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Catena 4.5 (2001) 49-71

CATENA

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Residence times of alluvium in an east Texas stream as indicated by sediment color

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Received 29 May 2000; received in revised form 17 January 2001; accepted 13 February 2001

Abstract

The relationships between sediment production, storage, and transport in fluvial systems are complex and variable. Key issues in addressing these relationships are the residence times of sediment delivered to the channel, and the proportion derived from recent upland erosion as opposed to remobilized alluvium. The systematic changes in iron geochemistry often experienced by sediments deposited in an anaerobic environment, such as a stream channel or waterlogged floodplain, are used here as an indicator of residence time over contemporary time scales. In areas such as east Texas, where upland soils are high in iron oxide content, these changes are reflected in soil color. Alluvium with red, yellow, or brown colors indicating ferric (oxidized) iron and sufficient organic matter for reduction to occur indicates a short (<1 year) residence time. Redox features along root channels may indicate the residence time of oxidized material without organic matter. Alluvium with gley colors (Munsell chroma < 3) indicates a longer residence time (> 1 year). Sediments with the longest residence times in alluvial environments ($\gg 1$ year) will not oxidize on exposure to the atmosphere due to the loss of iron, while those with ferrous iron remaining will experience oxidation and color change on exposure. In Loco Bayou, Texas, these indicators of residence time are shown to be generally consistent with other field evidence of erosion and sedimentation. Further, the color indicators correctly indicate the residence time in several cases where the latter is known from field observations. Published by Elsevier Science B.V.

Keywords: Alluvial residence time; Alluvium; Fluvial system; Iron oxides; Color indicators

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0341-8162/01/$ - see front matter. Published by Elsevier Science B.V.
PII: S0341-8162(01)00139-4

1. Introduction

Sediment storage plays a key role in how sediment moves through fluvial systems. Its importance was first recognized from the large disparities between measured erosion within a drainage basin and the sediment exported by the outlet stream (Meade, 1982; Walling, 1983). Considerable progress has been made since the early 1980s; however, sediment delivery in fluvial systems is still quite problematic (e.g. Hay, 1994; Fryirs and Brierley, 1999; Gomez et al., 1999). While much variation has been observed (see Meade et al., 1990 or Trimble, 1995 for reviews), storage magnitude can be quite large in humid regions, such as the U.S. coastal plain (Sheridan et al., 1982; Lowrance et al., 1986, 1988; Cooper et al., 1987; Phillips 1993, 1995, 1997). Storage can provide a significant source of sediment during postdeposition transport events. The focus here is on distinguishing “old” and “new” sediment.

New sediment is defined as sediment recently delivered to the stream. Old sediment has been stored in the channel or floodplain for a period of time and then remobilized. The problem is broadly analogous to that of distinguishing between old, preevent and new, storm water contributions to stream runoff, a common recent theme in isotope hydrology (Bonell, 1993). The general principle explored here is that “old” sediments have been in the fluvial or alluvial environment long enough to acquire characteristics reflecting that environment. This is discussed further below.

The relative contribution of sediment remobilized from storage sites to sediment yield can be substantial, but also can vary with time and location within a basin. Floodplain and channel storage sites were shown to be prominent sediment sources in Great Britain (Walling et al., 1998), southern California (Trimble, 1997), Wisconsin (Faulkner and McIntyre, 1996; Lecce and Pavlowsky, 1997), and Australia (Brierley and Murn, 1998; Wasson et al., 1998). Storage contributions to sediment yield vary by location on the Murrumbidgee River, Australia, where yields increase along the upper portion of a 1200 km reach due to major upstream sediment contributions, but decrease within the lower portion due to sediment redeposition on the floodplain (Olive et al., 1994). Furthermore, the results of Nakamura and Kikuchi (1996) suggest that contributions decrease with time as supplies are exhausted and energy dissipation increases with channel adjustment.

Currently, generalizations regarding the source, storage, time lags, residence time, and transport of fluvial sediment are difficult to derive and even more difficult to extrapolate. The ability to distinguish whether sediment originates from new erosion or storage sources would significantly decrease these difficulties. Moreover, such ability is needed as new regulations increasingly restrict the introduction of new sediment into systems already deemed impaired (EPA, 1991, 2000).

The relative amount of time sediment is stored at a particular location can indicate its source. Variations in environmental controls within a basin often produce systematic variation in a number of soil and sediment properties, including grain size distributions, mineralogy, geochemistry, biochemistry, biostratigraphy, magnetic properties, radionuclide concentrations, and weathering properties. All have been used to shed light on the spatial and temporal variations in sediment production, transport, and storage in drainage basins.

A number of methods have been used to determine sediment provenance or "fingerprint" source areas within a basin, including grain size and sedimentology, mineralogy, geochemistry, magnetic signatures, stable isotopes, and radioisotopes. In general, while these methods may be successful in identifying source areas within a drainage basin, they are not effective in distinguishing between old and new sediments or in estimating fluvial residence times. Chemical changes during alluvial storage can confound efforts to fingerprint alluvial sediments and interpret alluvial stratigraphy (Peart and Walling, 1986; Hudson-Edwards et al., 1998). However, systematic changes during storage offer the promise of providing an indicator of alluvial residence time. Chemical weathering properties have shown promise in this regard, but suffer from poor discrimination ability (Johnsson and Meade, 1990; Riezebos and Teunisse, 1992) and can only be applied where significant postdepositional weathering has occurred (cf. Sidhu and Gilkes, 1977). Radionuclides from both anthropogenic and lithogenic sources show great potential for distinguishing old and new fluvial sediment and estimating transit and residence times (Walling and Woodward, 1992; Olley et al., 1993, 1997; Plater et al., 1994; Bonniwell et al., 1999). However, these methods are generally expensive and time consuming.

This study seeks to distinguish the relative residence times of alluvium so as to determine what proportion of this sediment originates from new erosion as opposed to being remobilized from storage sources. Systematic changes in iron geochemistry are utilized to infer residence times over contemporary and historical time scales on the order of 10^{-1} to 10^{1} years. This study will evaluate the accuracy of inferred residence time against those determined using other field evidence of erosion and sedimentation and will assess the advantages and disadvantages of this new methodology.

2. Study area and field methods

The study area is Loco Bayou and Lake Nacogdoches in Nacogdoches County, Texas (Fig. 1). Loco Bayou is a tributary of the Angelina River in east Texas. The total drainage area upstream of the lowermost study site is about 265 km^2, with about 228 km^2 lying upstream of Loco Dam. The study area lies within the eastern Pineywoods region of the Texas coastal plain. The climate is humid subtropical, with a mean annual precipitation of about 1200 mm $year^{-1}$. Although the precipitation is reasonably well distributed throughout the year, summer droughts are not uncommon and August is the driest month. Streamflow is typically highest from December through February, and lowest in mid to late summer.

Lake Nacogdoches provides water supply for the city of Nacogdoches. It has an area of 896 ha, and a volume of 48,224,087 m^3 at the normal pool elevation of 85 m as of 1994 (TWDB, 1994). Loco Dam was completed in 1976.

The study design is based on examination of sediment regimes at three primary sites and supplemented by sediment sampling at three secondary sites (Fig. 1). The first primary site, termed the upper site, is upstream of the lake. While this site is 0.78 km above the lake, backwater ponding effects are clearly visible here. The second (middle)

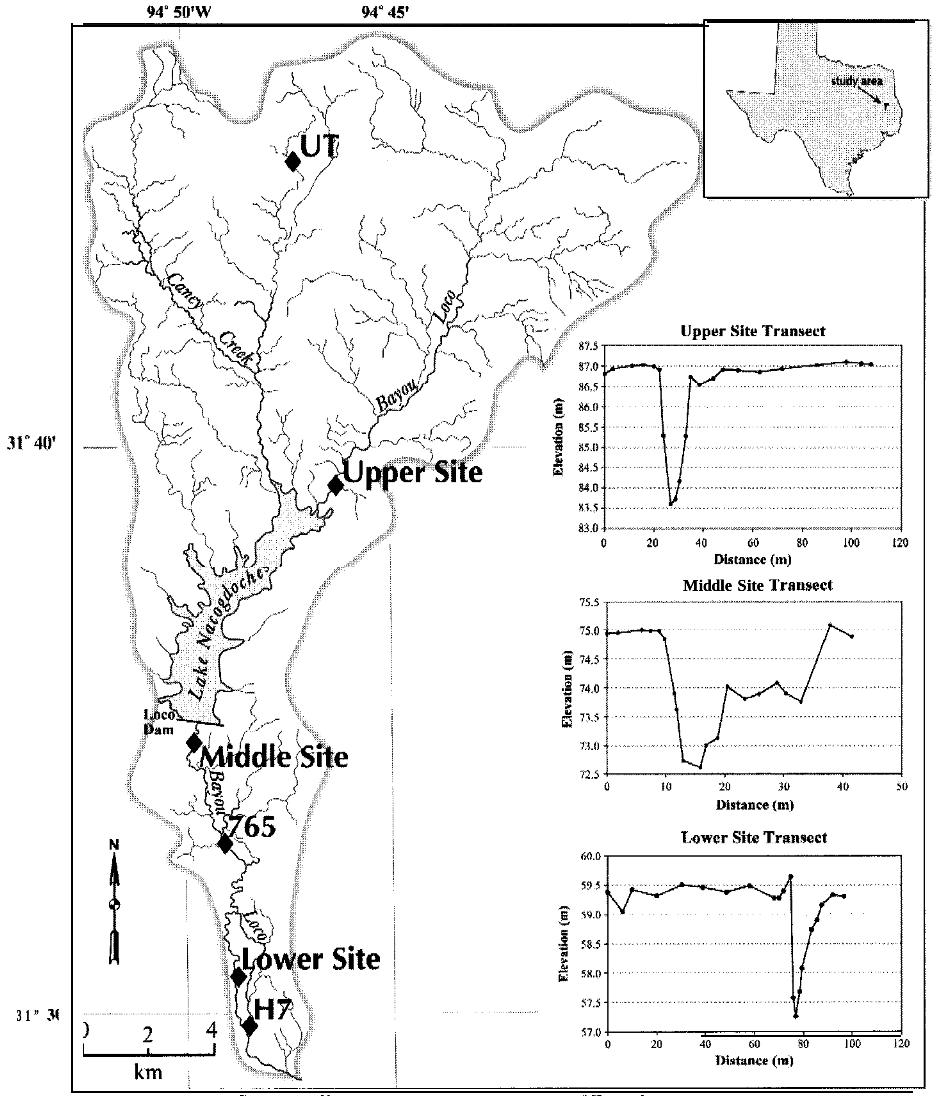

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Fig. 1. Loco Bayou basin showing Lake Nacogdoches and the upper, middle, and lower study sites. Sites of additional sampling are indicated as follows: UT, upper basin tributary; 765, Loco Bayou at county road 765; H7, Loco Bayou at Highway 7.

site is just downstream of Loco Dam. The third or lower site is 15.62 km downstream of the dam and 16 km upstream of the confluence with the Angelina River. Drainage area of the lower site is 264.7 km^2, 37.06 km^2 of which lies downstream of Loco Dam. By examining these three sites, as well as the other sites within the basin, sedimentation regimes upstream, immediately downstream, and further downstream of an impoundment can be compared.

2.2. Methods

Sediment color, to be discussed in more detail later, was assessed using Munsell soil color charts. Munsell chromas < 3 were considered as an indication of reduction or loss of iron (Bouma, 1983; Daniels and Hammer, 1992; Schwertmann, 1993). All color measurements were made in the moist state under natural sunlight. Vegetation, morphological, soil-stratigraphic and dendrogeomorphic evidence was examined at each site in an effort to determine historic sedimentation patterns, and aerial photographs of the sites from the 1970-1996 period were inspected to identify changes. In addition, lake surveys were utilized to estimate sediment influx to Lake Nacogdoches from volumetric changes.

Morphological evidence and soil stratigraphy provide indications of alluvial sediment dynamics and trends that can be compared to the color-based indicators or residence time. Likewise, dendrogeomorphological evidence has been used in several studies to estimate or measure the rate and nature of erosion, deposition, and sediment storage in alluvial environments (e.g. Hupp and Osterkamp, 1996; Hupp and Simon, 1991; Phillips, 1997; Robertston and Augspurger, 1999). Changes in lake volumes can be related to sediment inputs and, thereby, provide another line of evidence of sediment regimes to corroborate the iron oxide indicators.

Riparian vegetation in lowland alluvial rivers has an intimate relationship with geomorphic environments and processes. In addition to providing dendrogeomorphic evidence, analysis of woody vegetation communities can provide another indication of sediment regimes and floodplain stability, which can be compared with the color indices. The intimate relationship between bottomland vegetation communities and geomorphic environments in the Gulf coastal plain region is described by Wilkinson et al. (1987), Weller (1989) and Robertson and Augspurger (1999). The USFS (1998) Fire Effects Information System database provides information for individual tree species on habitat constraints, and preferences with respect to drainage, flooding, substrate stability, and successional relationships. Robertson and Augspurger (1999) focus specifically on the relationship of woody floodplain plant communities to the frequency and severity of geomorphic disturbance. Shear et al. (1997) show how bottomland vegetation in the southeastern U.S. reflects historical (decadal to century time scales) sedimentation trends. Because vegetation composition has a significant lag time in responding to geomorphic changes, such information is not necessarily a good reflection of the most recent events and processes. However, vegetation does integrate longer-term sediment storage (or mobilization) trends over years to decades, and is, thus, a useful indicator of trends and status in sediment residence times.

Each site was surveyed along a line normal to the channel using a level and stadia rod. At each study site, a vegetation transect was established in January 2000. Using previously surveyed cross-floodplain lines as a centerline, all living trees or shrubs in a 2 m swath (1 m either side of the centerline) were identified and the diameter at breast height (DBH) measured with a dendrological diameter tape. Trees were included in the survey if any part of the basal trunk was within a meter of the centerline. All tree species found are listed in the checklist of the vascular plants of Texas as occurring in the eastern Pineywoods region of the state in which the study area lies (Hatch et al., 2000).

Basal area (m^2) was calculated as $BA = [\pi(DBH/100)^2]/4$, where DBH is in cm. The relative dominance of a species was computed by the ratio of basal area to that of all trees on the transect. Relative density relates the number of individuals to the total number of trees.

3. Fluvial sediment signatures

3.1. Sediment sources and signatures

The distinction between old and new sediment depends in part on the method used. For example Bonniwell et al. (1999) used the cosmogenic radionuclide Be^7 to distinguish fluvial sediments, which had recently been subaerially exposed from those which had been in the stream long enough to lose their Be^7 signature. Because that isotope has a half-life of 55 days, the old vs. new distinction is approximately 2 months.

On the Solimoes River, Brazil, Johnsson and Meade (1990) found systematic differences in chemical weathering properties between recently mobilized fluvial sediments and those stored in a point bar. However, there was too much overlap in the weathering properties to allow discrimination between old and new sediment for a particular sample. Further, in other locations, it has been found that insignificant postdepositional weathering has occurred in alluvial soils, even in the intense weathering environment of the Indo-Gangetic plain (Sidhu and Gilkes, 1977). Translucent heavy mineral compositions in Oesling, Luxembourg were found to differ significantly between the regolith materials and alluvium (Riezebos and Teunisse, 1992). Despite the contrast, the heavy metal compositions do not allow reliable estimation of whether river sediment has been stored as alluvium.

The problems cited above are potentially avoided by a rapidly acquired weathering property that allows a distinction between old and new sediments. It is suggested below that iron-oxide mineralogy as reflected by soil color represents such an indicator.

3.2. Iron oxides as indicators of fluvial sediment residence time

Inorganic soil particles delivered to east Texas streams are composed of a mineral grain, often with a coating of iron oxide. Iron oxide is used here as a general term referring to iron in its ferric (Fe^{3+}) state without reference to whether the form is oxide per se, hydroxide, or oxyhydroxide. Iron oxides impart red, orange, yellow, or light brown colors, depending on the specific iron-oxide minerals present. Schwertmann (1993) discusses in detail the relationship between color and iron-oxide mineralogy. Inundated or saturated soils and sediments quickly become anerobic and a reducing environment develops. The ferric iron coatings are dissolved during the reduction process, exposing the uncoated grain. These are usually white; the more typical gray colors are attributed to tight adhesion of organic matter. Bacteria are responsible for the reduction of iron and other oxides, and require a carbon source (organic matter). Once reduced, iron will stay in a soluble ferrous form provided oxygen is not present. In consistently saturated conditions, iron will be depleted. If conditions become oxidizing, or if the solution flows into an aerobic zone, oxidization will occur and the iron will precipitate. Repeated oxidation/reduction cycles result in the formation of oxide concretions, gleyed soil colors, and bright mottles, termed redoximorphic features. The presence of such features is commonly used to identify wetland soils and substrates.

Given the high iron-oxide content of upland soils in Loco Bayou basin, east Texas in general, and humid tropical to temperate climates even more generally, color-related features associated with iron oxides have the potential to give insight into residence times in the fluvial system. In the most general sense, the basic idea is that sediments with high contents of ferric (Fe^{3+}) iron with associated brown, yellow, or red colors are delivered to the stream. In the channel or in wet floodplain environments, reducing conditions are encountered, which change the ferric iron to a ferrous (Fe^{2+}) state. The soluble ferrous iron tends to be lost from the soil over time. Thus, the extent to which reduction has occurred can indicate the amount of time the sediment has been in a reducing environment (see Fig. 2). The apparent redox status of alluvium has been used in a very general way to interpret fluvial sediment regimes. Happ (1945), for example, in his studies of piedmont valleys in South Carolina, noted that brown and reddish brown sediment in the upper two to three feet of alluvium "is similar in color to the subsoils of the adjacent gullied uplands, and these reddish-brown deposits are generally recognized as the products of accelerated soil erosion". These oxidized materials may "lie on a dark gray horizon, which is the buried, premodern alluvial topsoil" (Happ, 1945, p. 115). Similar interpretations were made by Happ et al. (1940) in North Central Mississippi, by Trimble (1974) in the southeastern U.S. Piedmont, and by Phillips (1997) in the southeastern U.S. coastal plain.

3.2.1. *Oxidized material*

Oxidized sediment with abundant organic matter (visible litter, or > 3% soil organic carbon) in a subaqueous or waterlogged environment is indicative of very recent delivery to the system, because reduction occurs rapidly, A riverine headwater forest created on mined land in Florida was reexamined by Clewell (1999) 11 years later. Redox features had developed in the soil by that time, but were probably formed early in the evolution of the constructed wetland. Brammer's (1971) studies of seasonally flooded alluvial soils in Bangladesh show reduction and gleying of the top few inches of soil within 2 weeks of flooding. Ross (1989) summarizes the results of theoretical studies showing loss of iron in waterlogged soil beginning in less than 5 days, with maximum concentrations of dissolved iron attained in less than 3 weeks. An experimental study reviewed by Ross (1989) is generally consistent as well, showing maximum concentrations of dissolved iron reached after 10 days of waterlogging.

Flooding or waterlogging of iron oxide-bearing soils (or deposition of such material in subaqueous or saturated environments) can clearly result in the development of features associated with reduction and iron depletion (e.g., low chromas and redox concentrations) on a seasonal time scale or less (Brammer 1971; Brinkmann, 1977; Ross 1989, p. 102). Bouma's (1983) review of processes in originally aerobic soils that become flooded suggests that reduction (first of remaining oxygen, then nitrate and manganese, then iron,) occurs over periods ranging from 1 week to several months. Mendelssohn et al. (1995) note that redox concentrations in conjunction with a living

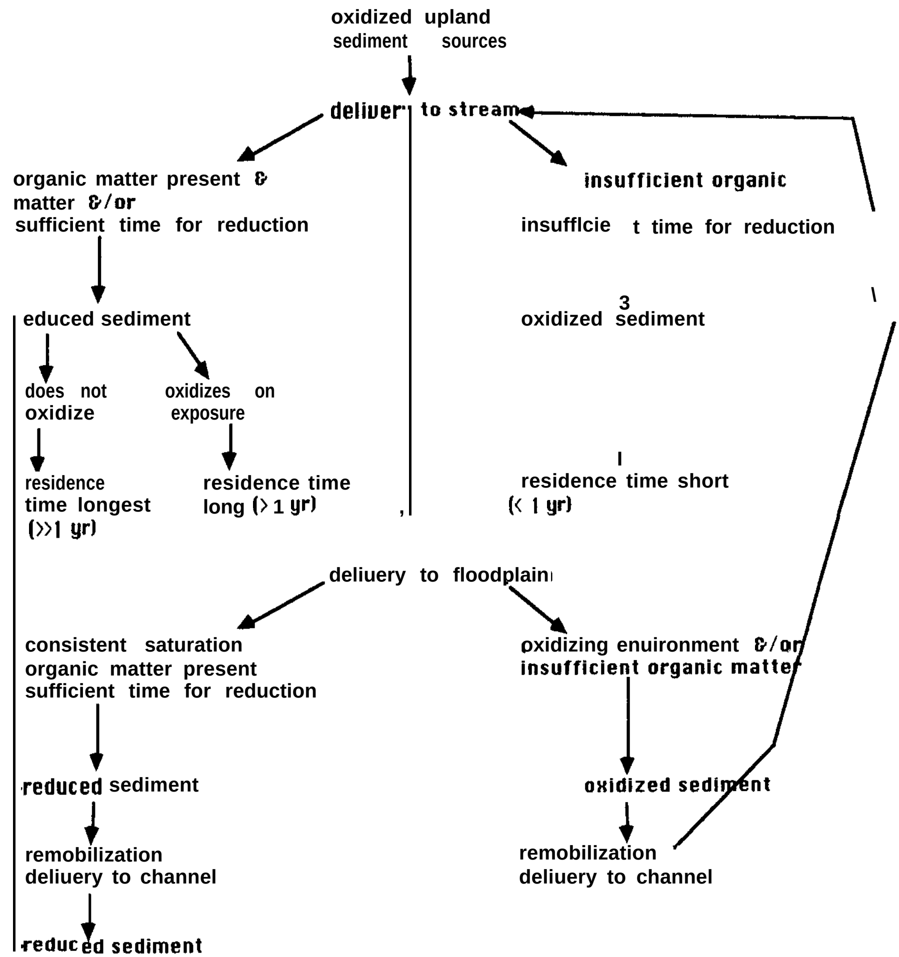

Fig. 2. General logic of the iron oxide-based approach for distinguishing between old and new sediments.

root indicate that anaerobic conditions occurred within the life span of the root. As such features occur in association with annual plants, this indicates that they may form over a seasonal time scale.

If oxidized material is found in an anerobic environment, assuming there is enough organic matter to facilitate reduction, it indicates that the material has been in place less than a year. It is worth noting one exception: in some cases a thin oxidized layer may occur at the soil/water interface due to the rapid rate of oxygen transport at the interface, small populations of O-consuming organisms, 0 production by algal photosynthesis in the water column, and mixing. This type of feature should not be problematic as long as it is recognized and accounted for in sampling and analysis.

Reduction is biochemically mediated and requires organic carbon. Thus, ferric iron may remain in an insoluble state, even in an anaerobic environment, if there is insufficient organic carbon. In humid temperate and subtropical fluvial systems, this is only likely where there is a large, rapid episode of sedimentation. Rapid sedimentation tends to isolate sediments quickly from the weathering environment and retard their alteration (Johnsson and Meade, 1990). In such instances, a large mass of mineral sediment may be deposited quickly, without time for incorporation of significant amounts of organic matter. However, reduction can occur even in these situations around roots and root channels. Thus, the occurrence of oxidized material without organic matter and with no redox features around roots or root channels also indicates sediment that has been in place less than a year. If redox features do occur around roots and root channels, the age of the latter features may give insight into the residence time of the surrounding material.

3.2.2. Reduced material

Oxidized sediment delivered to a channel or saturated floodplain environment in Loco Bayou should become reduced and develop redox features within a year under most circumstances. The longer the material remains in this environment, the more of the soluble ferrous iron that will be lost. If soils or sediments with gray colors indicating iron reduction are exposed to oxygen, they will begin oxidizing (and develop yellowish or brown colors) if any iron is remaining. If the iron has been removed from the system, they will remain gray (Daniels and Hammer, 1992, p. 169). Thus, a relative age discrimination can be made based on whether the gray material oxidized after exposure. Gray or gleyed sediment that does not change color under oxidizing conditions is older.

3.2.3. Summary

The status of iron oxides in channel or floodplain sediments is reflected by soil color, and provides evidence of residence time in the fluvial system. The basic logic of iron oxide-based indicators of old vs. new sediment is shown in Fig. 2. The relationships between redox state as indicated by color and sediment source or residence time are summarized in Table 1. They will be tested against other evidence of sediment delivery, storage, and remobilization in Loco Bayou.

Table 1
Relationship between redox state and residence time for fluvial sediments, as indicated by color

Colors	Relative age *	Absolute age *	Interpretation
Oxidized; organic matter (o.m.) present	young	< 1 year	Sediments must have been delivered from an oxidized source within I year
Oxidized, o.m. absent	young to variable	< 1 year to variable	Sediments must have been delivered from an oxidized source rapidly or in large quantities (to exclude o.m.), where **vegetated,** redox features along roots may be evaluated to determine age.
Reduced; oxidizes on exposure	older	> 1 year	There has not been sufficient time for all iron to be lost in solution
Reduced; does not oxidize	oldest	≫ 1 year	Iron has been lost in solution

* Residence time in subaqueous or waterlogged environment.

4. Results

4.1. Rate of redox-related color changes

Evidence from Loco Bayou confirms the nature of color changes associated with changes in the redox environment, and that such changes can occur over time scales of days.

Two channel-bottom samples were collected from the lower site at Loco Bayou. Both had low-chroma colors indicating reduction of iron; both samples also contained visible organic detritus. The samples were exposed in the laboratory and their moist colors evaluated at time of exposure, and again after 3 h, 4 days, and 21 days. Results are shown in Table 2. One sample had begun to change color in 3 h; both had done so within 4 days. Within 3 weeks, both samples had changed from dark or very dark grayish brown to reddish brown.

An opportunity to observe the rate of color change in oxidized sediments deposited in a reducing environment occurred in April 2000. There was a brief, spatially limited overbank flow event at the upper site, which resulted in deposition of 5 to 9 mm of sediment near the bayou banks. The site was visited 2 days after the event, when the floodplain was still wet and the water table near the surface.

The moist color of the deposited material was dark yellowish brown (10YR 4/4). The sediment was deposited on a layer of leaf litter. It was observed that sediment in contact with organic matter had already undergone reduction to the point of creating a thin (< 1 mm) reduced layer at the sediment/litter boundary. In the field, the color was grayish brown (10YR 5/2), whereas upon exposure in the laboratory the reduced layer oxidized within an hour to 10YR 4/4.

Thus, it is clear that reduction of oxidized material deposited in a channel or wet floodplain environment begins almost immediately, and that the oxidation of reduced sediments with remaining Fe occurs quite rapidly when they are reexposed to oxygen.

It is also necessary to show that sediment in channel or alluvial storage for periods of a year or more is not only reduced, but retains gley colors upon exposure. For this reason, three samples were taken from the bottom of a slough near the upper site. This area was not flooded from Bayou Loco for at least 14 months (February 1999 to April 2000), and there are no apparent local sources of sediment. The slough did, however, maintain standing water or a water table at or very near the surface throughout that period. Thus, the slough represents an environment where sediments are known to have been stored for > 1 year in a reducing environment.

Table 2
Color changes in channel sediments

	Sample 1	Sample 2
Initial color	very dark grayish brown 10YR 3/2	dark grayish brown 10YR 4/2
After 3 h	dark grayish brown 10YR 4/2	dark grayish brown 10YR 4/2
After 4 days	brown 10YR 4/3	dark yellowish brown 10YR 4/4
After 21 davs	reddish brown 2.5YR 4/4	reddish brown 2.5YR 4/4

Results in Table 3 confirm the low-chroma, reduced colors in this environment, and the persistence of these colors following exposure due to loss of iron. Two of the three samples experienced no change in color on exposure; all three retained their low chromas.

4.2. Upper basin sediments

Upland soils in the Loco Bayou basin upstream of Lake Nacogdoches are mainly in what are locally called the “redlands” soils of the Nacogdoches-Trawick and the Sacul-Cuthbert associations (Dolezel, 1980). All have red to dark red subsoils and the Nacogdoches-Trawick soils have dark red (2.5YR 3/6) or dark reddish brown (5YR 3/4) A horizons. Channel sediments from Loco Bayou tributaries generally reflect this color.

Channel bed samples from an upland tributary (see Fig. 1, Site UT) were yellowish red (5YR 4/6). The material was a gravelly sand; the gravel consisting of ironstone fragments up to 3.5 cm in diameter. This tributary is downcutting through Nacogdoches soils and releasing highly oxidized material. The entire bed of this tributary contained ironstone fragments. The ironstone material is essentially unalterable; however, the sand and finer fractions are oxidized. Given that there is no shortage of organic matter in the forested sample site, the channel sediments are judged to be recent and less than a year old.

Two channel bed samples were collected from the upper monitoring site. These were red (2.5YR 4/6) also and had plentiful organic matter, indicating new, recent sediments from the uplands.

4.3. Lower basin sediments

Upland soils in the basin downstream of Lake Nacogdoches fall into three general groups: redland soils of the Nacogdoches-Trawick association, sandier soils of the Cuthbert-Tenaha association, and terrace soils in the Attoyac-Bernaldo-Besner association (Dolezel, 1980). The Nacogdoches, Trawick, Cuthbert, and Attoyac have red to dark red subsoils; however, the Bernaldo, Besner and Tenaha have oxidized, but

Table 3
Sediments from slough at upper site

	Sample 1	Sample 2	Sample 3
Initial color	grayish brown 10YR 5/2 and strong brown 7.5YR 4/6	dark grayish brown 10YR 4/2 with strong brown 7.5YR 4/6 mottles	dark grayish brown 10YR 4/2 with strong brown 7.5YR 4/6 mottles
After 14 days	some increase in strong brown, but low-chroma material oersists	no change	no change

yellower or browner subsoils. The Nacogdoches-Trawick soils and the Attoyac have dark red or reddish brown A horizons (2.5YR or 5YR hues). The others have 10YR hues.

4.3.1. Channel sediments

Two samples of channel sediments were taken from the middle monitoring site just downstream of Loco Dam. One was dark yellowish brown (10YR 4/6). The other was very dark grayish brown (10YR 3/2) and strong brown (7.5YR 4/6). There was visible organic matter in both cases, and no color change on exposure for either sample.

Channel-bottom samples from a point between the middle and lower sites (Site 765; see Fig. 1) were dark yellowish brown (10YR 4/6) with grayish brown (10YR/2) streaks and mottles. When exposed for several days, the sample color converged to a relatively uniform yellowish brown (10YR 5/8).

At the lower site, channel bed samples were dark or very dark grayish brown (10YR 3/2 or 4/2). The gleyed samples oxidized on exposure as described earlier.

At the Highway 7 (H7) site just downstream of the lower site, channel bottom sediments were a mottled mixture of dark grayish brown (10YR 4/2) and dark yellowish brown (10YR 4/6). These colors did not change on exposure.

The channel sediment samples collected at Loco Bayou, their initial color, and any change after exposure are summarized in Table 4. The interpretations are discussed in the next section.

Table 4
Color of channel sediment samples collected at Loco Bayou

Location	Initial color	Change after exposure *
Upper tributary	yellowish red (5YR 4/6)	none
Upper site channel 1	red (2.5YR 4/6)	none
Upper site channel 2	red (2.5YR 4/6)	none
Upper site slough 1	grayish brown (10YR 5/2) and strong brown (7.5YR 4/6)	some increase in strong brown; low-chroma color retained
Upper site slough 2	dark grayish brown (10YR 4/2)	no change
Upper site slough 3	dark grayish brown (10YR 4/2)	no change
Middle site channel 1	dark yellowish brown (10YR 4/6)	none
Middle site channel 2	very dark grayish brown (10YR 3/2) and strong brown (7.5YR 4/6)	no change
CR 765 channel	dark yellowish brown (10YR 4/6) with grayish brown (10YR 5/2) streaks and mottles	yellowish brown (10YR 5/8)
Lower site channel 1	very dark grayish brown (10YR 3/2)	reddish brown (2.5YR 4/4)
Lower site channel 2	dark grayish brown (10YR 4/2)	reddish brown (2.5YR 4/4)
Highway 7 channel 1	dark grayish brown (10YR 4/2) with dark yellowish brown (10YR 4/6) mottles	no change
Highway 7 channel 2	dark grayish brown (10YR 4/2) with dark yellowish brown (10YR 4/6) mottles	no change

*Exposure time two weeks. “None” indicates oxidized samples for which no color change would be expected. “No change” indicates the presence of low chromas for which some color change might occur if sufficient iron is retained.

4.4. Sediment regimes and other field evidence

The implications of the color-based indicators of redox status can be compared to other field indicators of erosion, deposition, and sediment storage. This field evidence is presented in this section.

4.4.1. Floodplain aggradation at the upper site

There is considerable evidence of recent, rapid aggradation in this area. A small, intermittent tributary draining across the floodplain is downcutting near its mouth, with a nickpoint migrating upstream across the floodplain. There is no evidence of increased discharge of this ephemeral tributary, which would in any case be more likely to result in widening than downcutting. The latter could occur due to a lowering of base level or to rapid accretion of the floodplain surface. The former is not possible (base level has been raised since 1976 by the lake), so the morphology of this feature suggests aggradation.

There is a visually obvious stratigraphic discontinuity, and a distinct root layer and some in situ trees rooted in the buried surface clearly identify it as a former floodplain surface (Fig. 3). By measuring the vertical distance from the current floodplain surface to this buried surface along the stream bank, the vertical accretion can be measured. Eleven such measurements show that, on average, 1.5 m of sediment has accumulated here. Given the small size of some trees rooted in the former surface, the aggradation clearly postdates the construction of Loco Dam. The smallest tree that could be clearly identified as rooted in the former surface was an 11-year-old elm (age determined by ring count from core extracted with an increment borer).

Field evidence here shows clear evidence of accelerated sedimentation in the bottomland hardwood forest associated with the impoundment of Bayou Loco.

The vegetation at the upper site is prevailingly young beech (*Fagus grandifolia*) trees. Beech comprised almost half (21 of 43) the individuals in a sample transect across the floodplain. The trees were quite small, however, 18 of 21 had a DBH of less than 5 cm, and the largest had a DBH of 14.9 cm. The largest trees were tulip tree (*Liriodendron tulipifera*) on the left floodplain and willow oak (*Quercus phellos*) on the right. The largest tree in the vicinity of the sample transect was an oak (tentatively identified as willow oak) with a DBH of nearly 106 cm. Beech represents 8% of the total basal area of the transect (relative dominance = 0.08); however, 49% of the individuals (relative density = 0.49). Tulip tree, by contrast, has a relative dominance of 0.84 and a relative density of 0.19.

Tulip tree (also called tulip or yellow poplar) is generally a shade-intolerant pioneer species, which often invades open sites. Beech is a climax species, which grows underneath an overstory (USFS, 1998). Therefore, the species distribution on the east floodplain is consistent with a transitional stage in which the older early invading species are being replaced by a climax species. This suggests a degree of both substrate and hydroperiod stability in recent years.

Willow oak grows best on floodplains that are commonly flooded in winter and early spring, but rarely or briefly during the growing season (USFS, 1998), which is consistent with streamflow regime in east Texas. The slightly higher elevation of the west floodplain as compared to the east probably accounts for the prevalence of willow oaks.

Fig. 3. Channel bank exposure showing the former, preimpoundment floodplain surface (A). Partially buried trees rooted in the former surface are indicated (B). The vertical relief from the surface indicated by A to the current floodplain surface is about 1.5 m.

The cumulative evidence at the upper site suggests rapid floodplain aggradation since 1976, but that flooding is currently rare and the floodplain elevation is stable. The floodplain surface is occasionally saturated, but not enough to maintain a predominantly reducing environment, except at depth (> 1.5 m) and in the slough on the east floodplain. The vast majority of contemporary flows are confined to the channel.

4.4.2. Lake sedimentation

The upper Loco Bayou basin appears to be producing a great deal of sediment. The Texas Water Development Board conducted a detailed survey of Lake Nacogdoches in 1976 when the reservoir was constructed, and again in March, 1994 (TWDB, 1994, 1998). Those data indicate a reduction in lake volume of 3,447,633 m^3, or 6.6% of the 1976 capacity. While several factors may contribute to changes in reservoir capacity (including improved measurement technology; TWDB, 1994), the most likely and most important is infilling with fluvial sediment. Making the assumption that this is the cause of the volume reduction in the lake, the TWDB survey data suggest accumulation rates of 191,535 m^3 $year^{-1}$.

Typical bulk densities of floodplain soils in east Texas range from 1.3 to 1.6 g cm^{-3}. In delta deposits in Lewisville Lake, Texas, Williams (1991) found an average bulk density of 1.27 g cm^{-3}. Welborn (1967) studied the specific weight of fluvial sediment deposits in Texas, finding typical densities of 0.5 to 0.9 g cm^{-3} for newly deposited sediment, and estimating densities of 1.1 to 1.3 g cm^{-3} for deposited sediments after 50 years, based on the initial density and the particle size distribution. A study of Ohio lakes found bulk densities of lake-bottom sediments to be 0.5 to 1.7 g cm^{-3} (USDA, 1990). It is, therefore, reasonable to assume a bulk density of 1.0 g cm^{-3} for a rough estimate of the sediment mass deposited in the lake (this has the advantage of a direct conversion from cubic meters to metric tons). With a drainage area of 227.7 km^2, this implies a sediment yield for Lake Nacogdoches of 841 t km^2 year-‘, Of the 40 Texas lakes for which similar comparative survey data are available (TWDB, 1998), only a few suggest comparably high sediment yields. While there has been considerable logging activity in the upper Loco basin in recent decades, the sediment yields implied by the lake surveys are higher than previously reported in the region. Blackburn et al. (1990) found yields of 0.2 to 10.1 t km^2 $year^{-1}$ pretreatment and 2 to 70.5 t km^2 $year^{-1}$ posttreatment in five watersheds subjected to various logging practices in the Angelina National Forest, Texas. At sites near Alto in the Angelina basin, Blackburn et al. (1986) recorded sediment yields of 3.3 t km^2 $year^{-1}$ from undisturbed forested basins, and ranging from 18.8 to 293.7 following various logging treatments.

Comparison of 1980, 1989, and 1996 black and white aerial photographs from the U.S. Natural Resources Conservation Service shows significant wetland and shoreline progradation in the upper Lake, particularly in the northeastern arm of the lake fed by Loco Bayou. This infilling is consistent with both the lake sedimentation rates discussed above and the observations at the upper site. The lake sedimentation and aerial photographic evidence, thus, suggest significant erosion within the upper basin.

4.4.3. Middle site downcutting

The general channel morphology at this site suggests downcutting. The channel is entrenched below a layer of erosionally exposed roots that may represent the former channel bank. There is some exposure of tree roots and basal flares on trees on the left floodplain. This indicates some erosional scour. Also, tilted tree trunks occur along the channel banks. Such trees have been shown to typify the degradation phases of alluvial channels, when downcutting in the channel leads to slumping of the nearby alluvium and subsequent tilting of bottomland trees (Hupp and Simon, 1991; Hupp and Osterkamp, 1996).

Channel degradation downstream of dams is quite common. Despite the reduced and regulated flows, the very low sediment concentrations of the water released mean that the sediment transport capacity for a given flow is quite high. Thus, the scouring at the middle site is not unexpected, and in this vicinity there is clearly a reduced sediment supply to the bottomland forests.

In contrast to vegetation at the upper site, Beech is absent at the middle site, where water ash (*Fraxinus caroliniana)* is the most common species on the transect (relative dominance = 0.40; relative density = 0.50). An overcup oak, water ash, and sweetgum are the three largest individuals on the transect (23 to 33 cm DH), while the largest nearby tree is a Nuttall (?) oak with a DBH of 67 cm. The water ash is entirely on the lower, east floodplain. On the higher west side there are also some pines among the hardwoods, though none were on the sample transect. The vegetation structure at the middle site is consistent with a riparian environment still undergoing regular inundation, and with a lower degree of substrate stability that indicated by the community composition at the upper site.

4.4.4. Alluvial deposition at the lower site

Dendrogeomorphic evidence at the lower site suggests that it has been undergoing active deposition in recent decades in spite of the upstream dam. On the lower floodplain surface, excavations in winter 2000 showed that the litter layer from the fall/winter of 1998-1999 is buried by alluvium. The deposition ranged from 33 to 61 mm, with a mean of 43.7 mm.

Several trees at the site were examined in detail for evidence of recent burial and sedimentation. A small beech tree (DBH < 5 cm) on the edge of the upper floodplain had a basal flare buried by 71 mm of oxidized sandy loam. Adventitious rootlets are common in the buried zone. The tree is three years old, suggesting a minimum annual deposition rate of 23.7 mm year^{-1} since the tree became established.

A willow oak on the lower floodplain had a basal flare buried by 28 cm of alluvium, which was a combination of oxidized and uncoated sandy loam. A ring count shows the tree to be 25 years old, giving a minimum sedimentation rate of 11.2 mm/yr. An adventitious root in the buried zone had two annual rings and was buried by 69 mm of sediment. This suggests a 34.4 mm year^{-1} rate.

An ash on the lower floodplain had a basal flair covered by 180 to 210 mm of alluvium. A ring count shows the tree to be 10 years old, yielding minimum sedimentation rates of 18 to 21 mm year^{-1}.

All trees in the immediate vicinity of the monitoring site on the left bank were inventoried. On the lower floodplain (< 59 m elevation; Fig. 4), 75% were clearly buried (basal flares buried by alluvium at least 8 cm thick), and one was slightly buried. Of the middle floodplain (59-59.3 m) trees 42% were clearly buried, 29% slightly buried, and 29% were not buried. On the upper floodplain (> 59.3 m elevation), 70% were not buried and 30% slightly buried.

On the east side of the transect small beech trees (< 5 to 5.9 cm DBH) are becoming established. The largest tree in the sample is an overcup oak (*Quercus lyrata*); however, the largest trees in the vicinity are sweetgum (*Liquidambar styraciflua*; largest individual DBH = 110 cm). Sweetgum is a pioneer, invading species, so the vegetation data again indicate that older early invading species are being replaced by a climax species. The west floodplain is higher (Fig. 4), and much of it is in pasture. Water oak (*Quercus nigra*) dominates the streambank zone. A filled slough further out on the floodplain

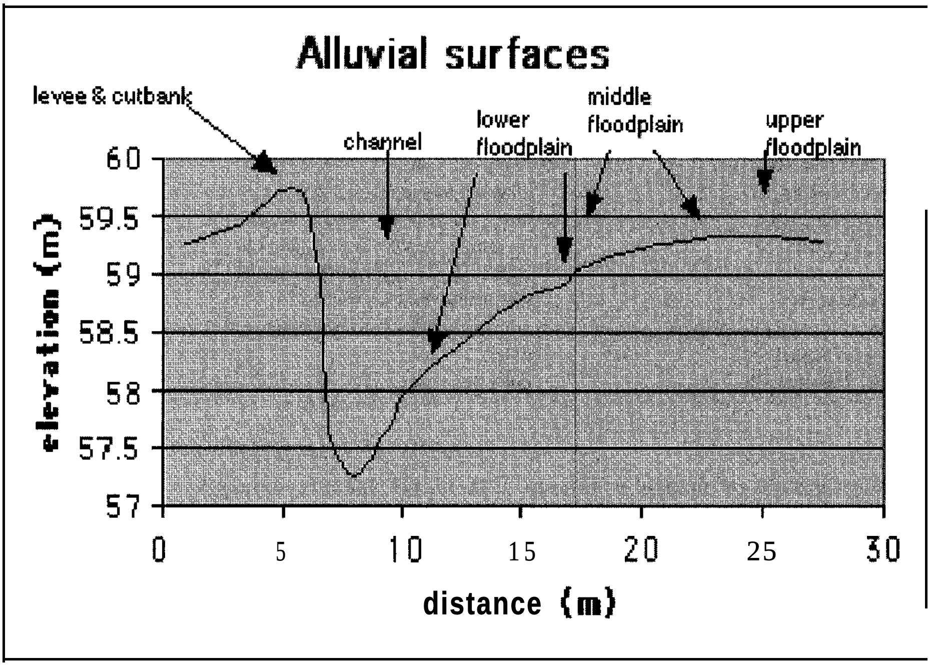

Fig. 4. Alluvial surfaces at the lower site. The overall transect is shown in Fig. 1.

contains various oaks, the largest an overcup oak. The location of water oak on the streambank levee is consistent with its preference for locations that flood frequently and deeply, but drain rapidly (USFS, 1998). Altogether the oaks dominate the transect, with relative dominance of 0.90 and relative density of 0.61.

Vegetation composition of this site suggests regular inundation of lower portions of the floodplain, but that the upper floodplain has become stable, allowing climax species to become established.

5. Discussion

5.1. Comparison. of iron-oxide indicators with other field evidence

The interpretation of fluvial sediment residence times from the data in Table 4 is given below in Table 5. A summary of the field evidence at each site and the color-based old/new interpretations is given in Table 6.

At the upper tributary site the color-based interpretation is fully consistent with field evidence. The channel is downcutting through red upland soils, and there is no indication of significant alluvial storage in floodplains or bars. The armoring of the channel bed with ironstone fragments indicates an active transport regime. Thus, sediments at this site are known to be new, and the color indicators are as expected.

Table 5
Interpretation of fluvial sediment residence times based on redox status as reflected by color (refer to Table 4 for color data)

Location	Interpretation of residence time
Upper tributary	new; < 1 year
Upper site channels 1 and 2	new; < 1 year
Upper site sloughs 1, 2, 3	alluvial storage for > 1 year
Middle site channel 1	new; < 1 year
Middle site channel 2	mixture of new (< 1 year) and old sediments remobilized from alluvial storage
CR 765 channel	dominantly new sediments, with some older (> 1 year) material
Lower site channels 1, 2	older; > 1 year
Highway 7 channels 1, 2	old; ≫ 1 year

Interpretations of channel sediments at the upper site also indicate an upland sediment source and a short residence time. This is consistent with observations at the upper site. The recent rapid sedimentation has created high banks, which rarely flood, as indicated

Table 6
Summary comparison of field indicators of sediment regimes and color indicators of new, older, and old sediments
See text for discussion.

Upper Tributary
Field: Morphological evidence shows recent and contemporary downcutting through oxidized upland soils.
Color: New.
Upper Site
Field: Morphology and dendrogeomorphic evidence show rapid, recent floodplain aggradation. Vegetation composition and dendrogeomorphology suggest that floodplain inundation is now rare and the substrate is relatively stable, confining most flows to the channel. Lake surveys suggest rapid recent erosion in the upper basin. Air photos show aggradation and shoreline degradation in the upper lake area, consistent with erosion in the upper basin and aggradation in floodplains just upstream.
Color: Channel sediments are new. Floodplain slough sediments are old.
Middle Site
Field: Dendrogeomorphic indicators and channel morphology show recent channel downcutting, frequent floodplain inundation, and evidence of some floodplain stripping.
Color: Channel sediments are new or a new/old mixture.
765 Crossing
Field: Morphology suggests an efficient channel with relatively rare floodplain inundation.
Color: Dominantly new, with some older sediments.
Lower Site
Field: Dendrogeomorphology shows significant recent aggradation on lower and minimal aggradation on upper floodplain; vegetation composition supports this and suggests recent stabilization of upper floodplain. Abundant morphological evidence of alluvial storage.
Color: Dominantly older.
Highway 7 Crossing
Field: Channel/floodplain morphology indicates frequent inundation and actively alluvial storage.
Color: Dominantly old.

by the vegetation. The channel morphology, thus, facilitates efficient transport through this reach, with little alluvial storage of newly delivered sediment. As no significant bank erosion was observed in alluvial portions of Loco Bayou, this suggests that sediments have a short residence time. The data from the slough at this location, where it is known that alluvium was stored for at least 14 months, suggests that material with longer residence times would have acquired a color signal indicating reduction of ferric materials.

Field evidence at the middle site shows both downcutting of the channel and some stripping of the floodplain surface. This activity entrains a combination of oxidized upland and higher floodplain surface source materials, and older, reduced floodplain sediments. One of the two channel sediment samples reflects this mixture; the other has a “new” sediment signature.

At the 765 site, Loco Bayou is well entrenched. While some overbank deposition was observed in winter 1999, the high steep banks make an efficient channel for transporting sediment. Further downstream, toward the lower and H7 sites, the banks are lower and alluvial storage in the form of point bars is more in evidence. Thus, the general age gradient suggested by the color data, from dominantly new at the middle and 765 sites, to older at the lower site, to old at the Highway 7 site, is consistent with the morphology of the channel and alluvial valley.

The lower site, particularly on the lower part of the floodplain, is continuing to actively accrete. This generally supports the oxide/color data, in the sense that short-term alluvial storage is clearly occurring in this reach.

In general, where the length of alluvial storage is known to be short (upper tributary) and long (slough at the upper site), the color indicators correctly reflect the residence times. At the middle site, the indicators accurately represent the known sediment sources. At the other sites, the color indicators are generally consistent with other field observations.

5.2. Relative importance of sediment sources

Sediment colors indicating iron-oxide status show that recent deposition is prevailingly new sediment at sites upstream of Lake Nacogdoches. Downstream of the dam there is a clear progression in apparent residence time. At the middle and 765 sites, there is a mixture of new and old sediment, dominated by the former. At the lower site channel sediments are dominantly older material (residence time $>$ 1 year). At the downstream-most site, the apparent age of channel bottom sediments is old ($\gg$ 1 year).

The interpretation of these results is not necessarily straightforward because of the sediment trapping effects of Lake Nacogdoches. Other than immediately downstream of the dam and upstream of the lake, there is no evidence of a major change in sediment regimes associated with the impoundment. Apparently, local erosion and tributary inputs below the dam supply ample sediment for maintenance and aggradation of floodplains. However, it is conceivable that the trapping of upper-basin sediment in Lake Nacogdoches is partly responsible for the higher proportion of older sediment in the lower part of the basin.

The upper tributary (UT) site is characterized by new sediment. Small tributaries draining directly to the lake are deeply incised and, thus, deliver new sediment.

However, it seems clear that sites far downstream of the headwaters are also dominated by new alluvium. Lake Nacogdoches captures 86% of all the drainage area upstream of the lower site, and the upper site is just upstream of the lake. However, at the upper site, samples indicate dominantly new sediment. Downstream of Loco Dam, older sediment is not dominant at the middle or 765 sites, comprising the majority of the material only at the lower site 16 km upstream of the bayou mouth. Old sediments also dominate the lowermost sample location (the Highway 7 site), though the latter is affected by backwater flooding from the Angelina and may not represent sediment dynamics of Loco basin. It seems clear that old sediment is dominant only in the lower reaches. This supports the notion that alluvial storage opportunities rather than distance from the headwaters account for the prevalence of old sediment near the basin mouth.

5.3. Methodological notes

The principle of using soil color to indicate redox and drainage status is well established in soil and wetland science. However, use of color indicators is also recognized to be subject to certain limitations and cautions. Soil and sediment colors are influenced by factors other than iron-oxide mineralogy and redox status, including parent material colors, soil development and stratigraphy, and organic matter content. Color determinations are also influenced by light and moisture conditions. While such variations can be minimized by careful and consistent procedures, they can influence results, particularly by inexperienced operators. Good discussions of some of the issues associated with color determinations and interpretations thereof are given in the volume edited by Bigham and Ciolkosz (1993).

While color-based indicators are low cost and robust, they are not useful unless upland or new sediment sources are largely impregnated with iron oxides. The method also applies only to bulk samples large enough to show redox features and, thus, does not apply to suspended or bed sediment in transit. Color-based indicators of old and new sediments are most useful in conjunction with independent evidence of fluvial and alluvial sediment storage and transport regimes (as done in this study) or with other indicators of sediment source areas or residence times.

Future refinements of this methodology should focus on the rate at which iron is lost from reduced sediments in waterlogged environments, and the extent to which such rates can be generalized. This would allow the relative distinction between “old” and “older” sediments to be further refined. In this study, evidence from the slough at the upper site suggests that loss of iron can occur within a few years or less, based on the presence of reduced sediment, which does not oxidize on reexposure in the uppermost layer.

6. Conclusions

A low-cost, low-technology method for distinguishing old vs. new sediment in Loco Bayou and other basins with a predominance of highly oxidized upland soils was developed. The method is based on systematic changes in the reduction and loss of iron in subaqueous or waterlogged environments, as reflected in soil color. The method is capable of distinguishing between new (residence time in the channel or wet floodplain environment < 1 year) from old sediment. Among older sediments, a further, relative residence time distinction is possible. In all cases, color evidence was consistent with field evidence of erosion and sedimentation trends. In several of these cases, the source or residence time of fluvial sediments were explicitly known, providing direct confirmation of the residence time suggested by the color indicators.

The color-based signatures of old and new sediment are quite robust and have the advantage of being low cost, low technology, and applicable in any basin with a predominance of oxidized upland or new sediment sources. The disadvantages are a lack of precision for old sediments, and applicability only to sediment samples large enough to show redox features. The method does not apply to suspended sediment samples.

Acknowledgements

This research was supported by the U.S.D.A. Forest Service, Southern Research Station under cost-share agreement no. SRS 33-CA-99-631. This project has benefited from the advice, support, and assistance of a number of people. These include Greg Malstaff of the Texas Water Development Board, Kevin Yeager and Allison Johansen of Texas A&M University, Nate Phillips of the Tobacco Road Research Team and the Cartography Laboratory, Department of Geography, University of Kentucky. The Department of Geography, College of Geosciences, Texas A&M University also provided support.

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