DIACHRONIC ANALYSIS OF FLOODPLAIN LAKES OF THE SACRAMENTO RIVER

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Diachronic analysis of floodplain lakes of the Sacramento River. This study is based on temporal (diachronic) analysis of floodplain lakes using aerial photographs (1942, 1962, 1985 and 1999). The synchronic analysis researches into the internal linkages of a system at a given point in time. A diachronic analysis regards the phenomenon in terms of developments through time. We analysed the planimetric changes in order to highlight the spatial structures and their stability over time. Aerial photography is used for diverse diachronic analyses of channel change on the Sacramento River, California. Georeferenced and rectified aerial photos and maps are most desirable for use in the analysis of meander migration and floodplain lakes. All data were integrated into a GIS database (ArcGIS 9.3). Three main types of floodplain lakes were observed according to their spatial geometry, plug length and connection to the main channel: the oxbow lakes, the straight backwaters and the straight secondary channels.
Key words: floodplain lake, diachronic and synchronic analysis, aerial photographs, GIS, Sacramento River

INTRODUCTION

Alluvial floodplain dynamics are regulated by fluvio-geomorphological processes and determine ecological succession (Bravard 1986, Bornette and Heiler 1994). Both lead to the occurrence of cut-off channels and lakes created by actively migrating river channel due to cut-off processes or avulsions (Reineck and Singh 1980). Channel meander bend cut-off dynamics produce floodplain water bodies such as backwater sloughs and oxbow lakes (Greco et al. 2007). The effect of the formation of cutoffs and oxbow lakes on meanders was recognized on the Mississippi and other rivers in the first half of the 20th century. Fisk (1947) already noted that the oxbow lakes gradually become filled with sediment and eventually more resistant clay plugs in the floodplain, which cause variation in rates of bend migration. The sinuous pattern created by bank erosion and deposition on pointbars is self-maintaining over time through progressive bend migration (Leopold et al. 1964). The particular incidence of cutoffs is explained by changes in discharge and many of these changes are attributed to human activities (Hooke 2004). The historical development of research into cutoffs has been also reviewed by Hooke (1995).

Lehotský and Grešková (2004) define a channel-floodplain geosystem as a morphological product of stream activity at the bottom of a valley presenting a specific geomorphological-substratum base of a riverine landscape. An abandoned channel is a part of a channel system separated from the original stream channel so that the stream does not flow through it. A current conception of French geomorphological school presents the floodplain lake in connection with humid perifluvial zones. A floodplain lake (Fig. 1) is an area of fluvial hydrosystem spatialy delimited by the axis of a former active channel. It is composed of two parts: humid perifluvial (aquatic perifluvial zone with ecotone zone) and terrestric zone presented by an alluvial plug (Rollet et al. 2004).

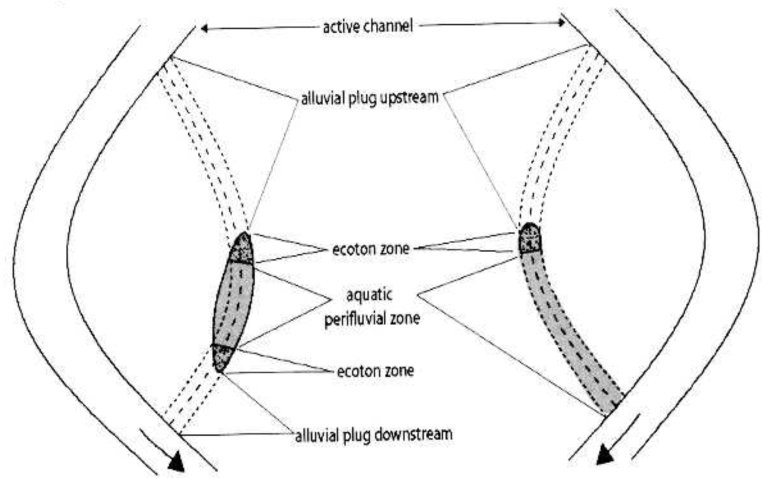

Fig. 1. Types of floodplain lake (Rollet et al. 2004)

a) disconnected, b) connected downstream

The cut-off process is a sudden abandonment of a part or the whole of a channel course. Avulsion is the rapid abandonment of a river channel and formation of a new river channel. Avulsion typically occurs during large floods, which carry the power necessary to rapidly change the landscape.

The cut-off process is generally associated with meandering rivers. Hooke (2004) proposes five possible explanations and alternative hypotheses for this phenomenon: (1) cutoffs as part of a chaotic system, (2) changes due to natural meander migration or evolution, (3) cutoffs due to extreme flood events, (4) changes due to adjustment to altered effective discharge, (5) changes due to adjustment to direct interference in the channel pattern. Gagliano and Howard (1984) present the conceptual model which distinguishes two phases: blockage and infilling. The blockage phase extends from the time the bendway is cut off until one or both junctions are blocked. The low and mean flows are blocked; the velocity decrease and conditions become lacustrine. The infilling phase gives way to a terrestrial phase. Hooke (1995) suggests that the thickness of the alluvial fill in the floodplain lake depends on age and proximity to the main channel. Old floodplain lakes situated close to the main channel can develop a large volume of fill (Bradley and Brown 1992, Erskine et al. 1992). Shields and Abt (1989) noted that plug accretion is controlled by the geometry of the floodplain lake. They showed that the bar in the upstream entrance of the cut-off bend extending into the bend was related to the angle of incidence and the gradual diversion angles produced very long bars, while larger diversion angles produced very short bars. The degree and rapidity of the sedimentary infilling of a cut-off tends to depend partly on the angle of the cut-off with respect to the main channel (Hooke 1995) and mostly on the channel connectivity and bank-flow influence from the main channel.

The meander floodplain lake can be formed by the channel breaching or through the development of a neck cut-off during high flow conditions. It represents a shortening of the stream length, decreases in the sinuosity of the channel, or it can make the water-slope steeper during the flood stage. The meander loop subsequently becomes plugged with instream materials. The abandoned meander gradually becomes isolated from the main channel. The loop may infill with fine-grained suspended load materials. Meander cut-off (Fig. 2a), a meander bend that has been cut through the neck, leaving an abandoned meander loop on the floodplain. The bends have an arcuate or sinuous planform. In plan-view, the typical form appears.

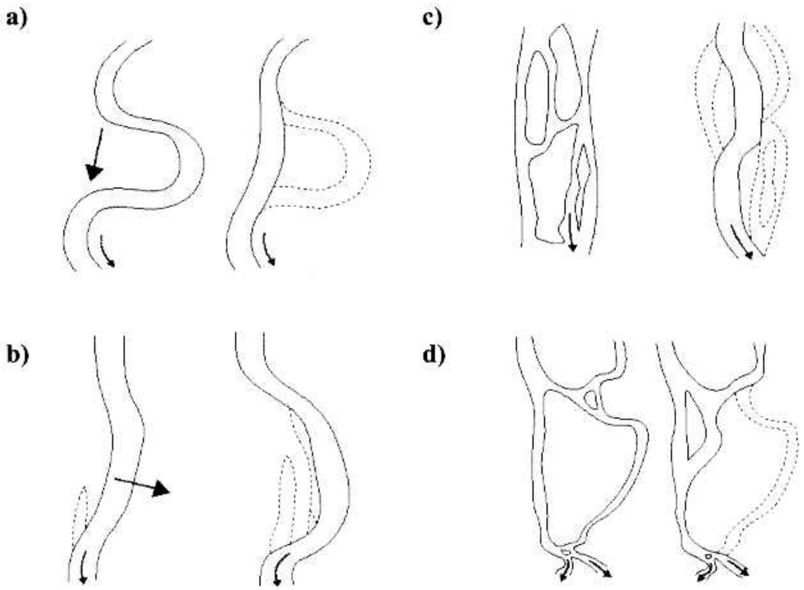

Fig. 2. Channel recoupement

a) chute cutoff with creation of oxbow lake, b) lateral movement with creation of floodplain lake, c) creation of floodplain lake on braided channel, d) creation of floodplain lake in anastomosing channel

Another type of cut-off involves the shortening of stream lengths or decreased sinuosity of the channel, and a steeper water-slope at the flood stage. Concentrated flow with high stream powers are able to cut across the bend. With chute cut-off extension, the bend may be abandoned, at which point the chute becomes the primary channel. The old channel bend is filled mostly with bedload deposits. Chute cutoffs occur in higher energy settings than neck cut-off.

Smoothly curved channel dissects the convex bend of the primary channel. The chute then becomes the primary channel. Chute cutoffs have a straighter planform than neck cutoffs. Bedload materials mostly fill them.

Appearance of cutoffs on braided channels can be the result of natural evolution or/and the riverbed incision on impounded rivers (Fig. 2c). The co-action of these two factors is frequent. The former braided channels are often supplied by groundwater and regularly subject to flood events (Bornette and Amoros 1991, Bornette and Heiler 1994). The decrease in connectivity between the river and the wetlands, which has been caused by the decreasing flood frequency and rate of lateral migration of the river has been described by Galay 1983, Foeckler et al. 1991, Bornette and Heiler 1994 and Citterio and Piégay 2000. As opposed to braided rivers, single-channel alluvial rivers tend to migrate laterally (Johannesson and Parker 1989, Hughes 1997).

According to Citterio and Piégay (2009) the middle year of the defined period in which the channel was abandoned was considered the date of the cut-off. Floodplain lake abandonment occurred along a relatively long period of time (three centuries). The cut-offs older than 60 years proved more difficult to date. Younger cut-offs were dated with a precision of 2-3 years. In addition to the channel cut-offs, lentic aquatic bodies and *Ludwigia* cover were also identified and considered as separate channel units.

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

STUDY AREA

The drainage area of the Sacramento amounts to 31,043 km^2 at Colusa representing approximately a half of the catchment. The Sacramento River is the largest river in California, USA.

The study area is a 160-km lowland sinuous reach of the Sacramento River (Tab. 1) between Red Bluff and Colusa (RM 243-143 – km 370-230). Upstream, the river is confined between the valley walls, and downstream, flood-control levees line the channel banks and restrict movement. Although levees are present in the downstream 50 km of the study area, they are set back from the river and spaced 0.75 to 2.5 km (approximately 1.0 to 3.3 times meander amplitude) apart, encompassing both the channel and proximal floodplain and allowing generally unconfined channel shifting to occur (Constantine 2006). A detailed description was presented in Michalková (2009).

The study reach is characterized by alternate actively migrating reaches, relatively slowly migrating reaches, and nearly stable reaches (Schumm and Harvey 1986). A study monitoring bank erosion along the Sacramento documented a positive correlation between the peak flow and the bank retreat (DWR 1979), which suggests that dam construction should have had a negative impact on mean reach migration rates upstream of Colusa where peak flows declined after dam impoundment (Singer, in press).

Tab. 1. Characteristics of the Sacramento River study reach (after Greco et al. 2007, Micheli et al. 2004)

River mile		245-144	
Channel sinuo sity		1.36	
Low-flow channel width		120	
River mile	243-211	211-174	174-143
D_{50} (mm)	35	20	15
Channel slope	0.0005	0.0004	0.00025
After 1946			
Discharge ($m^3 s^{-1}$)	2 500	2 700	2 700
Average depth (m)	3.9	4.1	4.1
Average width (m)	356	360	360

METHODS

As already mentioned, the analysis of fluvial evolution with regard to hydrological and sedimentary processes will be carried out at different temporal and spatial scales. Firstly, it means quantifying the inter-annual deformation of the active channel by calculating the areas of erosion and deposition for three periods: 1942-1962, 1962-1985, 1985-1999. The study shows the floodplain lakes, discerns their types, analyses the cut-off process and the post-abandonment evolution. This two-points/two times approach underlines the dependence of floodplain lakes on active channel behaviour.

This study is based on a synchronic and *diachronic analysis (Piégay and Schumm 2003) of floodplain lakes and the spatial and temporal analysis of floodplain lakes by applying the aerial photographs (1942, 1962, 1985, 1999). All the data were integrated in the GIS database, using the ArcGIS 9.3 software.*

The photographs were chosen for the similar discharge inferior to 400 $m^3.s^{-1}$ in order not to have the lake areas affected by changes in water level (Greco et al. 2007). The photos have been scanned (600 dpi), and rectified based on the imagery of 1/7200 as reference. The criteria for RMS were that it must be less than 5. The RMS mean is 3.61 for 1942, 3.71 for 1962 and 3.97 for 1985. The field verification study of the 2006 interpretive mapping techniques was performed.

Following Michalková (2009), the *same photogrammetric and cartographic methodological process was applied* to each historical aerial photograph set selected for temporal analysis.

According to the rectified photos the active channel floodplain was digitalized for 1942, 1962, 1985 and 1999. A cut-off channel is a channel that has been abandoned because of channel migration.

Channel pattern was used to classify the floodplain lakes according to their geometry, measured from the digitized polygon shapefiles. The data were analysed using nPCA. This method provides an average ordination of the sampling plots, and this averaged ordination then made it possible to delineate the lakes with different morphological characteristics. The channel pattern responsible for shaping each floodplain lake at the point of cut-off is given. Three processes were identified (meandering, braided and anastomosing). This three-fold classification does not however, consider the inherent complexity of the fluvial forms. With this in mind, floodplain lakes were characterized within the meandering reaches in one of two sub-categories: 1) the regular cut-off channel corresponds to the oxbow lake, and 2) backwaters located in the convex side of the meander. The latter correspond to water bodies positioned laterally to the main channel following the development of point bars (which then become *point bar backwaters*) (Citerrio and Piégay 2008).

The different ages of the studied floodplain lakes were used as independent variables. First, the age of every cut-off was set from aerial photographs taken for 1942, 1962, 1985 and 1999, but the 20-year intervals were found insufficient. The date of a cut-off was also determined from the GIS layers recording the active channel for 1896, 1908, 1923, 1935, 1937, 1946, 1955, 1956, 1960, 1964, 1969, 1976, 1981, 1991 and 1997. The University of California (Berkeley) data from land surveys and other historical records enabled the historical record to be extended. Together 19 delineations of the active channel and floodplain enabled the age of floodplain lakes to be determined at an average with accuracy of 5-year intervals.

RESULTS

From the aerial photographs, 87 floodplain lakes have been identified in 1942, 64 lakes in 1962, 75 in 1985 and 101 in 1999. The average size is 29,818 m^2 varying between 363 m^2 and 277,171m^2.

Three main types of lake were observed according to spatial geometry, their plug length and also their connection to the main channel. The correlation circle indicates the degree of association between the metrics and it is therefore possible to interpret three groups of dendrograms:

- Group 1, so called *oxbow lakes* (Fig. 3a), are the wide and sinuous lakes. They are characterized by a regular form with elevated values of the water body width and length. Oxbow lakes are generally the oldest lake types, removed from the principal channel, sinuous with the typical form of a horseshoe. They are the most stable ones, flowing only during extreme floods. The point bar form is huge and rounded. The progressive filling up is the result of the autogenously organic material and allogenic sediment supply.
- Group 2, so called *straight backwaters* (Fig. 3b), are characterized by the occurrence in the convex side of the meander. The water bodies are positioned laterally to the main channel following the development of point bars. Their form is irregular, elongated with jutting out small parts of the water body. One of the reasons for their appearance is the regressive erosion associated with the channel bed deepening or channel migration.
- Group 3, so called *straight secondary channels* (Fig. 3c), boast short upstream plugs. There are of straight form, elongated, without jutting out

parts. Straight active channels are often composed by numerous water plugs, but a single water body plug is also frequent. They are formed by the lateral channel movement and the general active channel narrowing of the Sacramento River.

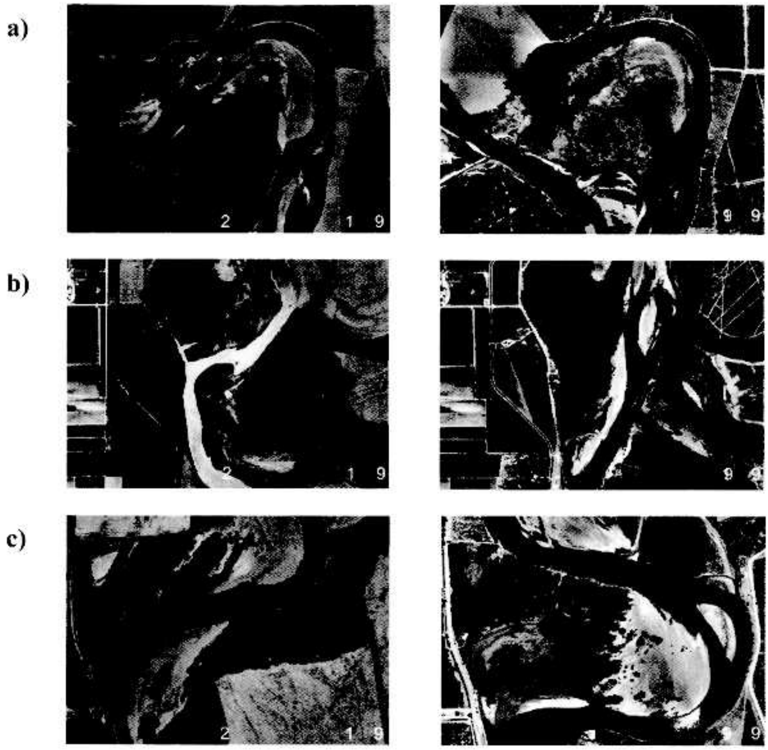

Fig. 3. Example of a) oxbow lakes, b) straight backwaters/lake and c) straight secondary channels/lake

There is only space to list the important lake types and to mention some examples, but these lakes may represent the basis for a deeper analysis in revitalization studies: meanders (L 196; L 180.8; R 168.4; R 170; R 167.2; L 212.7; L 203-205; L 161.5), straight backwaters (R 218.4; R 190; R 179.2; R 221.7; L 182.5; R 192; R 234.8; L 195; R 195; R 168.9) and straight secondary channels (R 212; R 178; R 194.3; L 203; L 234; R 174; R 236.8; R 193.5; R 189; R 221.6; L 210.9; R 168.8).

The box-plot representing the lake surface area (Fig. 4) indicates the temporal evolution of the lakes. Three groups have been distinguished: disappeared lakes, newly-appeared lakes, persistent and superpersistent lakes. The greatest lake surface area existed between 1942-1962, indicating that the subsequent construction of the Shasta Dam may have played an important role in their decline. The dam moderated the interval and intensity of floods and this also influenced the apparition of new lakes. During the period 1942-1962, appearance of new lakes was minimal.

Analysis of the longitudinal evolution of the surface area of lakes (aquatic zone) shows the decrease between the 1942 and 1985. The area of lakes increases again in 1999. Many lakes downstream disappeared from 1942 to 1962, but were partly compensated for by formation of new lakes over the entire period through 1999 (around 260 ha of floodplain lakes in 1942, 1962 and 1999).

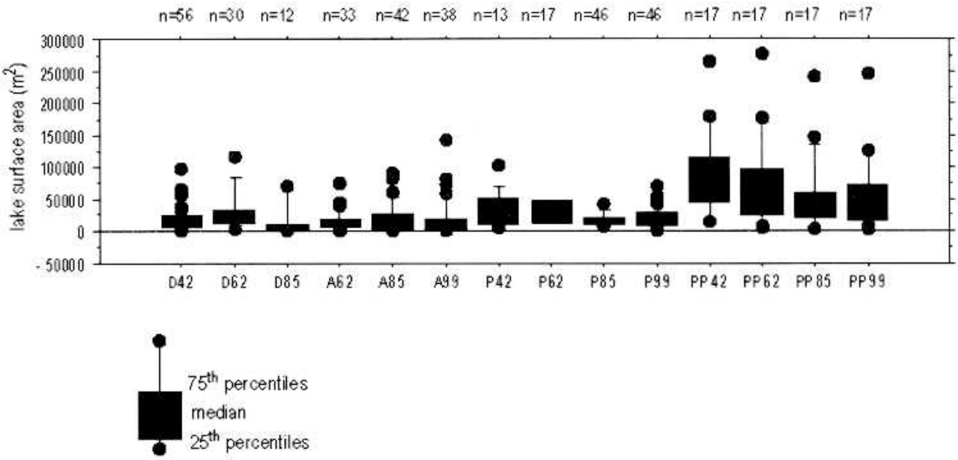

Fig. 4. Box-and-whisker plots of absolute surface areas (water+helophytes)

Where:

D42: size distribution of lakes present in 1942, vanished by 1962

D62: size distribution of lakes present in 1962, vanished by 1985

D85: size distribution of lakes present in 1985, vanished by 1999

A62: size distribution of lakes appearing in 1962 not present in 1942

A85 :size distribution of lakes appearing in 1985 not present in 1962

A99: size distribution of lakes appearing in 1999 not present in 1985

P42 :size distribution of lakes appearing in both 1942 and 1962, measured in 1942

P62 :size distribution of lakes appearing in both 1962 and 1985, measured in 1962

P85: size distribution of lakes appearing in both 1985 and 1999, measured in 1985

P99: size distribution of lakes appearing in both 1985 and 1999, measured in 1999

PP42: size distribution in 1942 of lakes persisting throughout the study period

PP62: size distribution in 1962 of lakes persisting throughout the study period

PP85: size distribution in 1985 of lakes persisting throughout the study period

PP99: size distribution in 1999 of lakes persisting throughout the study period

DISCUSSION AND CONCLUSION

According to Greco et al. (2007), the results of this study proved the dynamic and continuous change of the Sacramento River landscape. Generally, the specific evolution of a river channel is due to the following causes: geology, discharge conditions, flood occurrence, sediment transport, erosion resistance, type, presence and density of vegetation. All these causes, except geology, 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 in downstream reach by the channel bank revetment. The type of vegetation has been changed completely along the study reach. Riparian vegetation has been replaced by agricultural land, mainly by orchards. This propagation became more intensive. In 1962, the orchards were also observable in meander loops without surface access. Natural vegetation has been conserved only in the lower floodplain. Micheli et al. 2004 compared the migration rates and bank erodibility for reaches bordered by the agricultural land, to the reaches bordered by riparian forest with the result of consistent trend of more rapid channel migration through agricultural land. These changes in the land use, river training connected with changes in flow dynamics and sediment transport have resulted in progressive disappearance of active floodplain area and caused significant changes in lateral activity at many meandering rivers including Sacramento River, creating the system of cut-offs and oxbow lakes. Knowledge about the morphological processes, erosion/deposition under the existing constrains, creates the necessary background for the better understanding of the River's behaviour in the given time scale. Quantification and analyses enhanced by wide range of field measurements and observations have proved successive diminishing of the active floodplain and also higher occurrence of the river cut-off lakes. The major part of these changes occurred through the period associated with the strongest effect of human activities.

By the analysis of the aerial photographs 87, 64, 75 and 101 floodplain lakes were identified in 1942, 1962, 1985 and 1999 respectively. The average size is 2.9 ha varying between 363 m^2 and 27.7 ha. The study reach of Sacramento River showed the most important activity in the period 1962-1985. The erosion rates are highest for the period 1966-1987 and so is the number of new lakes. Greco et al. (2007) confirm this result by the information that more new land was created in this period. If the channel movement is important, the lateral erosion is higher, the lateral channels are abandoned, floodplain lakes appear and a new land surface is formed.

Three main types of lakes were observed according to spatial geometry, their plug length and their connection to the main channel. Oxbow lakes are wide and sinuous pools. Straight backwaters are characterized by the occurrence in the convex side of the meander. Straight secondary channels are formed near the active channel, elongated, without jutting out parts. The area of disappeared lakes was most important between 1942 and 1962. It means that the lakes were disappearing in this period immediately after the construction of the Shasta Dam. The interval and intensity of floods has been eliminated and this fact has also influenced the appearance of new lakes.

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DIACHRONICKÁ ANALÝZA NIVNÝCH JAZIER SACRAMENTA

Termín mŕtve rameno (biol. odstavené/odrezané rameno) je definovaný ako oblasť fluviálneho hydrosystému priestorovo delimitovaná osou v minulosti prietočného, aktívneho koryta. Mŕtve rameno sa skladá z tzv. humídnej perifluviálnej zóny a z terestrickej časti (Rollet et al. 2004). Humídna perifluviálna zóna sa skladá z vodnej (aquatickej) a ekotonálnej oblasti. Vodná oblasť je definovaná ako vodná plocha so stojatou alebo tečúcou vodou s možnou kolonizáciou vodným rastlinstvom na dne. Ekotonálna oblasť je zónou prechodu medzi vodným a terestriálnym prostredím.

Analýzou leteckých snímok bolo na skúmanom úseku rieky Sacramento (California, USA) identifikovaných 87 mŕtvych ramien v roku 1942, 64 ramien v roku 1962, 75 v roku 1985 a 101 v roku 1999. Priemerná rozloha ramena je 2,9 ha s rozpätím od 363 m^2 do 27,7 ha. Skúmaný úsek rieky bol najaktívnejší v období rokov 1962-1985. Erózna činnosť bola najvyššia v rozmedzí rokov 1966-1987, čo koreluje s vysokým počtom novovzniknutých jazier. Zvýšená činnosť koryta vedie k laterálnej erózii, opúšťaniu bočných korýt a tým k vzniku mŕtvych ramien. Najväčšia plocha mŕtvych ramien zanikla v období 1942-1962, teda bezprostredne po stavbe priehrady Shasta Dam.

Tri hlavné typy korýt boli definované v súlade so zistenými geometrickými charakteristikami, dĺžkou zazemneného úseku, ako aj na základe pripojenia k hlavnému toku. Jazerá meandrového typu (*oxbow lakes*) sú charakterizované širokými korytami s vysokým parametrom zakrivenia. Priame zátočiny (*straight backwaters*) vznikajú na konvexe meandra a priame sekundárne ramená (*straight secondary channels*) sa formujú blízko aktívneho koryta toku. Sú charakteristické predĺženou formou s krátkymi, vystupujúcimi časťami.