongest effect of human activities.

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ANALÝZA LATERÁLNEJ AKTIVITY KORYTA RIEKY SACRAMENTO Z LETECKÝCH SNÍMOK

Historická letecká fotogrametria ponúka možnosť štúdia dynamiky časovo-priestorových procesov prebiehajúcich na zemskom povrchu, predovšetkým tých, ktoré zanechávajú výraznú morfologickú stopu. Rýchlo sa meniace formy podliehajúce aktívnym procesom a korytá veľkých riek s výrazným laterálnym pohybom sú mimoriadne vhodné na morfologickú analýzu. Poznanie historického stavu je základnou premisou pre realizáciu revitalizačných opatrení. Pre potreby štúdie bola zmapovaná, popísaná a štatisticky analyzovaná laterálna aktivita koryta rieky Sacramento v úseku medzi Red Bluff a Colusou (exaktne v dĺžke sto riečnych míľ, teda 160,936 km; medzi riečnou míľou 143-243). Na realizáciu uvedeného boli použité série leteckých snímok územia z rokov 1942, 1962, 1985 a 1999. V prípravnej fáze sa riešili: rektifikácia leteckých fotografií, zakreslenie koryta v jednotlivých rokoch, tvorba tabuľky GIS atribútov a štatistické zisťovanie. Analýza vývoja úsekov s dĺžkou 250 m v osi koryta umožnila identifikovať základné tendencie erózno-akumulačných procesov. Ďalším, doplňujúcim cieľom bolo vytvorenie funkčného geografického informačného systému perifluviálnej zóny rieky Sacramento.

Po vykonaní dôsledných meraní a analýz, určení eróznych a akumulačných úsekov bolo identifikované zúženie a zväčšenie celkovej dĺžky koryta. Dĺžka toku v osi koryta postupne stúpala z hodnoty 143 km v roku 1942, na 148 km v roku 1962 až na 150 km v roku 1999. Uvedené zistenie je v súlade s následným znížením počtu preťatí meandrovej šije na dolnom úseku toku, keď sa so zvýšeným zakrivením koryta zvyšuje aj jeho dĺžka. Šírka aktívneho koryta sa zmenšuje v období rokov 1985-1999, zúženie predstavuje priemerne 3,51 m za rok. Erodovaná plocha aktívneho koryta na celom sledovanom úseku bola 48,8 ha za rok v období rokov 1985-1999, obdobne aj v rokoch 1942-1962. Signifikantne vyššia hodnota bola zistená pre obdobie 1962-1985 (56,4 ha za rok). Maximá brehovej erózie spôsobenej laterálnym pohybom toku sa prejavili v oblasti riečnym míľ RM 178, RM 203 a RM 214.