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SEDIMENT DYNAMICS IN THE RESTORED REACH OF THE KISSIMMEE RIVER BASIN, FLORIDA: A VAST SUBTROPICAL RIPARIAN WETLAND[†]

E. R. SCHENK[a*], C. R. HUPP[a] and A. GELLIS[b]
[a] *U.S. Geological Survey, National Research Program, Reston, Virginia USA*
[b] *U.S. Geological Survey, Maryland Water Science Center, Baltimore, Maryland USA*

ABSTRACT

Historically, the Kissimmee River Basin consisted of a broad nearly annually inundated riparian wetland similar in character to tropical Southern Hemisphere large rivers. The river was channelized in the 1960s and 1970s, draining the wetland. The river is currently being restored with over 10 000 hectares of wetlands being reconnected to 70 river km of naturalized channel. We monitored riparian wetland sediment dynamics between 2007 and 2010 at 87 sites in the restored reach and 14 sites in an unrestored reference reach. Discharge and sediment transport were measured at the downstream end of the restored reach. There were three flooding events during the study, two as annual flood events and a third as a greater than a 5-year flood event. Restoration has returned periodic flood flow to the riparian wetland and provides a mean sedimentation rate of 11.3 mm per year over the study period in the restored reach compared with 1.7 mm per year in an unrestored channelized reach. Sedimentation from the two annual floods was within the normal range for alluvial Coastal Plain rivers. Sediment deposits consisted of over 20% organics, similar to eastern blackwater rivers. The Kissimmee River is unique in North America for its hybrid alluvial/blackwater nature. Fluvial suspended-sediment measurements for the three flood events indicate that a majority of the sediment (70%) was sand, which is important for natural levee construction. Of the total suspended sediment load for the three flood events, 3%–16% was organic and important in floodplain deposition. Sediment yield is similar to low-gradient rivers draining to the Chesapeake Bay and alluvial rivers of the southeastern USA. Continued monitoring should determine whether observed sediment transport and floodplain deposition rates are normal for this river and determine the relationship between historic vegetation community restoration, hydroperiod restoration, and sedimentation. Published in 2011 by John Wiley & Sons, Ltd.

KEY WORDS: floodplain; sediment; suspended sediment; sediment dynamics; bedload; riparian vegetation; river restoration; Florida

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INTRODUCTION

Riparian wetlands provide valuable ecosystem services for river systems by trapping nutrients, sediment, and contaminants (Noe and Hupp, 2009). However, the hydrologic connection between the channel and floodplain must be maintained (in this case, restored) through periodic flooding to allow trapping of material on the hydraulically rough riparian area. Flow across the floodplain allows for the development of a complex microtopography that provides habitat for a wide spectrum of flora and fauna. In Florida, this includes many species of concern (e.g. snail kite, *Rostrhamus sociabilis*; wood stork, *Mycteria americana*) and several wading bird rookeries. The diverse functions of riparian wetlands are often negatively impacted by human alterations to the river channel through dam construction, stream channelization, and canal and levee construction. Impacts may include dramatic reductions in the peak stages, frequency and duration of over bank flows, and sediment transport (dams, Williams and Wolman, 1984), and a dramatic reduction in overbank flow and attendant sediment trapping (channelization/levees, Hupp *et al*., 2009). Interest in mitigating, or preventing, these negative impacts have grown steadily in the last few decades (Hupp *et al*., 2009; Opperman *et al*., 2009).

The Kissimmee River lost the majority of its riparian wetland to channelization in the 1960s and early 1970s, a process that is currently being partially reversed as part of the world's largest river restoration to date (Dahm *et al*., 1995). Prior to channelization, the hydrology of the Kissimmee River was unique among North American rivers (Toth *et al*., 1998). Floods occurred frequently with portions of the floodplain inundated nearly year-round (Toth *et al*., 1998). The river was more similar to large tropical rivers of the Southern Hemisphere like the Amazon, Senegal, or Niger rivers than most North American rivers (Koebel, 1995). Continuous floods lasting several months were common and facilitated the development of a subtropical riparian wetland rich in wildlife and wetland vegetation (Warne *et al*., 2000; Toth *et al*., 2002).

The pre-channelized Kissimmee River was a sinuous (1.67–2.1), low-gradient channel ($0.07\,\mathrm{m\,km^{-1}}$) with a

*Correspondence to: E. R. Schenk, U.S. Geological Survey, National Research Program, 12201 Sunrise Valley Dr. MS 430, Reston, VA 20192, USA.
E-mail: eschenk@usgs.gov
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bankfull width of 15–35 m and depth of 1–3.5 m (Koebel, 1995; Warne *et al*., 2000). Although the Kissimmee River was described as transporting suspended sediment with low concentrations (Warne *et al*., 2000), sand transport was a principal factor in developing and maintaining a dynamic floodplain (Warne *et al*., 2000).

Wetland habitat in the Kissimmee River Basin was degraded from both dam construction (water control structures and associated navigation locks) and more pervasively and severely from channelization. Channelization occurred between 1962 and 1971 (Koebel, 1995) following a series of prolonged floods in the 1940s. The sinuous anabranching historic channel was abandoned with the dredging of the C-38 canal, effectively shortening the river from 167 to 90 km (Whalen *et al*., 2002). Approximately 12 000–14 000 ha of riparian wetlands were lost with the creation of the C-38 canal (Koebel, 1995). Even before the channelization process was completed, various groups were decrying the decline in water birds, fish, and water quality (Koebel, 1995; Bousquin *et al*., 2005). Channelization led to a 92% decrease in wintering waterfowl on the wetland (Perrin *et al*., 1982), the loss of over five billion small fish (Toth, 1990), and a significant decline in game fish (Miller, 1990).

The restoration of the river was authorized by Congress with the Water Resources Development Act of 1992. Restoration began in the late 1990s and as of this writing is still ongoing. Restoration consists of removing two of the six water control structures (S65B and S65C, Figure 1A), backfilling approximately one third of the C-38 canal and restoring flow to approximately 70 km of sinuous 'naturalized' channel (Figure 2, Dahm *et al*., 1995; Toth, 2010a). The river restoration program when completed will return hydroperiods to several thousand hectares of floodplain. Two of the five canal reaches have been restored to create one river reach (designated Pool B/C derived from the pre-restoration reaches). The downstream canal reach Pool D is scheduled to be restored in the near future creating one restored reach (Pool B/C/D). The upstream and downstream canal reaches (Pool A and E, respectively) will remain channelized and controlled by lock structures for flood abatement purposes.

A key indicator of successful restoration is the re-establishment of pre-channelization habitat function and structure (Toth *et al*., 1995). Regular inputs of fine fluvial sediment from annual floods is essential for maintaining broadleaf marshes and wet prairies historically found throughout the Kissimmee River floodplain (Toth *et al*., 1995). Monitoring the hydrologic reconnection of the riparian wetland with the newly restored portions of the Kissimmee River channel may enable the quantification of habitat restoration. Understanding how sediment transport and sediment supply in the Kissimmee River affect floodplain processes is also important. Our specific objectives include the quantification and interpretation of floodplain sedimentation patterns, fluxes, and character (sediment size, bulk density, organic content) relative to flood frequency and magnitude, landform, vegetation type, and sediment transport. Our study is part of a larger project with focuses on channel geometry and sediment discharge (Gellis *et al*., 2010; Mossa *et al*., 2010). Ultimately, our results can be used to facilitate the development of a sediment budget. This paper presents initial results (2007–2010) of our riparian wetland sediment monitoring.

SITE DESCRIPTION

The Kissimmee River drains approximately 7804 km^2 of central Florida. The river begins in a lake region south of Orlando, Florida, known as the Kissimmee Chain of Lakes and ends at Lake Okeechobee. Historically, the river flowed for approximately 166 km in a low-gradient anabranching channel that frequently flooded for weeks to months annually (Toth *et al*. 1995). Historic descriptions of the river indicate a broad marsh punctuated with live oak hummocks and a channel delineated by a narrow levee of willows and mangroves (*sic*, most likely wetland shrubs) (Preble, 1883). After finishing channelization in 1972, the channel was 9 m deep and 64–105 m wide (Toth *et al*., 1993). The channel was separated into five 'pools' created by six lock and dam structures when the river was constrained by the C-38 canal. Approximately 44% of the riparian wetland was converted to pasture after channelization (Milleson *et al*., 1980). Thus far, two pools have been merged (Pool B and C) with the demolition of the S65B structure to create a naturalized river channel (Toth, 2010b). The reconnected riparian wetland within the restored reach consists of backfilled C-38 canal, borrow areas used to fill the canal, and the natural floodplain. We delineated a distinct fourth landscape unit, natural levees, to better explain sedimentation patterns. The natural floodplain occupies the majority of the landscape (80% of the restored reach) with borrow areas a distant second (15%). Approximately 40% of the channelized river will be restored providing wetland habitat and reducing sediment and nutrient loads before they further impact downstream resources.

METHODS

Site/transect selection and establishment

We established 16 sediment monitoring transects generally aligned perpendicular to the channel that began on the river edge and continued from 50 to 575 m across the floodplain. Transect length was determined by accessibility and the landscape or vegetation type that we were attempting to sample. Thirteen transects (Figure 1B) were in the restored river reach (87 sampling points); three transects were in channelized, yet unrestored Pool D (14 sampling points)

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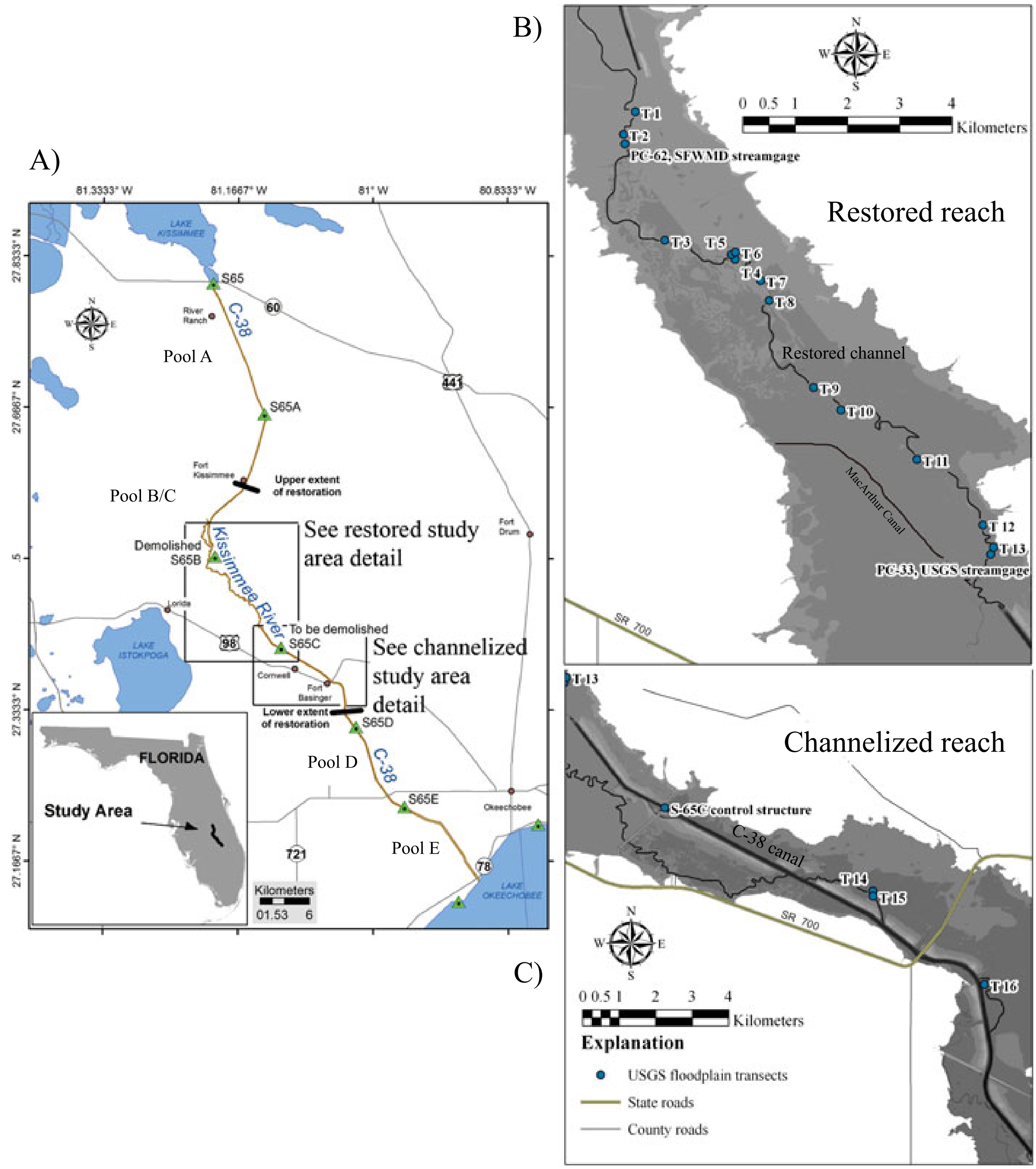

Figure 1. (A) Kissimmee River including lock structures and detailed maps of transect locations in both the restored study area in (B) Pool B/C, location of PC-62 and PC-33 streamgages, and (C) the channelized, unrestored Pool D. Transects on Pool D begin near the remnant river channel, not the channelized active river (labeled as the C-38 canal). Shading on detailed maps (B and C) represents elevation; darker shades are lower in the landscape than lighter shades. Portions adapted from Mossa *et al*. (2010). This figure is available in colour online at wileyonlinelibrary.com/journal/rra

(Figure 1C). Transects were numbered from upstream to downstream and contained three to 11 sampling points each. Sampling points consist of white feldspar clay pads and associated sediment samples. Periodic measurements were made of deposition on the clay pad as well as texture, bulk density, and composition of the deposits (carbon and phosphorus were measured in a subset of these points).

The restored Kissimmee River floodplain was separated into four categories: backfilled C-38 canal, borrow areas used to backfill the canal, original floodplain, and levee (Figure 3). Borrow, backfill, and natural floodplain landscape designations were assigned by the South Florida Water Management District (SFWMD) and provided in a GEOGRAPHIC INFORMATION SYSTEMS (GIS) format for our

Figure 2. Aerial photos in 2005 of an example of the C-38 canal with a portion of a remnant river channel (left) and a naturalized reach of the Kissimmee River (right). Photo credits: Brent Anderson, SFWMD. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

analyses. Data from Pool D was not used in the landscape analyses to ensure appropriate comparisons of landscape function along the restored channel. The majority of the restored study area (between T1 and T13) was natural floodplain with large sections of borrow areas (Table I).

Transect locations were stratified based on representative floodplain vegetation, landscape type (borrow, backfilled C-38 canal, and original floodplain), and location within the restored reach. Most transects crossed several landscape and vegetation types. We believe this sampling design allowed for a reasonably unbiased estimate of sedimentation rates along the restored reach. Each transect was leveled in detail using a laser level. Bank heights were measured near the beginning of each transect from the top of the bank to the low water elevation; all bank height and elevation measurements were normalized to water elevation using a series of stage gages maintained by the SFWMD. Water elevations were tied to a U.S. Geological Survey (USGS) streamgage (SFWMD river structure PC-33, USGS streamgage 02269160). Additionally, sites were compared with elevation and vegetation cover using GIS software. Vegetation and elevation data were provided by SFWMD. Most sites were established in the spring/winter of 2007 and measured periodically for deposition; the most recent measurements were taken in January 2010. Establishment of transects 11, 12, and 13 was delayed until January 2008 because of the backwater effect of the S65C control structure in the first half of 2007. Thus, most sites were monitored for three wet seasons with three transects measured for two wet seasons. The PC-62 streamgage (operated by SFWMD)

Figure 3. An aerial photograph of the four dominant floodplain landscape types along the Kissimmee River. The backfilled C-38 canal, borrow areas to fill the canal, the natural floodplain, and levees are depicted by the letters A, B, C, and D, respectively. The naturalized channel is on the right-hand side of the photograph. Photo credit: Brent Anderson, SFWMD, February 2010. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

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Table I. Sedimentation in the restored riparian wetland area between transects 1 and 13 by landscape type, mean sedimentation rate, number of sedimentation observations per landscape type (*n*), percentage of organic content, soil bulk density, and approximate mass per year per square meter

Landscape type	Area (m^2)	Rate (mm per year)	*n*	SE	Percentage of organic content	SE	Density ($g cm^{-3}$)	SE	Total mass ($g m^{-2}$*year)
Borrow	4 330 000	7.4	18	1.7	29.8	6.9	0.49	0.05	3583
Backfill	1 000 000	5.0	12	1.2	23.8	9.5	0.85	0.21	4201
Floodplain	23 542 000	10.1	25	1.2	32.2	5.4	0.45	0.04	4582
Levee	418 000	27.1	13	7.4	9.0	3.6	0.56	0.13	15 093

Standard error (SE) determinations for each of the measurements is provided.

and the USGS PC-33 streamgage were both used to determine the flow regime during the study (Figure 4). The SFWMD also operates a streamgage at the upstream S65A control structure; these data were used to determine upstream hydrologic inputs.

Sediment deposition and sampling

Artificial marker layers (clay pads) were placed at each sampling point ($n = 87$ on the restored reach). These markers are made by placing powdered white feldspar clay approximately 20 mm in thickness over an area of about 0.5 m^2 on the soil surface that has been cleared of coarse organic detritus. This clay becomes a fixed plastic marker after absorption of moisture that permits accurate measurement of short-term net vertical accretion (Baumann *et al*., 1984; Hupp and Bazemore, 1993; Kleiss, 1996). The clay pads were examined periodically and measured for depth of burial during the course of study. Landscape spikes were placed on the edges of claypads to measure possible erosion and to aid in re-locating the claypad. Clay pads were measured in May 2008 and again in December 2008 to assess sedimentation dynamics after a tropical storm-generated flood. The restored reach transects were sampled a final time in late January 2010 to determine the effects of the annual summer flood in 2009 and conclude the present portion of analyses.

Sediment samples were taken at all sampling stations at the beginning and end of the study. The last sample was, when possible, taken from the soil surface to a depth matching that of deposition above the claypad so that current (past three wet seasons) processes were reflected in the sediment analyses. Sediment sample analyses included (1) bulk density, by taking a known volume, which was then dried and weighed (Burt, 2004); (2) size class composition by dry sieving in a vibratory sieve (Schenk and Hupp, 2009); and (3) organic fraction of the top 5 cm of floodplain sediment by a 400°C 16-h 'loss on ignition' procedure (Nelson and Sommers, 1996). A subset of samples were ground and passed through a 1-mm sieve, combusted at 400°C for 16 h, solubilized using microwave-assisted acid digestion with HNO_3, HCl, HF, and HBO_3, and then measured for total P content using inductively coupled plasma optical emission spectrometry.

Sediment particle size was determined by grinding a known amount of oven-dried sediment with a mortar and pestle and then processing the sediment through a sonic sieve for 12 min. Sediment texture (particle size) was arranged according to phi size class units (Krumbein, 1936). Results are presented as silt/clay, very fine sand, fine sand, sand, and coarse sand fractionations.

Fluvial sediment transport

Bedload and suspended-sediment transport were quantified for Pool C from 21 July 2007 through 30 September 2009 at the USGS streamflow-gaging station on the Kissimmee River at PC-33 near Basinger, Florida (USGS ID 02269160) (Figure 1B). The drainage area of the Kissimmee River at the USGS station is 5270 km^2.

Suspended-sediment samples used in the computation of suspended-sediment loads were collected using both manual and automatic samplers in accordance with USGS protocols (Edwards and Glysson, 1999). Suspended-sediment and bedload samples were collected using a boat during scheduled bimonthly site visits, as well as during periods of high flows. An automatic-pumping sampler with a peristaltic pump was installed at the site to collect suspended-sediment samples on a more frequent interval. Daily suspended-sediment loads were computed using the subdivision method (Porterfield, 1972) with the USGS-software program, GRAPHICAL CONSTITUENT LOADING ANALYSIS SYSTEM.

Bedload samples were collected during the same site visit when suspended-sediment samples were collected (bimonthly and during high flows) using a BL-84 bedload sampler. The Equal Width Interval (EWI) method was used in the collection of bedload (Edwards and Glysson, 1999). A bedload-rating curve was produced from the relation of instantaneous discharge and measured bedload transport. Daily bedload transport was computed using the line of best fit from the bedload-rating curve and applied to the mean discharge for each day of the study period.

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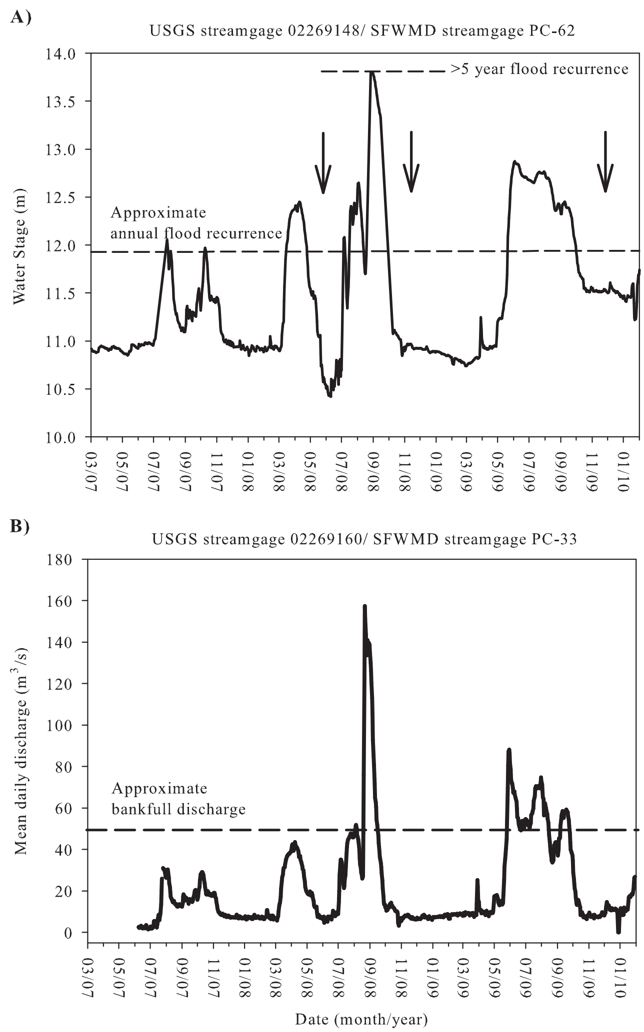

Figure 4. (A) Mean daily flow measured at the PC-62 streamgage near the old Pool B/C control structure. Arrows indicate dates when sediment deposition above clay pads was measured. The approximate annual and greater than 5-year flood recurrence is also noted (from Leroy Pearman, USGS Orlando, Florida, personal communication). (B) Mean daily discharge at the PC-33 streamgage near Basinger, Florida. Approximate bankfull discharge is also noted

RESULTS

Hydrologic regime

There was no flow in the channel from October 2006 to May 2007 because of low-water levels upstream in Lake Kissimmee and associated actions to mitigate those water levels (closing of river control structures to retain lake water). During this period, water levels at upstream sections of the restored channel were lower than normal lows; dry conditions existed on the majority of the floodplain except in moist depressions and some sloughs. In contrast, areas of the restored channel near and just upstream of the downstream lock structure experienced a sustained high-water stage because of water ponding behind the temporarily closed S65C control structure. Floodplain depressions and sloughs were inundated and most areas of the floodplain were moist to very wet in the ponded area.

Between the resumption of flow from Lake Kissimmee in May 2007 and our first sampling date in May of 2008, there was only one period in March and April of 2008 that inundated the majority of the floodplain. This spring flood crested above bankfull elevation along portions of the Kissimmee River (as recorded at the PC-62 streamgage Figures 1B and 4A) and had a return interval of approximately 1 year (Figure 4A; Leroy Pearman, USGS Orlando, FL, personal communication). The water stage in June 2008 dropped to approximately 0.6 m lower in elevation than the stage during the no-flow hydrologic regime, and was the lowest stage during the study period. By July 2008, however, summer rains increased stage, culminating with Tropical Storm Fay (19 August 2008) creating the highest flows of the study period (approximately 2.5 m above June 2008 levels). Rainfall total associated with Tropical Storm Fay ranged from 254 to 635 mm (http://www.hpc.ncep.noaa.gov/tropical/rain/fay2008filledrainblk.gif). Measurements in early May 2009 documented minor deposition in Pool D (largely trace amounts unrelated to inundation).

Riparian wetland sediment deposition rates

Sediment deposition was measured on 69 pads, erosion was detected on 2 pads, and no change was recorded on 2 pads; 14 pads were lost or destroyed because of disturbance during the study period. Total rates (n=73) ranged from −17.6 (erosion) to 71.1 mm per year (levee deposition). Mean sediment deposition was 11.3 mm per year for Pool B/C (n=73). Total deposition measured in May 2008 before Tropical Storm Fay ranged from 0 to 37 mm. The mean deposition was 7.0 mm for Pool B/C (n=81). Deposition after the second annual recurrence-interval flood (summer 2009) ranged from −156 (levee erosion) to 75 mm (levee building) with a mean of 8.2 mm on the restored floodplain. Mean deposition from the two annual flooding events was within the range of typical deposition for wetlands in the southeastern USA (Hupp, 2000). Deposition following the tropical storm (August 2008) ranged from −9 (erosional) to 188 mm (levee building) with a mean deposition of 15.8 mm. The overall deposition rate (11.3 mm per year) is high because of the effect of the Tropical Storm Fay event.

Clay pads were installed at 14 locations in the unrestored Pool D floodplain. Sediment deposition was measured on 10 pads; erosion measured at one pad and three pads were lost during the study period. Deposition rates ranged from −1.9 to 7.3 mm per year (n=11). Mean sediment deposition was 1.7 mm per year in Pool D for the entire study period and

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1.6 mm per year when measured in May 2008; both means are an order of magnitude lower than the restored reach.

The highest deposition rates were in the furthest upstream transects and in the downstream segment of the restored reach. Transects 12 and 13 are exceptional; transect 12 is located on a relatively high natural hummock and isolated from overbank flow, whereas transect 13 is located on the west floodplain on the opposite bank from where flow is diverted into a ditch draining into the downstream channelized reach. The amount of soil organic matter varied widely (Figure 5 and Table I) but was generally highest near floodplain depressions or side channels. The highest proportions of organic matter were on the natural floodplain, slightly lower amounts occur within the borrow areas and the backfilled canal, and the lowest proportion occurs on levees (sites within 5 m of the channel or dominant overbank flow routes; Table II). Mean percentage of organic content on the floodplain increased between early 2007 and February 2008 after overbank flow was returned to the system (Table II; $p < 0.008$ for sites measured repeatedly, paired t-test, $n = 12$). Since the return of flood flow, the organic content of deposits has remained high throughout the riparian wetland (Table II) and highest low on the landscape. Sediment concentrations of total phosphorus (mean total phosphorus in $mg\,g^{-1} = 1.42$, $n = 12$) are relatively high for southeastern US riparian wetlands. Phosphorus concentrations increase linearly with organic content ($R^2 = 0.74$, $p < 0.01$), making the sloughs and depressions the greatest sinks for phosphorus.

Landscape effects on sedimentation

Sediment deposition, organic content, and bulk density varied greatly between landscape types, probably driven by pronounced elevation differences (Figure 6) between the four landscape categories (Table I). Natural floodplain areas represent the majority of our monitored sites and have the highest soil organic matter composition of the four landscape types. The majority of mineral sedimentation, on the restored floodplain, occurs along main channel levees. Estimates for annual sedimentation loads on the floodplain are provided in Table III. The median mass deposited from the three storm events was 411 000 Mg, with 285 000 Mg of the total consisting of mineral sediment and 123 000 Mg consisting of organic material. The natural floodplain trapped the majority of both the mineral and organic sediment (77% and 84%, respectively). The mean percentage of organic content in the channelized Pool D floodplain was 21.1%, lower than all restored floodplain landscape types except for levees.

The landscape changes longitudinally as the restored floodplain changes from a single-threaded dominated channel system in the upstream basin to a downstream basin affected by the backwater of the S65C control structure. The downstream basin is low lying and frequently inundated (Figure 7). Floodplain sediment deposition reflects the longitudinal change in the river basin with significantly more deposition on the levee ($p = 0.01$) and floodplain ($p = 0.002$) on the downstream sub-basin during Tropical Storm Fay (Figure 8). Although not significant, there was noticeably more erosion at levee sites on the downstream basin from the annual flood 1 year after the tropical storm.

Samples for sediment texture were taken at selected sites five times during the study. Sediment ranged from primarily silt and clay (less than 63 µm) to fine sand (125 µm) depending on location and flood event. Sediment texture trends in the borrow area and floodplain landscape types appear to be driven by channel processes with coarser sediments near the channel and dominant flood flow paths. Sediment texture changed significantly ($p < 0.001$, analysis of variance, $n = 13$) from the beginning of the study to after the spring flood in May 2008. Initially, the majority of the floodplain sampled had a mean diameter near 63 µm, classified as very fine sand. The sediment fined into the silt/clay range after the annual flood in spring 2008 and then coarsened again to very fine sand after Tropical Storm Fay with the influx of mineral sand. The annual event in spring 2008 appeared to have mostly redistributed organic material. Whereas, the larger fall event moved considerable mineral sediment near the channel and simultaneously deposited large amounts

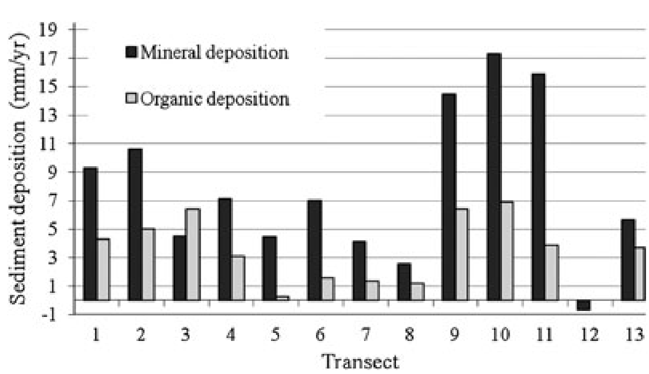

Figure 5. Mean mineral and organic sedimentation by transect from upstream to downstream in Pool B/C

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Table II. Soil percentage of organic content by date including mean percentage of organic content, standard error, and number of samples by date

	Soil percentage of organic content			
	January/May 2007	February 2008	May 2009	January 2010
Mean	13	27	26	25
Standard error	2	3	2	3
n	34	64	64	43

(greater than the spring flood) of organic material in areas away from the channel. Sediment fined again after the second annual flood in the summer of 2009 with deposits composed of both fine sands and silts and clays ($p < 0.001$, *t*-test, $n = 27$).

Vegetation effects

South Florida Water Management District completed a vegetation survey of the floodplain in 2008. The data were provided in a GIS coverage used for floodplain deposition analyses. The data were simplified into the following categories: forbs (flowering herbaceous vegetation, e.g. *Cyperus* spp., *Cirsium nuttalli*), wetland shrubs (e.g. *Cephalanthus occidentalis*, *Ludwigia peruviana*), broadleaf marsh (e.g. *Sagittaria lancifolia*, *Pontederia cordata*), and graminoids (grasses, e.g. *Panicum hemitomon*, *Rhynchospora inundata*). Sediment deposition rates within vegetation categories were 5.3, 11.5, 12.1, and 13.9 mm per year, respectively ($n = 14$, 13, 11, and 27, respectively). There was a significant difference in deposition rate between grasses and forbs ($p < 0.02$). Forbs occur on the highest ground within the floodplain, with grasses occupying intermediate elevations, and marshes occurring on the lowest elevations [forbs are 0.12 m above grasses, 0.18 m above shrubs, and 0.27 m above broadleaf marshes as delineated from a Digital Elevation Model (DEM) using GIS software].

Fluvial sediment transport

For three storm periods (Spring 2008, Summer 2008, Summer 2009), a substantial volume of flow left the main channel through a breach in the natural levee near T10, upstream of the PC-33 station and flowed down MacArthur Canal, reentering the Kissimmee River below PC-33 (Figure 1B). Discharge was measured five times in MacArthur Canal but was estimated for a continuous record using the difference in discharge recorded at PC-33 and the discharge measured at the S65C structure, which is managed by the SFWMD. For the period July 2007 through September 2009, 28% of the combined discharge of MacArthur Canal and PC-33 flowed down MacArthur Canal. Two of five measurements made in MacArthur Canal were higher by 2% and 3% than the difference in flow accounted for by subtracting PC-33 from S65C, and are within the range of errors reported for discharge measurements (Sauer and Meyer, 1992). Three of five discharge measurements made in MacArthur Canal were 6–9% lower than the difference between the two streamgages. This difference indicates that a small percentage of flow is either entering MacArthur Canal below the point where the discharge measurements were made or some flows may be entering the Kissimmee River between the two streamgages through another tributary. Nevertheless, the amount of flow that is not accounted for is small and does not affect our overall interpretations. Suspended-sediment samples obtained in MacArthur Canal were used to generate a relation of flow and suspended-sediment concentration in MacArthur Canal.

The total sediment load for the period 21 July 2007 through 30 September 2009 was 150 900 Mg with an annual sediment yield of 5.5 mg km^{-2} per year. Of the total sediment load, 72% (109000 Mg) was transported as suspended sediment at the PC-33 gage, 4% (6200 Mg) was transported as bedload, and 24% (35 700 Mg) was transported as suspended-sediment in MacArthur Canal (Figure 9). The majority of suspended sediment was transported during the three high flow events (Table IV), with Tropical Storm Fay transporting 55% of the total suspended-sediment transport.

The total monthly organic content of the suspended sediment measured at the PC-33 streamgage ranged from 2% to 38% (Figure 9B). During the three storm periods, the organic suspended-sediment load ranged from 3% to 16% of the total for each flood event. The lowest organic percentage occurred during Tropical Storm Fay. The inorganic suspended-sediment load percentages for the period of study were highest during the three storm events (Table IV). The transport of sand in suspension is correlated with discharge and for overbank events ($>50\,m^3\,s^{-1}$). The sand in suspension for discrete samples ranged from 28% to 90% (Figure 9C). Using the relation of flow and percentage of sand in Figure 9C, it is estimated that 62 800 Mg or 62% of the total suspended-sediment load for the period of study was transported as sand. During the three storm events, 70% of the suspended-sediment load was sand and accounted for 92% of total annual suspended sand load (Table IV).

DISCUSSION

Our results are the first wetland sedimentation rates determined for a subtropical or tropical river basin using feldspar claypads and an analysis of sediment texture, organic content, and bulk density. The observations provide a basis for further fundamental geomorphic science. This is also

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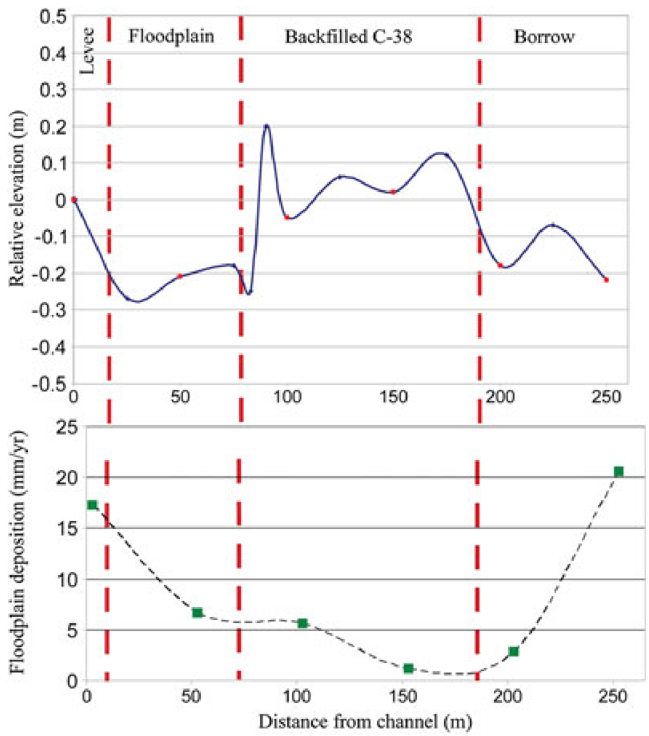

Figure 6. Relative elevation and floodplain deposition along a transect with all four landscape classifications (transect 7). The transect has six feldspar clay pads (marked by squares in the bottom graph). The pad closest to the channel is on the levee, there is one pad on the floodplain, two pads on the backfilled C-38 canal, and two pads on the borrow landscape. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

the first quantitative study on sedimentation patterns on a truly large scale (>5000 ha) riparian wetland restoration effort. Understanding the interplay between sedimentation, connectivity, elevation, and vegetation may help managers evaluate restoration success and to predict results before large-scale restoration programs are implemented.

The river channel has been restored for less than a decade and, probably, continues to actively adjust bed elevations, wetted perimeter, bank geometry, and channel form. The short-term impacts on the floodplain have been, and should continue to be, levee formation and adjustment and higher than normal amounts of sediment trapping. The nonlinear response of channels to disturbance has been well studied (Graf, 1977; Petts and Gurnell, 2005) and is applicable for this newly restored river. Elevated sedimentation rates can be expected because of the amount of erosion occurring in the river channel as the channel responds to the restored flow (Graf, 1977; Marston, 2010; Mossa *et al*., 2010). Over time, the channel may reach a quasi-equilibrium where levee building and sediment trapping in the riparian wetland will probably decrease.

During our study, the river experienced two approximate annual-recurrence interval (RI) floods and one large flood (about 5-year RI) caused by Tropical Storm Fay. The two flood magnitudes and the dry period at the beginning of the study present an opportunity to understand sediment processes occurring during wide variations in flow along the restored riparian wetland. From a restoration standpoint, the project may be considered successful given the return of overbank flow to the Kissimmee River and the associated

Table III. Approximate mass of mineral, organic, and total sediment deposited by landscape type

Landscape type	Area (m^2)	Total mass ($g m^{-1}2$*year)		Total mass (Mg per year)	Mineral (Mg per year)	Organic (Mg per year)
Borrow	4330000	3583		15516	10898	4618
Backfill	1000000	4201		4201	3200	1001
Floodplain	23542000	4582		107876	73114	34763
Levee	418000	15093		6309	5743	566
			Sum	133902	92955	40947

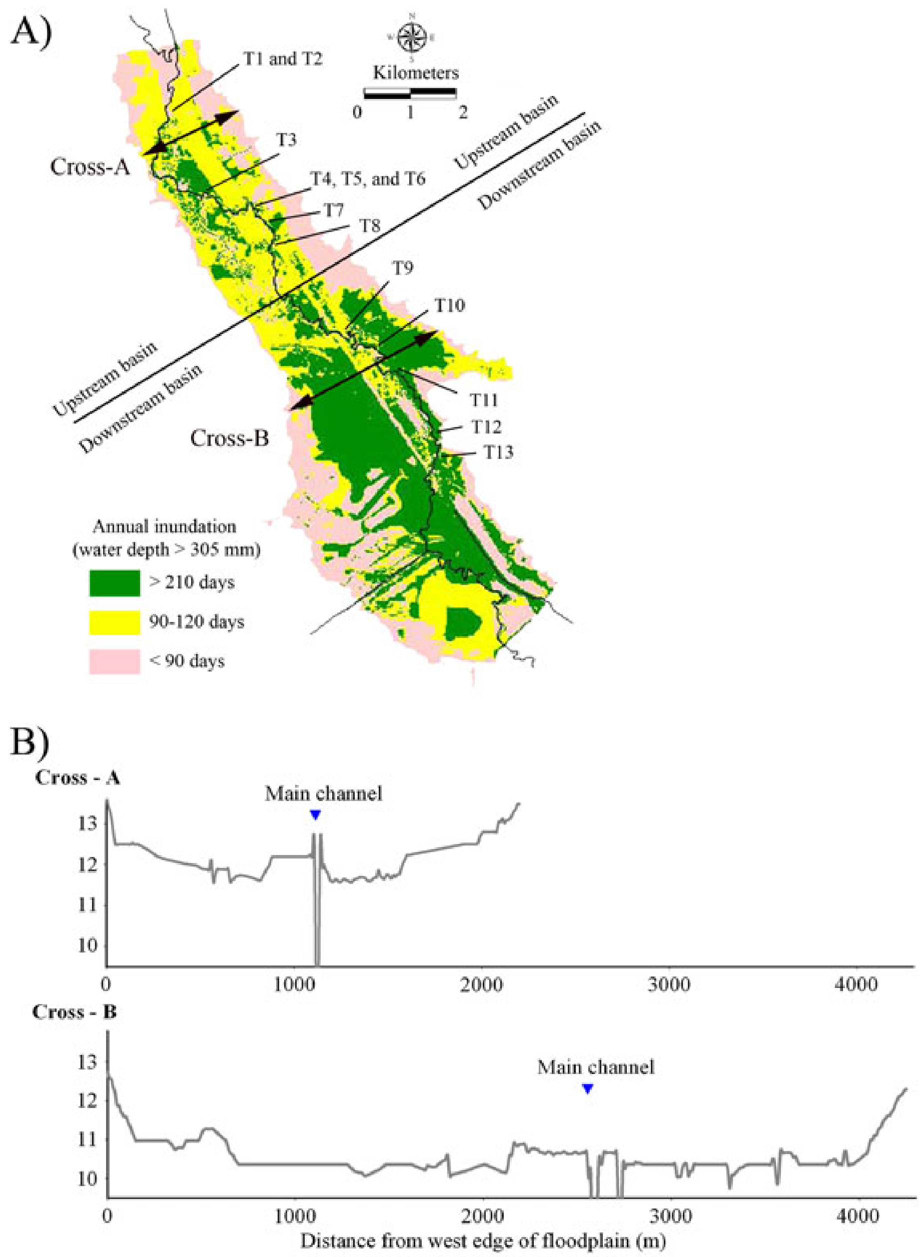

Figure 7. (A) The restored Kissimmee River basin (Pool B/C) separated into an upstream sub-basin dominated by a single-thread river channel and a persistently inundated downstream sub-basin. Annual flood inundation was calculated on 19 April 2010 using the SFWMD Water Depth Assessment Tool (Rutchey *et al*., 2010). Floodplain monitoring transects are included for reference to sediment deposition rates. (B) Two DEM-derived valley–wall to valley–wall cross-sections demonstrating the change from a single-thread system to a more complex downstream system. This figure is available in colour online at wileyonlinelibrary.com/journal/rra

delivery of fluvial sediment and nutrients to the reconnected floodplain wetlands. Sedimentation occurs as expected in a fluvial system with coarse deposits on levees and fine organic rich deposits in the lower areas away from the main channel. Restoration may have been compromised given that in 2006 and 2007, the control structures were closed to preserve upstream lake levels. During this period, the river functioned as a series of pools with drier than normal (no stage control) conditions on the upstream section of each pool and wetter than normal conditions on the downstream section near the control structure. Continuation of this policy may lead to dramatic human-induced effects on the restored reach during droughts (Toth, 2010a). The effect may not be limited to water levels but may include sediment

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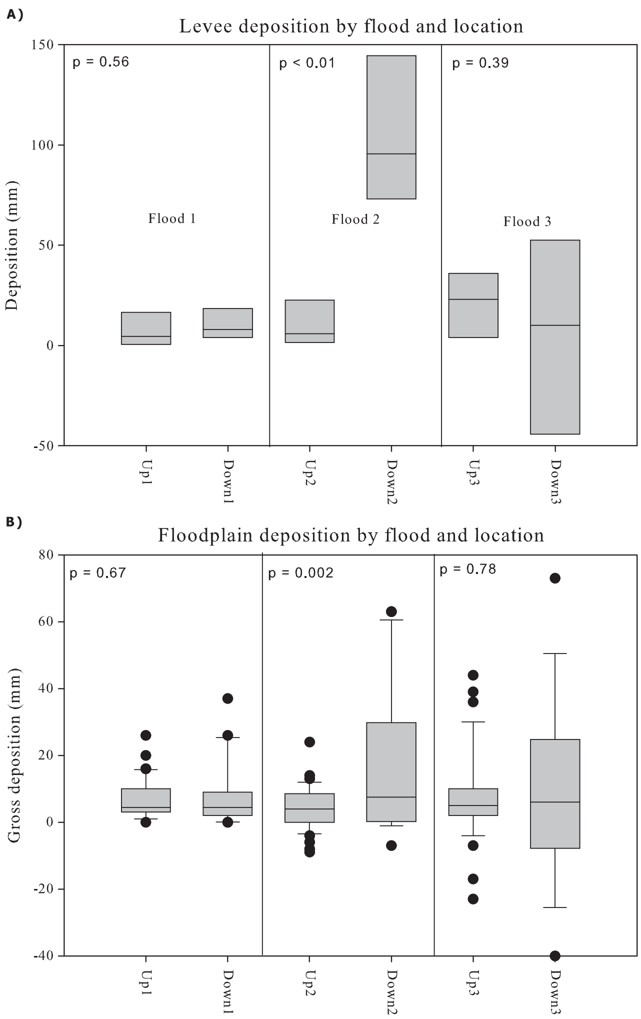

Figure 8. (A) Sediment deposition (mm) by flood event on the upstream single-threaded channel levee (up1, 2, or 3) and the downstream basin channel levee (down1, 2, or 3). (B) Sediment deposition by flood event on the upstream single-threaded channel floodplain (up1, 2, or 3) and the downstream persistently inundated floodplain (down1, 2, or 3). Levee sites were delineated as within 5 m of an active channel during flood stage; floodplain sites are defined as all other clay pad sites in the study regardless of landscape type. Flood 1 occurred in Spring 2008, flood 2 was Tropical Storm Fay in August 2008, and flood 3 was in Summer 2009

dynamics, habitat displacements, and altered biogeochemistry dynamics because of altered redox potentials.

The majority of our sampling sites on the restored wetland experienced sediment deposition (79%) with 16% of the sites unreadable, mostly as a result of feral pig (*Sus scrofa*) activity. Deposition was also measured on 71% of the channelized floodplain, though with an order of magnitude lower rate. Approximately 20% of the pads were unreadable, but unlike the restored reach, these pads were disturbed by humans. The mean deposition rate of 1.7 mm per year on Pool D is probably because of aeolian processes (wind derived sedimentation) and perhaps localized sheet flow during intense rain events. There has been no overbank flow on the channelized floodplain since the C-38 canal was completed.

Deposition rates on the restored reach from the two annual RI floods (7.0 mm, spring 2008 flood; 8.2 mm, summer 2009 flood) are within the normal range for southeastern rivers (Hupp, 2000). Tropical Storm Fay resulted in a higher deposition rate (11.3 mm per year) indicating that the floodplain traps sediment during both normal and large floods with minimal amounts of scour on the majority of the floodplain. The tropical storm was notable for its impact on the channel and floodplain, with several meters of erosion on cutbanks and widespread levee building along the channel. Levees were created or extended and were composed almost exclusively of well-sorted fine sand (Figure 10). Very fine sand was found throughout the restored floodplain (riparian wetland), probably derived from the large-scale erosion occurring in the channel at the time of the flood.

Unlike blackwater river systems of the region, it is notable that this river deposits sediment on the floodplain in the same order of magnitude as temperate alluvial Coastal Plain systems rivers that convey sediment from Piedmont and mountain physiographic provinces (brownwater systems, see Hupp, 2000). Long-term monitoring will determine whether present deposition rates are unnaturally high because of channel response to restoration or whether the system naturally has sediment loads in the same order of magnitude as temperate alluvial systems. The dominant source of sediment to the floodplain is suspended-sediment transported by the Kissimmee River; upland; nonchannel inputs of sediment are insignificant. Deposition rates are related to the connectivity of the floodplain to the suspended sediment laden main stem. The three storm events transported 90 600 Mg of suspended-sediment of which 63 300 Mg (70%) was sand (Table IV). The highest deposition rates recorded with the clay pads occurred during Tropical Storm Fay that also delivered 55% of the total suspended sediment load for the period of study (Figure 9A and Table IV). Organic content of the Kissimmee River suspended sediment is an important source of floodplain organic material and for the three storm events, the total organic suspended-sediment load measured at PC-33 ranged from 3% to 16%.

Sediment measurements were not collected prior to restoration, and therefore, the sediment data collected here cannot be used to determine if sediment transport rates measured in the Kissimmee River are similar to the pre-channelized transport conditions. The sediment yield for the Kissimmee River (5.5 $Mg\,km^{-2}$ per year) is within the range of other low-gradient rivers in the draining the Chesapeake Bay and southeastern United States (Figure 11). Future monitoring will determine how these first years of sediment transport compare with a longer period of record.

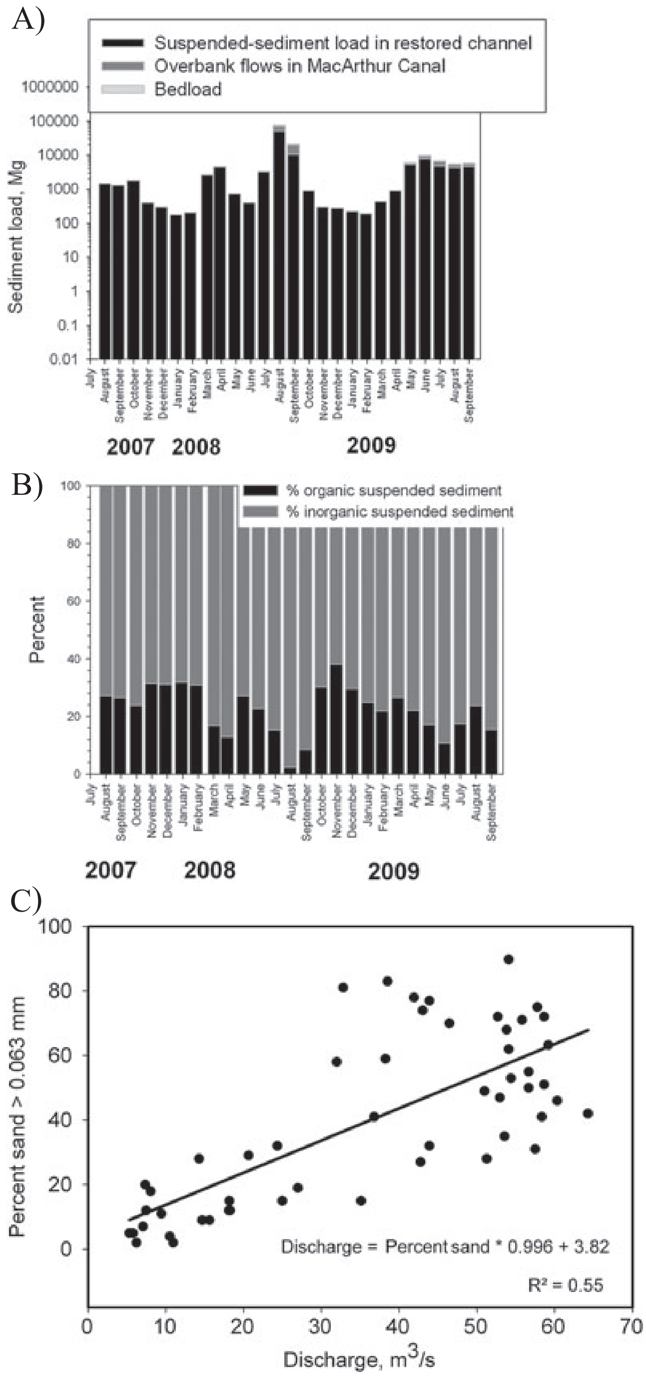

Figure 9. (A) Total monthly suspended sediment loads and bedload measured at PC-33 and estimated suspended sediment loads in MacArthur Canal, (B) percentage of organic and inorganic contents of monthly suspended sediment measured at PC-33, and (C) sand transported in suspension past the PC-33 gage

Coarse-grained deposits are limited to levee building regions near the main channel and fringes of preferential overbank flow routes. Fine-grained deposits occur throughout the floodplain with the finest sediments in the areas most isolated from flow. Connectivity is a function of several factors including elevation, distance along dominant overbank flow routes, and intervening vegetation (Hupp *et al*., 2009). Dominant flow paths are complicated on the Kissimmee floodplain and are likely affected by side channels, dominant slough patterns, and other microtopographic features (e.g. backfilled areas, natural hummocks) that appear related to historic (prior to channelization) anabranching side channels, and distance from the main Kissimmee River channel. The river basin is also strongly affected by the remaining control structures. Upstream water control and management has and will continue to complicate the measurement of restoration success because it introduces a systemic basin-wide human disturbance. The proximity of the downstream S65C control structure impacts the restored reach by ponding water at the downstream end of the pool, creating an exceptionally wet floodplain on this reach (Toth *et al*., 1995). This same area serves as a settling basin during extreme flows as water ponds behind the control structure. This was evident when the downstream Pool B/C basin had significantly higher deposition rates than the upstream unaffected wetland during Tropical Storm Fay (Figure 8). The S65C structure is slated for demolition in the next phase of restoration. After removal, the downstream section of Pool B/C (Figure 7) should become drier during low and no-flow regimes and should drain faster during extreme flooding events.

Organic deposition was positively correlated with fine sediment deposition. Organic deposition is important for restoring substrate and nutrients that supports historic broadleaf marshes and wet prairie ecosystems (Dahm *et al*., 1995). Fluvial contribution to the organic sediment pool was significant after the first overbank event in 2008 (Table IV). The nearly fourfold increase in organic content indicates the importance of regular wetland inundation. As expected, organic deposition occurred in areas of fine sediment deposition such as floodplain segments low on the landscape. Levee deposits were nearly pure mineral sediment, primarily fine sand. If current sediment deposition patterns continue, marshes should convert to a mix of wet prairies and broadleaf marshes, whereas levee sites should support less hydric species similar to the historic patterns of cypress and willow (Milleson *et al*., 1980; Dahm *et al*., 1995). The backfilled canal will probably take longer to support natural vegetation types because of the low soil organic content. Organic deposition was also lower on backfilled sites than other floodplain landscape types (Table I) probably because of the higher elevation (Figure 6).

The most recent vegetation survey (2008), and our own field observations, indicate that vegetation has adjusted to river restoration, with communities delimited by elevation and flow regime. Broadleaf marshes occupy the lowest elevations and are consequently areas with high sediment and organic deposition rates. Wet prairie, as delineated as

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Table IV. Summary of suspended sediment transport in the Kissimmee River at PC-33 for three storm events compared with totals measured at PC-33 for the period of study

	MARCH APRIL 2008	AUG SEPT,2008	June- Sept 2009	Total for 3 storm events
Total suspended-sediment transport, Mg (% of suspended-sediment transport for the 3 storm events compared to the period of study)	7,100 Mg (6.5%)	60,900 (55.9%)	21,500Mg (19.8%)	89,600Mg (82.2%)
Organic suspended sediment in restored channel, Mg (% of organic suspended-sediment transport for the 3 storm events compared to the period of study)	1,000Mg (9.4%)	2,100Mg (19.1%)	3,400Mg (31.6%)	6,500Mg (60.2%)
Inorganic suspended sediment in restored channel, Mg (% of inorganic suspended-sediment transport for the 3 storm events compared to the period of study)	6,100Mg (6.2%)	58,800Mg (59.9%)	18.100Mg (18.4%)	83,000Mg (84.6%)
Sand load, Mg (% ot total sand transport for the 3 storm events compared to the period of study)	2,500Mg (3.6%)	47,300Mg (69.7%)	13,500Mg(19.0%)	62,800Mg (92.4%)

Values are shown as storm period total mass and percentage of storm period total mass to the total suspended-sediment mass transported at PC-33 during the period of study.

'grasses', also had high deposition rates despite being found at a slightly higher elevation than the broadleaf marshes. Forbs occupy the highest elevations (about 0.27 m higher on the landscape than marshes) and therefore have the lowest total and organic deposition rates on the riparian wetland. Broadleaf marshes still inhabit only a fraction of their former range within the basin (Toth, 2010a), possibly because of the spread of exotic woody species (*Ludwigia peruviana*), a lack of sufficient organic substrate (Toth, 2010b), efficient localized drainage provided by remnant ditches, and below average precipitation during the study period. The role of remnant ditches in wetland hydroperiod in the basin remains unclear; however, their impact is currently under study (Gellis *et al*., 2010).

Our results indicate that fluvial sedimentation has returned to the extensive riparian wetlands of the Kissimmee

Figure 10. Levee formation following Tropical Storm Fay along a straight river reach. Well-sorted fine sand was deposited approximately 0.3 m deep along many sections of the bank (in white in the picture). Note the mass wasting that has occurred since the flood (flood occurred August/September 2008, photo was taken in December 2008). This figure is available in colour online at wileyonlinelibrary.com/journal/rra

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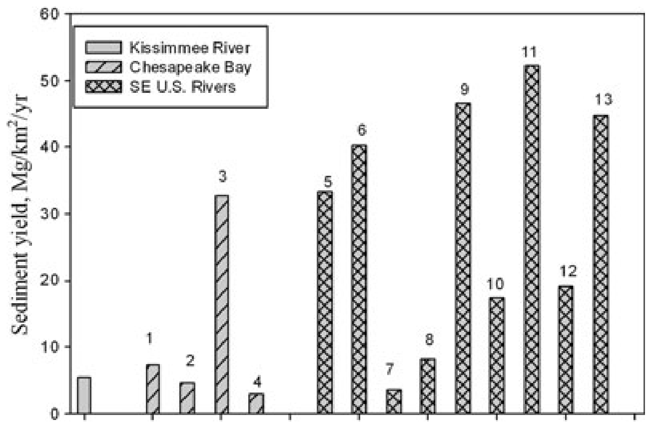

Figure 11. Sediment yield of the Kissimmee River (2007–2009) compared with rivers in the Chesapeake Bay and southeastern US rivers (Holeman, 1968; Curtis *et al*., 1973; Gellis *et al*., 2005, 2009) (1. Choptank R., 2. Hunting Creek, 3. Killpeck Creek, 4. Mattaponi R., 5. Alabama R., 6. Alabama R., 7. Apalachicola R., 8. Ogeechee R., 9. Pearl R., 10. Pee Dee R., 11. Sabine R., 12. Tar R., 13. Tombigbee R.)

River. Restoration will likely be furthered with the removal of the S65C structure allowing more natural drainage patterns along the restored reach. The remaining upstream control structure, and its associated managed flows, will continue to affect the basin and continued restoration efforts. The restored reach has trapped approximately 285 000 Mg of mineral sediment and 123 000 Mg of organic material between 2007 and 2010; a large amount of this material may have otherwise impacted downstream resources (Lake Okeechobee), or in the case of organics, potentially be introduced into the air column because of soil carbon oxidation.

CONCLUSION

Floodplain sedimentation studies are relatively rare yet important for monitoring river restoration, pollution abatement, and for understanding wetland biogeochemical processes, biodiversity, and ecosystem service/function. The 3-year study on the Kissimmee River confirms that streamflow in the naturalized channel has successfully reconnected with the extensive floodplain during annual and high flow events. The mean floodplain sedimentation rate was 11.3 mm per year for the restored reach, with deposition rates varying by landscape type, vegetation, and elevation. The unrestored reach had a mean deposition rate of 1.7 mm per year, probably because of wind deposition or biogenic processes.

Suspended sediment measured at the USGS streamgage was predominately mineral (62–98%) and sand (62% of total suspended sediment). Over half of the suspended sediment measured during the study was mobilized during Tropical Storm Faye. Most of the suspended sediment was measured in the main channel though a significant proportion (>20%) was measured in the MacArthur canal, a remnant ditch that serves as a preferential floodplain flow path at high water.

Fluvial sediment transport and sediment yields in the Kissimmee River are similar to other low-gradient streams in the eastern and southeastern USA and contain a high amount of sand in transport. Mineral sedimentation rates and trends are typical of southeastern low-gradient alluvial rivers. However, the organic content associated with the deposited sediment is similar to eastern US blackwater systems (higher content than alluvial rivers). The restored reach appears to have sufficient floodplain hydrologic connectivity to build sand levees and create organically rich fine sediment zones near sloughs and depressions. The hydrologic regime is still affected by backwater effects near the S65C control structure and by infrequent manipulations of discharge using upstream control structures. The Kissimmee River is unique in North America because it reflects both alluvial and blackwater sedimentation characteristics. Currently, we do not know if the high organic content is typical because of the lack of floodplain sedimentation studies on extensively inundated subtropical and tropical rivers.

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