1 Anthropogenic Landforms and Sediments from Dredging and Disposing Sand
2 Along the Apalachicola River and its Floodplain

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26 Revision Submitted to Geomorphology:

27 March 10, 2017

29 Abstract

30 The Apalachicola River, which begins at the confluence of the Chattahoochee and Flint rivers
31 near the Georgia-Florida State line, has multiple human impacts. Water inputs declined due to
32 upstream irrigation and urbanization in Georgia. Sediment trapped by numerous small to large
33 dams, including construction of Jim Woodruff Dam in 1954 near the Apalachicola-
34 Chattahoochee-Flint (ACF) confluence has increased degradation. Shortly thereafter, the river
35 was modified for a navigation project, with $29.6 \times 10^6 \text{ m}^3$ dredged between 1957-2002 from
36 the Apalachicola alone. This study investigates how historic dredging coincides with the
37 modern morphology of the channel and how historic dredging, disposal, and other activities
38 have modified the floodplain landforms and sediments. This analysis of the navigation impacts
39 in the middle Apalachicola River (River Miles 40 to 65) ties spatial and temporal variations of
40 dredging, field-derived bathymetry, historic maps, patterns of floodplain disposal of dredge
41 spoil from LiDAR imagery, and modern point bar channel change of the Apalachicola River.
42 Floodplain mounds of coarse material, built from out-of-bank disposal constitute more than
43 $800,000 \text{ m}^3$ in the study area. Approximately $7.7 \times 10^6 \text{ m}^3$ of sediment was dredged within the
44 study reach, roughly 11% of the volume dredged remains on the floodplain. Sand bars were
45 disposal sites thus their increased area of 263% is partly tied to this practice. Thus, the legacy
46 of dredging affects the modern sedimentology and morphology of the floodplain and channel.
47 Findings show that a failed navigation project could have been pre-empted with better
48 geomorphic, geologic and hydrologic study and suggest that vegetative restoration of point
49 bars would help in narrowing and stabilizing this dynamic system.

50 *Keywords:*

fluvial geomorphology; dredging; human impacts; anthropogenic sediments; spoil; channel change

1. Introduction

Sediments displaced by anthropogenic activities can affect channel form, both locally, and over larger spatial scales by altering sediment budgets and channel processes (Gilbert, 1917). By excavating sediments from the channel bed and disposing of them at a different location, dredging alters river channels (cross section and long profile), and in many cases, floodplains. Rivers and floodplains most prone to dredging and thus most vulnerable to dredging impacts include large rivers deemed navigable, those with floodplains protected by artificial levees comprised partly of dredge material, or rivers channelized for flood control. Some examples of such impacts include the channelization of the naturally meandering Lower Kissimmee River, Florida, into the straight C-38 channel during the 1960s (Toth, 1995; Mossa, 2015), and dredging of the lower Mekong River in Vietnam in the 1990s to reclaim wetlands, build berms on channel banks, and to provide construction aggregate (Bravard et al., 2013). The lower Mississippi in Louisiana is dredged for navigation, and that material is then used to build artificial levees (Yuill et al., 2016), but it is a perpetual process. Dredging along the Nile is considered a mixed prospect that requires careful study and has locally resulted in lower water levels (Ismail and Samuel, 2011) with some sediment being used to increase the area of mid-channel islands (Sadek, 2013). Bed levels along the lower Rhine River in Germany are maintained by a combination of sediment additions in reaches with sediment deficits and dredging in reaches undergoing shoaling (Frings et al., 2014), an intensity of management

feasible only in rivers that serve an important economic function. Dredging alters many rivers and floodplains, but comprehensive geomorphic and sedimentologic studies of these impacts are lacking.

Very few studies have examined spatial and temporal variations of dredging and spoil deposits along rivers in the context of long-term alterations. This study investigates the anthropogenic landforms and sediments associated with a failed navigation project on the Apalachicola River in northwest Florida, southeastern USA. The focus is on the middle portion of the river between river miles (RM) 40 and 65, a zone in which disposal of dredged material in the floodplain and river corridor produced morphological and sedimentological changes in the channel and floodplain. Associated concerns include direct and indirect losses of riverine habitat affecting listed freshwater mussels and important swamp tree species. This analysis synthesizes archived USACE (U.S. Army Corps of Engineers) reports, historical maps and imagery, Light Detection and Ranging (LiDAR) data with primary bathymetric and sedimentological data to interpret floodplain deposits, channel changes, and the role of human activities in the study area.

2. Regional setting

2.1 Physical conditions

Draining approximately 50,945 km² (19,400 mi²), the Apalachicola River begins at the confluence of the Chattahoochee and Flint rivers at the state boundary between Georgia and Florida (the confluence is now under the waters behind Jim Woodruff Dam), and then flows 170 km through Florida to the town of Apalachicola on Apalachicola Bay (Fig. 1). Commonly known

as the ACF basin, most of the river's drainage area, approximately 44,550 km² (17,200 mi²), lies in Georgia and Alabama.

The main channel of the Apalachicola River has a dominantly meandering form at low flow. Many secondary channels become active at various flow levels. More than 300 sloughs connect to the main-stem river, with over 370 km (230 mi) of length (Light et al., 1998). The largest tributary to the Apalachicola itself (i.e., below the confluence of the Chattahoochee and Flint rivers) is the Chipola River, which drains a catchment of 3290 km² (1270 mi²) in Florida (mostly and Alabama, and connects with the main-stem Apalachicola about 67 and 45 km (41.5 and 28 RM) upstream of Apalachicola Bay. Flow in the lower Chipola River is augmented by flow diverted from the main-stem Apalachicola River through the Chipola Cutoff, about 66 km upstream of Apalachicola Bay. Streamflow from the Chattahoochee and Flint river basins comprises most of the Apalachicola's discharge, with local precipitation, groundwater discharge, and other inputs contributing relatively little to the magnitude or variability of flow (Matraw and Elder, 1984).

2.2 Water supply issues and alterations

Flow in the Apalachicola River is affected by upstream uses, including diversions from the headwaters of the Chattahoochee to supply metropolitan Atlanta, whose population grew fivefold since 1959 to over five million in 2015, and especially the expansion of center-pivot irrigation in the Flint River basin since 1970 (Leitman et al., 1993). Base flows from the Flint River have declined since the early 1970s (Rugel et al., 2012), triggering a policy in 2001 to pay farmers not to irrigate or withdraw groundwater during droughts (Wright et al., 2012). However, program implementation was flawed and some landowners who had not previously

irrigated took advantage of the opportunity to profit (Couch and McDowell, 2006). These increasing demands have decreased flows in the Apalachicola, especially during drought years, resulting in desiccation of the floodplain forest, altered salinities in Apalachicola Bay, and other ecological impacts (Darst and Light, 2008). Disputes over water use and river flows (Feldman, 2008) have culminated most recently in a case before the U.S. Supreme Court between Florida and Georgia (Florida, Plaintiff v. Georgia, Case No. 22O142, docketed: October 4, 2013). There are several stream gages on the Apalachicola River, but the longest and most consistent (1922 to present) is at Chattahoochee (USGS 02358000), just downstream of the Jim Woodruff Dam. Comparing the earlier decades of discharge record on the Apalachicola River at Chattahoochee prior to inception of the navigation plan to the last few decades, the higher flows are similar but the lower flows are more common (Fig. 2).

The Apalachicola River and estuary system is of exceptional ecological importance, and constitutes one of the least polluted, most undeveloped, resource-rich systems left in the United States. Partly because of reduced flows from upstream, the non-profit organization American Rivers (2016) identified the ACF basin as the most threatened river system in the USA. Reduced flows and water levels have dried out the floodplain and sloughs, causing significant botanical changes, namely a drier forest composition and the loss of important swamp tree species such as Ogeechee tupelo (Light et al., 1998; Darst and Light, 2008; Stallins et al., 2010; Smith et al., 2013). The basin has threatened and endangered freshwater mussels that die during drought (Johnson et al., 2001; Gagnon et al., 2004; Peterson et al., 2011; Shea et al., 2013). The floodplain provides critical spawning, nursery, and feeding grounds for many fish species; in turn, connectivity and inundation of the floodplain drive fish populations and

recruitment (Burgess et al., 2013; Dutterer et al., 2013). Droughts or extended periods of low water or floods exceeding $854 \text{ m}^3/\text{s}$ ($30,000 \text{ ft}^3/\text{s}$) for 100 days reduce oyster populations in Apalachicola Bay (Wilber, 1992).

2.3 Navigation modifications and impacts

2.3.1 Early changes to improve navigation

The Apalachicola River has had a long history of navigation and associated human interventions. During the 1830s, after some years of snag (fallen tree) removal and deepening in locations, steamboats regularly traveled between Apalachicola, Bainbridge and Columbus (Thurston, 1973). In the mid-nineteenth century, during the U.S. Civil War, Confederate troops built forts, constructed artillery batteries, created massive logjams, and even blocked and rerouted the river to prevent navigation by Union ships (White, 1999).

De-snagging, which involves the removal of woody material for navigation or flood control, was once a widespread practice (Triska, 1984), but is now recognized as detrimental for stream ecology (Shields and Smith, 1992). The Apalachicola River is one of many rivers listed in The Annual Report of the Chief of Engineers of the US Army to the Secretary of War dating back to 1874 as having snag boats in operation (Wohl, 2014) and even earlier reports suggest that de-snagging dates back to 1827 (Thurston, 1973; Hoehn and Leitman, 2000). However, this practice pre-dates knowledge of the benefits of woody debris to streams (Benke et al., 1985; Benke and Wallace, 1990).

Spotty and occasional dredging began in the 1870s (Hoehn and Leitman, 2000). In 1874, Congress authorized the dredging of a 1.83 m (6 ft) channel of the Apalachicola (Vanderhill 1975; Rockwood and Leitman, 1977). At this time, Moccasin Slough was dredged, straightened, and de-snagged, becoming the main river channel (which is present-day Virginia Cut). Efforts to clear and deepen the river and harbor continued intermittently. During an early peak of steamboat travel, the river had eight steamboats operating on the river, carrying approximately 37,000 passengers annually.

2.3.2 The ACF waterway or navigation project and known impacts

These early efforts at channel modification paled in comparison to river alterations once the Apalachicola navigation project was authorized as part of the River and Harbors Act of 1945 and 1946 (Hamann, 2013). Originally, the purposes of this project were navigation, hydropower generation, and flood control. There are five federal dams along the Chattahoochee-Apalachicola river system, and at least 24,500 small dams on tributaries, trapping sediment and increasing fragmentation (Ignatius and Stallins, 2011). The federal dams were part of an ambitious navigation scheme by the US Army Corps of Engineers to provide a 2.7 m (9 ft) deep and 30.5 m (100 ft) wide navigation channel from the Gulf of Mexico to Columbus, Georgia, on the Chattahoochee River (U.S. Army Corps of Engineers, 1939). In total, the capacity of the federal reservoirs is a small percentage of the river's average annual runoff, with 62% of the basin storage capacity behind Buford Dam, the upstream-most dam that forms Lake Lanier. The other Chattahoochee dams have less storage, including West Point (18%), W. F. George (14%), and Woodruff forming Lake Seminole (6%) (Carter et al., 2008) and thus have relatively minor influences on flow regime.

By trapping sediment, dams alter the sediment balance downstream, commonly producing sediment starvation in the reach downstream, which can result in channel incision and bed coarsening (Williams and Wolman, 1985; Kondolf, 1997). In the reach directly downstream of Jim Woodruff Dam, the water levels in the Apalachicola River decreased 1.5 m (5 ft) between 1954 and 2004 (Light et al., 2006), during low flows of $142 \text{ m}^3/\text{s}$ ($5000 \text{ ft}^3/\text{s}$) and below. These effects generally decrease to RM 65, the upstream end of the study area near Estiffanugla, where bank sides are comprised of higher, older and more resistant sediments than much of the alluvial river. There low flows of $142 \text{ m}^3/\text{s}$ ($5000 \text{ ft}^3/\text{s}$) have stages about 0.30 m (1.0 ft) lower. The maximum stage drops for a given flow occur between RM 50 and 40, with slightly more than a 0.61 m (2 ft) drop in stage at the lower $142 \text{ m}^3/\text{s}$ ($5000 \text{ ft}^3/\text{s}$) flows. Although no one has documented deepening other than downstream of the dam, parts of the river have widened during the interval between 1954 and 2004, based on comparing changes in tree-line width of the main channel at similar flow levels, the study area showed width increases from about 1-40% (Price et al., 2006). The botanical changes that the floodplain experiences, namely a drier forest composition (Light et al., 1998; Darst and Light, 2008; Stallins et al., 2010; Maxwell and Knapp, 2012; Smith et al., 2013), are thus not just due to reductions in water supply but aggravated by stage decreases for a given discharge by degradation and widening.

The earlier amounts of sediment dredged were less than one-hundredth the amount dredged during the navigation project (Fig.3). Dredging to achieve this navigation depth required more dredging in some locations than others. The reach downstream of the Chipola Cutoff at RM 41 is shallow and thus troublesome because it is difficult to maintain navigation depth (McCollum, 1994). In this area, the Chipola Cutoff diverts approximately 27% of the total flow away from

201 the Apalachicola River to the Chipola River, velocity decreases and coarse bed-material load
202 settles in the reach just below the Cutoff. Approximately 76,455 m³ (100,000 yd³) was removed
203 annually to maintain the navigation channel, filling up approved disposal sites in an area with
204 limited alternatives (McCollum, 1994). During the planning and early years of the navigation
205 channel, between 1950 and 1980, the basin was relatively undeveloped and the climate proved
206 to be relatively wet, causing water managers to expect ample water (Leitman and Howell,
207 1991) and thus deeper flows to sustain navigation much of the year.

208 In part due to hydrologic, geomorphic and ecological changes, coupled with aesthetic and
209 economic changes, the problems with this project became more apparent. The long-standing
210 water conflicts among the three involved states of Alabama, Florida and Georgia amplified
211 (Vest, 1992; Carriker, 2000; DuMars and Seeley, 2004; Ruhl, 2005; Snowden, 2005; Abrams,
212 2008; Hamann, 2013), sometimes pitting federal rights vs. states's rights (Fowler et al., 2006).
213 Flow often dropped below the level required for barges, 285 m³/s (10,000 ft³/s) at
214 Chattahoochee, and the project was an economic disappointment. Comparing the two periods
215 shown earlier (Fig. 2), this value was exceeded 85% of the time in the earlier decades and only
216 69% of the time in recent decades. However, the navigation depths for barges required higher
217 flows, and were achieved 25% or less during the last four years of the project (U.S. Army Corps
218 of Engineers Mobile District, 2003). The required dredging and low commercial barge traffic
219 made this endeavor the most expensive Corps river project in the southern USA with an
220 average cost per ton-mile from 1995-98 of \$0.14, almost 24 times more than the cost of the
221 Upper Mississippi River of \$0.60 (U.S. Senate, Committee on the Environment and Public
222 Works, 2002). Traffic was never high with 97 barge movements in 1998 and fell to a low of four

223 barges in 2001. This maintenance cost per ton-mile was another 24 times higher than earlier
224 estimates or more than 500 times higher than for the Upper Mississippi. Ultimately, dredging
225 was curtailed with the Restore the Apalachicola River Ecosystem (RARE) Act of 2002 (U.S.
226 Senate, Committee on the Environment and Public Works, 2002). Despite the lack of dredging,
227 the project is not yet de-authorized; the Corps still operates the reservoirs for navigation, flood
228 control, and hydropower, while also considering fish and wildlife protection, water quality
229 protection, and recreation (Carter et al., 2008).

230 3. Materials and methods

231 This study utilized several primary and secondary data sources to characterize the topography
232 of the study area and its changes. Table 1 lists the purposes and sources for data we used in
233 this study. Software including ESRI ArcGIS 10.2, Microsoft Excel, and Sonar Viewer were utilized
234 to process and analyze data.

235

236 Table 1. The purposes and sources of primary and secondary data utilized in this study.

Data	Date	Purpose	Source and other info
Sonar survey	2015 to 2016	Estimating the water depth and computing the bathymetry	Field data collection trips (Aug 2015, March 2016, and Aug 2016)
Sediment samples	2015 to 2016	Estimating the size of sediments	Field data collection trips (March 2016, and Aug 2016)
LiDAR point clouds	2007 to 2010	Creating high-resolution digital elevation model	USGS Earth Explore: http://earthexplorer.usgs.gov/
Contour line of 1:24,000 topographic map	1940s, 1990s, and 2010s*	Creating interpolation surface for spoil mound elevations change analysis	USGS The National Map: https://viewer.nationalmap.gov/ The 1945 and 1990 maps were rectified by the USGS Historical Quadrangle Scanning Project.
Aerial photography	8/31/1940 9/3/1940 9/12/1940 2/21/1941	Comparing sand bar areas	Price et al. 2006 [Effective Flow at Chattahoochee: 287- 441 m ³ /s (10,100 - 15,500 ft ³ /s); Average flow: 379 m ³ /s (13,286 ft ³ /s)]
NAIP imagery	3/10/04 4/3/04 4/4/04	Comparing sand bar areas	Price et al. 2006 [Effective Flow at Chattahoochee: 340- 475 m ³ /s (11,957 - 16,710 ft ³ /s); Average flow: 381 m ³ /s (13,385 ft ³ /s)]

* Note, here the contour lines in 2010s' topographic map were created based on the USGS National Elevation Dataset (1/3 arc-second). More details are given in section 3.1.

3.1 Bathymetry and channel profile

In this study, sonar data were combined with LiDAR data to estimate the bathymetry elevation and channel profile. In the field, sonar data were collected using a Lowrance[®] GPS-depth sounder, which recorded the GPS locations and water depths of the study reach. The boat zigzag traversed the river, resulting in about four strands of data, typically at least two of these were in the deeper portions of the channel, with others to the side to get the better lateral coverage. Soundings were taken in deeper portions of the channel including the thalweg, but away from woody debris, thus may not always have captured the deepest portion. The transducer measurements of depth were calibrated with a 7.6 m long surveyor's rod comparing transducer and rod measurements in 13 locations over a wide range of depths. Depth readings were corrected by a mean offset of 58.9 cm (1.93 ft) because the transducer was mounted below the boat, not at the water surface. Point values of locations and depths were recorded on a memory card as a Sonar Log Viewer file (.slg) and exported to Excel spreadsheets.

In order to estimate the underwater bed elevation, a water slope was derived and then depths were converted to bed elevations given the local stage levels by using adjusted stage data at USGS gaging stations at Blountstown (RM 77.5), Wewahitchka (RM 41.8) and Sumatra (RM 20.6). Equations were developed based on the water surface elevation and river miles for the survey days. With a shallow gradient and no rapids, there were no abrupt changes in slope, thus a linear water slope represents this reach fairly well and corresponds with more detailed field-measured water surface profiles in Light et al. (2006).

Based on the water slope equations from gaging stations, the water surface elevation was estimated for each sonar record. To determine the river mile for each sonar point, river mile

263 markings on the 1990 topography map were applied and each mile split into hundredths. Water
264 surface elevation between gage stations was interpolated for each 16 m (0.01 river mile).
265 Corrected water depths were subtracted from water surface elevations to get channel bed
266 elevations.

267 Sonar survey data were coupled with LiDAR point clouds by building a terrain database, which
268 created a continuous elevation surface from land to below water. The terrain dataset is a
269 triangulated irregular network (TIN) based model; for later visualization and analyses, it was
270 converted to a square-cell format with 1.5 m resolution.

271 For this particular study, the minimum value within each 16 m (0.01 mi) segment represents the
272 thalweg. Based on the elevation model from bank to bank, a Zonal Statistic function was used
273 to obtain the minimum elevation values and derive a longitudinal profile of bed or thalweg
274 elevation.

275 3.2. Historic data, de-snagging, dredge quantities and disposal areas over time and space

276 The two major concerns of dredging in the Apalachicola River were how much and where
277 material would be dredged, and secondarily where would it be disposed. There is some general
278 information about the entire river and its dredging and snag removal history in Corps of
279 Engineers Annual Reports to Congress.

280 The U.S. Army Corps of Engineers-Mobile District (2003) Annual Maintenance Report for the
281 Apalachicola-Chattahoochee-Flint Waterway lists annual dredging quantities from 1957 to 2001
282 across reaches that varied from 0.16 to 4.8 river km (0.1 to 3 river miles). Annual records were
283 recompiled into 160 m (0.1 mi) blocks so they could be plotted on an x-y graph. Annual dredge

quantities were aggregated into groups of approximately ten years (1957-1969, 1970-1979, 1980-1989, 1990-2002) to synthesize spatial and temporal variations in dredge quantities as a linear scatterplot.

In the earlier years of the dredging project, disposal sites were not marked or permitted and much of the disposal was on the floodplain. After some time, the U.S. Army Corps of Engineers-Mobile District (1986) listed disposal sites and areas for the Apalachicola-Chattahoochee-Flint Waterway, although not all permitted sites were ultimately disposal sites. This information was compiled and synthesized using spreadsheets for better presentation of the permitted historical dredge spoil sites along each bank.

3.3 Floodplain dredge spoil volumes and change analysis

Floodplain dredge-spoil mounds between RM 40 and 64 were inventoried or visually located using the LiDAR-derived Digital Elevation Model (DEM). Mounds had steeper slopes and higher elevations than surrounding floodplain features. Polygons were digitized around the base of dredge spoil mounds. The average floodplain elevation adjacent to the mounds was used as a reference surface to calculate floodplain volume and incorporated in the polygon attributes. Spoil mounds were grouped and identified by the nearest 800 m (0.5 mi). The DEM was then clipped to the spoil mounds, and the resulting spoil mound DEMs were converted to Triangular Irregular Network (TIN) surfaces. The Polygon Volume tool was used to calculate the volume and surface area of each spoil mound above the corresponding reference elevation described above.

To document spoil mound changes over time, the two largest spoil mounds were selected. Volumes and changes in volume, attributed either to more disposal or lateral erosion from channel migration and flooding, were computed from volume changes in the DEMs. Since 1940, the survey quality of the topographic maps improved. The USGS used plane-table surveying during 1943 to 1944 for the 1945 map. Photogrammetric methods were used in 1975, and maps were revised during 1983 to 1984 using aerial photos and published in 1990. Most recently, in 2012, the USGS used LiDAR technology for 2011 National Elevation Dataset (1/3 arc-second) to generate a 1.52 m (5 ft) interval contour. As such, uncertainty estimation is necessary to verify if the uncertainty does not exceed the change over time. James et al. (2012) reviewed the uncertainty estimation studies related to geomorphic change detection studies. They combined historical survey data with LiDAR data and estimated the horizontal and vertical errors. We also estimated the errors with following equation:

$$\epsilon_o = \sqrt{\epsilon_{t1}^2 + \epsilon_{t2}^2 + \epsilon_{t3}^2} \quad (1)$$

where ϵ_o is the total error for the change over time estimation. The ϵ_{t1} , ϵ_{t2} , and ϵ_{t3} indicate the estimated error for each topographic map, which is the summation of vertical and horizontal errors:

$$\epsilon_{ti} = \sqrt{\epsilon_v^2 + (\epsilon_h \tan \alpha)^2} \quad (2)$$

where ϵ_v represents vertical error and the ϵ_h represents horizontal error. The offset horizontal error for 1945 and 1990 topographic maps were calculated by multiplying ϵ_h and the tangent of local slope, α . The horizontal errors included the uncertainty from cartographic, map ratification and digitalization.

The contour line and horizontal control marks were digitized from multiple topographic maps from 1945 and 1990. Then the 2012 topographic map contour line was acquired and contour lines for all maps were converted into 10 by 10 m square-cell grid DEMs. Elevation data from the earlier map were converted, with a NGVD29 datum, to NAVD 88 on the most recent mapping. According to the Orthometric Height Conversion website (https://www.ngs.noaa.gov/cgi-bin/VERTCON/vert_con.pr1) of the National Geodetic Survey, the shift between NAVD 88 and NGVD 29 is about 0.168 m in the study area. After creating the DEM, changes in volume were assessed using the Cut-and-Fill functions to estimate locations of gross and net changes.

3.4 Sediment analyses

Surface sediment samples were collected with a hand-held auger to better quantify the size range of dredge spoil deposits, point bars and water-laid deposits during floods (Fig. 4). These sediment samples documented spatial variations of sediment size in natural and artificial depositional environments along-river in the study area. We took GPS points, focused on sampling point bars where we collected 28 samples, most during August 2016. During March 2016, following a very high flow of $4925 \text{ m}^3/\text{s}$ ($173,000 \text{ ft}^3/\text{s}$) in late December 2015, a few floodplain dredge spoil mounds were sampled, evident by their elevation and contact with fine-grained sediments (Fig. 4A) and recent sandy flood deposits (Fig. 4B). On several of the point bars, 3-5 samples were collected to characterize grain-size variations at various relative elevations near the water line during low flow to the higher part of the bar being colonized by incipient vegetation (Fig. 4C). Part of this sampling was to document which grain sizes might best support plantings for river restoration. The samples were oven-dried for 48 hr, and ground

348 with a mortar and pestle to break up fine aggregates. Sediments were sieved at 0.5 ϕ intervals,
349 from -2 to +4 ϕ , weighed, and values were recorded in a spreadsheet and graphed as
350 cumulative frequency curves.

351 3.5 Point bar areal change

352 Georeferenced imagery were acquired from Price et al. (2006); these included black and white
353 photography from 1940, before there was major disturbance due to dredging, and color NAIP
354 images from 2004, shortly after dredging was curtailed in 2002 as an indicator close to the
355 maxima of disturbance (Table 1). Point bars were digitized, interpreting point bar increase as a
356 potential indicator of direct or indirect channel disturbance. Then, the river corridor was
357 divided into 160 m (0.1 mi) increments to correspond with the other data including dredge
358 quantities (160 m increments) and bathymetry (16 m increments). Both sets of images have
359 average flow levels less than 3 m³/s apart, roughly 379-381 m³/s (13,286-13,385 ft³/s). This
360 flow is approximately in the 40th percentile of the flows between 1928 and 2016.

4. Results

4.1 Bathymetry and channel profile

The plot of minimum channel elevation vs. river mile shows that the reach directly below Chipola Cutoff at RM 41.5, where part of the Apalachicola River flow diverts into the Chipola River, is a zone of relatively high channel elevations (Fig. 5). The riffle-pool amplitude or difference between the minimum values of high and low spots decreases from 5 to 8 m upstream of Chipola Cutoff to less than 4 m downstream of Chipola Cutoff. The elevations of both riffles and pools are higher downstream of this juncture. When plotted with the water surface during the August 2015 and March 2016 field excursion, when most of the bathymetry data were collected during a flow toward the lower end of the discharge range (12th percentile), the shallowness of the water depths (<2 m) at these flows is evident compared to the desired navigation channel (2.74 m). Knowing that these are generally minimum elevations, and that the desired width of the navigation was 30.5 m, this zone would have been troublesome for dredging and maintaining navigation.

4.2. Dredge quantities and disposal sites over time and space

The Apalachicola River has a long history of dredging, dating back to before 1920. Once Congress approved the Navigation Channel, dredging quantities increased tremendously, with a peak in 1957 of greater than 2.7 million cubic meters (Fig. 3). Subsequently, dredge quantities varied from year to year. Generally the next highest rate was during the 1970s and dredging ended in 2002. A total of 33.1 million cubic meters were dredged and moved elsewhere.

381 De-snagging has a long history in many rivers, including the Apalachicola River (Fig. 3). Prior to
382 inception of the navigation project, snags were removed from the channel and banks to
383 improve navigation. Snag removal, and removal of trees from channel banks were
384 commonplace during the heyday of the navigation project, exceeding 10,000 trees removed
385 annually during some years in the 1950s, 1960s and 1970s (Fig. 3). Spatial details for snag
386 removal sites are not known, and thus cannot be compared to erosion rates, although such
387 massive removal likely increased bank erosion and possibly sand bar areas. Since the dredging
388 ended in 2002 following greater awareness of the importance of woody debris, the Corps only
389 conducted shearing of snags just below the water surface of the debris most hazardous to
390 navigation.

391 Within the study area, certain portions of the Apalachicola River navigation channel were hot
392 spots for dredging. Data from the U.S. Army Corps of Engineers Mobile District, (2003) Annual
393 Maintenance Report shows that the most intensively dredged section is between RM 40 and 42
394 (Fig. 6). This coincides with the troublesome location identified by McCollum (1994) just
395 downstream of the Chipola Cutoff where the flow partly diverts into the Chipola and the
396 velocities and bed-load sediment drop. This also coincides with a relatively shallow zone along
397 the longitudinal profile (Fig. 5). At this location, channel dredging peaked during the 1990s and
398 secondarily the 1980s (Fig. 6). Two other much smaller dredge hot spots in terms of quantity
399 are a short section near RM 50 and a section near RM 64, close to where the channel impinges
400 on the Estiffangula Bluff (Fig. 7). This area was dredged due to excess sediment from historic
401 and modern bluff erosion. In both of these locations, peak quantities of dredging occurred
402 during the 1980s, and secondarily the 1990s.

In 1986, all of the permitted disposal sites for the navigation project in the study area were within-bank sites, with none of the spoil deposited on the floodplain (U.S. Army Corps of Engineers, Mobile District, 1986) (Fig. 8). Some of these sites would have more frequent disposal, ranging from twice annually to every five years. Remarkably, some of the locations where material was deposited are a considerable distance from the locations where dredging was conducted. However, because all the sediment was within-bank it was subject to movement during higher flows. Ultimately, coarser thalweg or channel bottom sediments were deposited by dredges on point bars at higher elevations in the cross section. This synthesis estimates that 28.8% of the left bank in the study area was a permitted in-channel disposal site, whereas 35.6% of the right bank in the study area was a permitted in-channel disposal site. Thus, along the study area 64.4% of the channel corridor had permitted spoil deposition within both banks. The Corps disposed material at only 60% of these sites between 1977 and 1985 (U.S. Army Corps of Engineers, Mobile District, 1986), probably at sites closest to dredging problem areas.

Disposal at within-bank sites was supposed “to emulate nature's processes by placing dredged material in natural accretion areas (i.e., point bars) along the rivers, thus avoiding environmental impacts to other more stable aquatic habitats or to bottomland hardwoods and other vegetation communities in the adjacent flood plain” (U.S. Army Corps of Engineers, Mobile District, 1986). The Corps selected within-bank sites for disposal based on the historic location of required dredging, the nature of expected adverse impacts, and the lack of more desirable alternative disposal areas (U.S. Army Corps of Engineers, Mobile District, 1986). By their definition, the life of a within-bank disposal area was perpetual because of reworking

annually by high water. Although this is true for a great majority of the within-bank sites, certain sites have indicated a tendency for material to accumulate, thus reducing their annual capacity. The Corps considers Chipola Cutoff one of the problem reaches on the Apalachicola River, due to lack of adequate within-bank disposal capacity for the proposed navigation maintenance plan.

4.3 Floodplain dredge spoil volumes and change analysis

Topographic features such as mounds, hummocks and hills on high-resolution LiDAR topographic data from March 18, 2007 indicate locations of floodplain dredge spoil. The largest areas of anthropogenic deposits are also evident on topographic maps. These sources give helpful insights because floodplain spoil deposition was commonplace but poorly recorded in the early decades of the navigation project. The LiDAR and topographic maps give visual information of the landforms of natural and human-modified portions of the floodplain (Fig. 9), and help identify sites of topography largely influenced by anthropogenic processes (Table 2).

439 Table 2. Volumes and surface area of dredge spoil mounds identified on LiDAR (March 2007
 440 data) in the study area.

RM	Average Elevation (m)	Floodplain Volume (m ³)	Surface Area (m ²)
40	6.4	425,475	101,673
41.5	6.7	196,949	83,947
47.5	7.9	12,309	8361
50	8.2	3364	3428
50.5	8.2	12,309	12,542
53	9.1	16,591	8445
54	9.0	6269	11,789
54.5	9.4	4511	6605
55.5	9.0	32,723	25,669
57	9.1	29,512	33,361
60	11.0	3288	4515
60.5	11.4	5123	8947
63	9.8	32,876	21,154
64	11.6	26,607	22,993
TOTAL		807,905	353,431

441

442 Table 3 lists estimated values of vertical and horizontal errors. The overall estimated error for
443 1945, 1990 and 2011 maps was 1.86 m, which did not exceed the change of elevation. Note,
444 this estimation did not include the surveyor's error; this error is possible due to the remoteness
445 of study area. In addition, the possible uncertainty of the difference between vegetation height
446 and ground elevation in the densely vegetated Apalachicola River floodplain (James et al., 2012)
447 was not estimated.

448 Table 3. Sources and values of uncertainty for the elevation change analysis.

Source of Uncertainties	Values (m)	Reference/Comment
Horizontal error (only for 1945 and 1990 maps)		
Cartographic	12.2	National Cartographic Accuracy Standards
Registration	12.2	USGS Historical Quadrangle Scanning Project*
Digitalization	1.84	Estimated**
<i>Slope in area of interest</i>	0° (1945), 15°(1990)	
Vertical error		
	1.524(1945), 0.762(1990 & 2011)	National Cartographic Accuracy Standards
Total error	1.5 (1945), 0.80 (1990), 0.76 (2011)	The overall error is 1.86 m

449 *According to the USGS Historical Quadrangle Scanning Project, the ratification error does not exceed
450 the original map. Here we use the maximum value.

451 **We randomly selected 10 locations to compute the distance between digitalized polyline and contour
452 line on map and calculated the averaged value as the digitalization error.

453

454 The analysis of a large dredge spoil mound on the left bank near Chipola Cutoff near RM 41.5
455 shows current addition to and modification of this feature by anthropogenic and natural
456 processes. The volumes of the largest floodplain spoil area increased 306,400 m³ between the
457 1940s and the 1980s; this difference is attributed to anthropogenic deposition. The volume
458 during the second interval from the 1980s to 2010s includes 21,800 m³ of gain and more areas
459 of loss of 141,400 m³, with the gain being attributed to anthropogenic deposition and the losses
460 due to riverbank erosion and reintroduction to the river (Fig. 11). The change analysis
461 presented here for a spoil mound on the right bank, across from Swift Slough, near RM 40.3
462 shows a gain of 174,200 m³ between the 1940s and the 1980s connected to spoil deposition.
463 Between the 1980s and 2010s there were additional gains of 299,300 m³; this might be due to
464 disposal in the early 1980s as this was no longer a disposal site in 1986 or include errors

reflecting improved mapping technologies. Additionally, there were losses of 73,100 m³ largely due to river erosion at the edges (Fig. 12) as is common in the study area (Figs. 4A and 10D).

4.4 Sediment analyses

Sediment samples were acquired for floodplain dredge spoil mounds, recent flood deposits and extensive sampling of point bars at elevations near the water line during low flow to the higher part of the bar being colonized by incipient vegetation (Fig. 13). Although the samples were collected at similar relative elevations to the river, the dredge spoil mound deposits (dashed lines) are approximately 2 ϕ coarser than the recent flood deposits (solid lines) (Fig. 14). This difference was expected because the dredge spoils are derived from the channel, but grain-size analysis documents that these differences are anthropogenic. Interestingly, the point bar deposits include samples of similar size to the dredge mound deposits as well as similar size to the recent flood deposits, showing a range close to 3 ϕ (Fig. 15). This mixture was also expected, given the combination of anthropogenic processes and natural reworking. The flood of water year 2016 inundated the point bars, with deeper flows closest to the channel and shallower flows at the vegetated margins. Generally, the point bar deposits closest to the water line were coarser and gradually became finer at higher relative elevations. Deposition of dredge spoil through within-channel disposal contributes coarse, thalweg bed materials. Therefore, the bar sediments may be coarser than they would have been before dredging associated with the navigation project began in the 1950s, because they include some of the coarsest material from the thalweg. To confirm this, comparative analysis of bars that were and were not disposal sites is recommended, possibly ascertained from further historical work.

The finest sediments highest and farthest from the channel drop out in the currents slowed by increased resistance associated with vegetation at the channel boundaries. In turn, plantings would promote deposition of finer sediments that support increased colonization.

4.5. Point Bar Areal Change

Sand bar areas as measured from digitized aerial photography from 1940-41 before the navigation channel was authorized comprised very little area below RM 50, and were largest between RM 61 and 64 with 8600 m² per 0.1 mile (92,500 ft² per 0.1 mile) and secondarily between RM 55 and 58 (Fig. 16). The largest area of sand bars in 1941 is located next to a large source, an actively eroding higher bank, Estiffanugla bluff. At the time, before the navigation channel was authorized, the small sand bar area reflects comparatively less disturbance and minimal bank erosion. During 2004, the second period when sand bar areas were measured, discharge levels were similar (i.e., close to the 40th percentile of flow values at Chattahoochee). Although dredging was curtailed two years beforehand, the combination of dredging, within-channel and floodplain deposition and snag removal over 45 yr created extensive disturbance in the system, including anthropogenic sedimentation in the floodplain and channel and increasing bank erosion. Resulting from this legacy of disturbance, the total sand bar area was much larger, with several peaks along the study area in different sections. The largest peak of 12,000 m² per 160m or 0.1 mile (129,800 ft² per 0.1 mile) is near RM 43.5. Furthermore, the analysis of data from 2004 shows numerous other peaks of sand bar areas throughout the study reach in locations where they were not present in the prior period (Fig. 16).

Comparing how areas changed in each 160 m (one-tenth mile) sector, using the same data just described, sectors that gained or lost point bar area are shown (Fig. 16). Given the more

509 frequent occurrence of positive numbers, this suggests that sand bar area was much greater in
510 2004, reflecting prior disturbance from the navigation project both directly and indirectly (Fig.
511 16). Thus, sand bar area is interpreted to be directly, but only partly, due to within-bank
512 disposal from dredging. Removal of snags also reduced bank protection, possibly increasing
513 bank erosion during the navigation project, and sandy portions of the floodplain (i.e.,
514 Estiffanugla Bluff, remobilized dredge spoil mounds, fluvial terrace deposits), to contribute sand
515 to the channel. Third, according to Light et al. (2006) this portion of the river has somewhat
516 lower stages at this flow level, varying from 0.15 m from the northern part of the study area to
517 0.6 m (0.5-2 ft) in the southern part of the study area. This stage decline has been attributed to
518 dredging impacts downstream of RM 42 and artificial cutoffs near RM 30, and would have the
519 greatest influence on sand bar area in the lower part of the study area. Thus, indirect factors,
520 such as water level declines, explain part of the increased bar area in the southern part of the
521 study. Another contributing factor concerns water supply issues or reduced flows from
522 upstream tributaries that lower average velocities, which would increase sedimentation and
523 the size and number of sand bars. All of these factors need further investigation. Summarizing
524 the change over the period between 1941 and 2004, there was 27.6 ha (68.2 ac) of net gain in
525 sand bar area over the study period or an overall increase of 263%. Areas where the size of
526 sand bars decreased in each 160 m or one-tenth- mile sector might be due to downstream
527 migration of fluvial features.

5. Discussion

The historic areas of dredging (Fig. 6) coincide with topographic highs on the longitudinal profile (Fig. 5) which are the shallowest zones at low water. The Corps of Engineers dredged large quantities of sediment from the channel bottom and thalweg of the Apalachicola River during the navigation project. In our study area, the two areas with the greatest historic dredging activity have hydrologic influences and geologic controls. The major dredge problem area is near RM 41 below Chipola Cutoff, where some flow passes into the Chipola River. Geologic controls, including the hard point near RM 40.8 (U.S. Army Corps of Engineers, Mobile District, 1986) and the higher, older bluffs near Estiffanugla that are actively eroding and providing more sediment than the lower lying banks, also influenced spatial patterns of dredging.

Although more subtle than the anthropogenic features associated with hydraulic mining (Gilbert, 1917), dredging and the navigation project altered the Apalachicola River landforms and its sediments in various ways. Removal of sediment, placing dredge spoil outside of the channel, within-channel deposition of spoil, and large-scale de-snagging have left a legacy of an altered floodplain topography with mounds, hummocks and hills of coarser sediments than surrounding floodplain deposits and more and larger sand bars. Also, as with hydraulic mining, some impacts associated with dredging are long lasting, including the sediment pulses from erosion of floodplain mounds back into the river system and the altered form of the channel.

The two largest floodplain mounds in the study area between RM 40 and 42 sit above the floodplain but are eroding due to their proximity to the channel. For the Chipola Cutoff spoil mound complex, our rough change analysis estimated 328,200 m³ of gain (306,400 m³ + 21,800 m³) and 141,400 m³ of loss, resulting in 186,700 m³ of sediment remaining on the floodplain.

550 The change analysis of the spoil mound complex across from Swift Slough shows a gain of
551 $473,400 \text{ m}^3$ ($174,200 \text{ m}^3 + 299,300 \text{ m}^3$) and a loss of $73,100 \text{ m}^3$, resulting in an estimated
552 $400,300 \text{ m}^3$ of sediment remaining on the floodplain. While mixing sources of diverse quality,
553 this crude assessment suggests that 42% of the volume of Chipola Cutoff mound and 15% of the
554 mound across from Swift Slough eroded back into the river. These two sites combined, totaling
555 $587,000 \text{ m}^3$ of sediment, represent more than half of the floodplain dredge spoil in the study
556 area, estimated at approximately $808,000 \text{ m}^3$. In total, approximately $7.7 \times 10^6 \text{ m}^3$ of sediment
557 was dredged within the study reach during the navigation plan (U.S. Army Corps of Engineers
558 Mobile District, 2003) suggesting that more than 10% of the volume dredged remains on the
559 floodplain. These mounds, as well as others (Fig. 9), are forested and might be mistaken for
560 geological features or ancient Indian mounds if not for historical and sedimentological analyses.

561 Sand bars in the study area were also much more numerous and larger in 2004 than they were
562 prior to intense dredging activity. The literature provides a variety of explanations for increased
563 bar size, many connected to human activity. The size of sand bars on the Lower Colorado River
564 increases from flood pulses on large tributaries (Wiele et al., 1996) and from artificial floods
565 downstream of the Glen Canyon Dam (Hazel et al., 2010). Jacobson and Gran (1999) related
566 changes in bar size along the Current River, an Ozark stream, to land-use changes that occurred
567 in the 160 yr prior, finding that historical land use had stronger ties to gravel distributions than
568 the present, with valley morphology being a secondary factor. Floodplain sand and gravel
569 mining activity, particularly when not well regulated, has increased bar size due to avulsions,
570 increased erosion and flooding over bare landscapes (Mossa and Marks, 2011). Rapid channel
571 migration can form large, unvegetated gravel bars, in part related to the legacy of historical

572 human activities (Martin and Pavlowsky, 2011). In the Kissimmee River, sand bars grew once
573 the canal C-38 was backfilled and flow was reactivated in the original channel; this was due to
574 water inputs and associated processes of erosion and deposition in former stagnant areas
575 (Mossa, 2015). In our study area, the growing bars are likely a combination of direct
576 anthropogenic deposition of dredged sediment from the thalweg area, lower stages for a given
577 discharge, sediment from bank erosion, and possibly other factors.

578

579 Legacy sediment, typically associated with past human activities and sedimentation, is
580 becoming more commonplace in the Anthropocene (James, 2013). Anthropogenic
581 geomorphology plays an important role in the floodplain and channel of the Apalachicola River,
582 and these artificial landforms have manifold influences on the biota, soils, microclimate, and
583 modify natural processes (Szabó, 2010). Direct anthropogenic processes include floodplain
584 deposition of dredge spoil, resulting in constructive landforms in Haigh's (1978) classification
585 such as mounds, hummocks and larger hills. The excavational features in Haigh's (1978)
586 classification of removal areas are generally subaqueous and more difficult to identify without
587 historical, repeated bathymetric mapping, but clearly existed at one time to create a navigation
588 channel larger than the original river dimensions and to have been a source for the large
589 amounts of sediment extracted. The point bars appear to represent a combination of direct
590 anthropogenic deposition or within-channel disposal, as well as indirect sedimentation, from
591 removal of snags increasing bank erosion. More work is necessary to assess the role of lower
592 water levels associated with decreased flows, which can increase point bar areas by exposing

593 more of the bed, and the lower velocities associated with lower flows result in more
594 sedimentation.

595 For comparison, the lower Yuba River in California has an estimated $250 \times 10^6 \text{ m}^3$ of hydraulic
596 mining sediment from the 19th century (Gilbert, 1917; James, 2013), the quantities of material
597 dredged in the Apalachicola alone are $29.6 \times 10^6 \text{ m}^3$ during the period of active dredging for the
598 navigation project (1957-2002). Only some of this is evident, however, due to the shift from
599 floodplain deposition to within-channel deposition during the extent of the navigation project.

600 Although this constitutes about 12% of the amount of direct disturbance as in the Yuba River,
601 given the biodiversity and economic value of ecological resources including freshwater mussels,
602 fisheries, oysters and riparian vegetation, this impact is nonetheless of great concern to the
603 ecosystem of Florida. If impacts to the Chattahoochee and Flint were included, these amounts
604 would be much larger.

605 Geomorphic studies can be helpful in evaluating the viability of navigation projects. A
606 longitudinal profile of channel bed elevations, as compared to water levels, sheds light on
607 potential dredging problem locations, and the scope of the problem along the study reach (Fig.
608 5). Due to hydrologic influences, such as the Chipola Cutoff where part of the flow diverts into
609 the Chipola, some sections of the profile are comparatively shallow. With the current
610 morphology of the river, flow levels of well over $285 \text{ m}^3/\text{s}$ ($10,000 \text{ ft}^3/\text{s}$) would be required to
611 give 2.74 m navigation depths. Even with water that deep, this does not ensure that the
612 channel would be wide enough to handle barges of the size mentioned in the navigation plan.

613 Additionally, there was very little geological investigation of the river prior to the navigation
614 project. Decades following authorization of the project, the Corps (U.S. Army Corps of

615 Engineers, Mobile District, 1986) identified a “hard point” of resistant clay materials near RM
616 40.8 that protrudes into the channel changing the morphology of the smooth bank (Fig. 9A). At
617 the time, the Corps proposed to cut this away, to create an additional bend easing, but that
618 never came to fruition.

619 Although the Corps refers to earlier hydrographic surveys, dating at least to 1960 (U.S. Army
620 Corps of Engineers, Mobile District. 1986), these post-dated the navigation project inception
621 and major river disturbance was already underway. Lidstone and Anderson, Inc. (1989) have
622 crude longitudinal profiles comprised of approximately 10 bed elevations in our study area for
623 1980, 1981 and 1984. McComas and Copeland (1996) include a longitudinal profile that covers
624 the entire river but is less detailed than the field survey for this study. If predecessors had
625 coupled water surface profile with bed elevations it would be evident that maintaining 2.74 m
626 depths here would require a substantive amount of dredging, particularly below Chipola Cutoff.

627 If complemented by an understanding of concepts such as the role of base level (Leopold and
628 Bull, 1979), there would be more realization that intense, persistent dredging would be
629 required to maintain a channel of such dimensions and that this project would not be
630 economically viable. The minimum bed elevations in much of the study area, particularly the
631 lower end, are near or below sea level and prone to sedimentation given the inability of rivers
632 to cut below this level. Below RM 65, the channel does not appear to deepen (Light et al.,
633 2006), thus the geomorphic response to disturbance included widening, the primary response
634 to increased flows in the Atchafalaya, a large coastal plain river with bed elevations below sea
635 level (Mossa, 2016).

636 A thorough geomorphic study of this reach, beginning with more bathymetric work in relation
637 to water levels, might have prevented the navigation plan from moving forward. The reduced
638 flows from upstream, partly compounded by reservoirs built for the navigation plan, have
639 placed many stresses on aquatic biota and riparian forests. Areas across the world that are
640 considering development of navigation would be wise to assess the geomorphology, geology
641 and hydrology before undertaking such works.

642 Historical activities, ongoing upstream water control and extraction affected this resource rich
643 ecosystem of exceptional ecological importance. Much learning has occurred, such as
644 recognizing the importance of large woody debris in streams, and consequently the rates of
645 snag removal in the Apalachicola are minimal, only to minimize navigation hazards. Yet,
646 potential threats to the water supply will likely increase (Georgia Environmental Protection
647 Division, 2011). Periods of low water levels are now more frequent and longer in duration than
648 prior to 1954, resulting in longer periods during which floodplain streams are dewatered,
649 isolated, or not flowing, and swamps and bottomland hardwood forests are dry (Light et al.,
650 2006).

651 Specific practices that can help restore the function of the Apalachicola River include improving
652 water supplies for ecosystem allocation (Richter et al., 2003; Fitzhugh and Richter, 2004), and
653 narrowing the channel through vegetative plantings, which could increase flow into sloughs
654 comprising floodplain habitats. In the ACF, water withdrawals for urban and agricultural use
655 result in the pre-allocation of much of the water with limited consideration of the water needs
656 of freshwater ecosystems. Best practice is to begin with ecosystem needs, and adjust dam

operation to provide minimum flows year-round (Richter and Thomas, 2007). Floodplains provide flood storage, add roughness that results in velocity reductions, sequester carbon, trap sediment and nutrients, and support aquatic biota. Therefore it is important to restore lateral connectivity (Kondolf et al., 2006). Dredging has ended for more than a decade, and the higher portions of the bars are becoming colonized by willows because other local disturbances are minimal. As the river narrows by natural processes, perhaps assisted or accelerated with vegetative restoration of point bars, resultant water-level increases would help in bringing more flow to the floodplain sloughs.

Now in the Anthropocene (Zalasiewicz et al., 2008), humans have become the most important geomorphic agent. This study adds dredging as an example of direct human change, but indirect changes also cause human impacts to exceed natural sediment production by an order of magnitude (Hooke, 2000; Syvitski et al., 2005; Wilkinson, 2005). In both form and function, the Apalachicola River floodplain and channel reflect two centuries of alterations, most pronounced in the past six decades. The modifications and consumption in the two main tributaries, the Chattahoochee and the Flint, affect the downstream inputs of water and sediment to the Apalachicola, and there have been consequences to channel form and ecology. Some artificial legacies of the navigation project, particularly floodplain mounds, will persist for some time.

6. Conclusions

Along parts of the Apalachicola River corridor, the floodplain topography and sedimentology is anthropogenic, comprised of dredge hummocks and larger hills of sand associated with

678 dredging for a navigation channel maintained until 2002. The anthropogenic hummocks and
679 hills are mostly coarse sands from the thalweg and are in some cases eroding back into the
680 channel. The trouble zones for dredging are apparent when combining a water surface and bed
681 surface profile; furthermore, hydrologic factors, specifically flow diversion through Chipola
682 Cutoff, and geologic factors influence bed-elevation high zones. Essentially, a comprehensive
683 geomorphic study could have averted the failure of the navigation project.

684 Most of the dredge disposal since the 1980s has been within the channel, resulting in increased
685 sand bar area along the system. Additionally, indirect components of the navigation plan might
686 be increasing the sand bar area such as the extraction of large amounts of woody debris that
687 decreases bank resistance and increases sediment supply. Also, the lowering of water levels
688 due to dredging-triggered widening and channel adjustments to artificial cut-offs downstream
689 expose more of the bed. Reduced discharges with lower velocities, associated with less water
690 supply, could increase sedimentation and contribute to the size and number of sand bars.

691 Assuming no future major disturbances, many of the sand bars are expected to decrease in size
692 through colonization by vegetation over many decades. As the river narrows by natural
693 processes, perhaps assisted or accelerated with vegetative restoration of point bars, gradual
694 increases of water-level would help in bringing more flow to the floodplain sloughs. Given the
695 biodiversity and economic value of this river's ecological resources, these approaches for
696 hydro-geomorphic and habitat restoration are worthwhile endeavors.

697 Acknowledgements

698 Support for this work was provided by the Florida Fish and Wildlife Conservation Commission
699 (FWCC) Project 00120439 (NID: 72664) Apalachicola River Mussel Habitat and Fluvial
700 Geomorphic Assessment, Aquatic Habitat Restoration/Enhancement Subsection (AHRES)
701 program. The content is solely the responsibility of the authors and does not necessarily
702 represent the official views of the FWCC. We thank B.J. Jamison of FWCC for project
703 management and Dan Tonsmeire of Apalachicola Riverkeeper who coordinated boating
704 logistics and provided deep understanding of the river and its history. Helen Light, retired from
705 the USGS, and Ted Hoehn of the FWCC shared resources and knowledge that contributed to
706 this study. Two anonymous reviewers, Allan James, and Scott Lecce gave helpful feedback.
707 Finally, we thank Allan James, Scott Lecce and Jonathan Phillips for inviting us to participate in
708 the theme session on Anthropogenic Sediments at the Association of American Geographers
709 meeting and for organizing and editing this special issue of *Geomorphology*.

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938 **FIGURE CAPTIONS**

939 Figure 1. The Apalachicola River and its drainage. The Chattahoochee and Flint rivers are shown
 940 in the inset. The Apalachicola River originates at the confluence near the Florida boundary, held
 941 back in part by the Jim Woodruff Dam. A large tributary, the Chipola River, joins farther south.

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943 Figure 2. Flow or discharge duration curves at the Apalachicola River at Chattahoochee prior to
 944 the navigation project (1922-1949) compared to the last few decades (1980-2016). Higher flows
 945 are similar but the lower flows have clearly decreased (Data source: USGS).

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Figure 3. Dredging and de-snagging on the Apalachicola pre-dates 1920. Quantities of sediments and snags removed increased tremendously once Congress approved the navigation channel. Dredging stopped in 2002, although the project is not yet de-authorized. The Corps currently conducts maintenance snagging of trees that are navigation hazards, with methods that shear the top of the tree and cause the least disruption to the channel bed (Sources: Hoehn and Leitman, 2001, unpublished and Corps of Engineers, Mobile District, 2003, 2013, 2014).

Figure 4. Sandy sediments that were sampled in the study area included: (A) dredge spoil deposits overlying original floodplain finer sediments, shown with dashed line; (B) recent flood sand deposits have no vegetation; and (C) point bar deposits from the water line to the vegetated back part of the bar (Photographs taken by Joann Mossa and Yin-Hsuen Chen).

Figure 5. A longitudinal profile of the study reach. The top line is the water slope derived from water levels during the March 3, 2016 field excursion. The next water surface was on August 14-15, 2015 field excursion from the Blountstown (RM 77.5), Wewahitchka (RM 41.8) and Sumatra (RM 20.6) gages. The lower line shows minimum channel elevations derived from subtracting the deepest of multiple values collected with a sonar in 16 m or hundredth-mile sectors from the water surface elevation. This reach shows a strong riffle-pool morphology typical of sandy alluvial rivers. By comparing the low water surface and bed elevations, shallow zones that needed considerable dredging during the navigation plan are evident.

Figure 6. Dredge quantities in the study area, broken up into 160 m or one-tenth river-mile sectors. The total dredge quantities within the sector as well as a breakdown into approximately decadal periods to characterize the spatial and temporal variability in dredging of the river corridor. (Data source: U.S. Army Corps of Engineers, Mobile District, 2003).

Figure 7. Photographs of the eroding bluff at Estiffangula, RM 63.5 taken on March 3, 2016 following a legacy of much higher flows earlier in the water year. (A) Frontal view of large

wooden poles that used to be a fence line now hanging on a steel cable in front of the bluff due to erosion; and (B) Lateral view also shows the poles, large sediment blocks near the base, the fresh exposures, and overhanging roots. This active erosion site contributes sediment to this section of the profile (Photographs taken by Joann Mossa).

Figure 8. During the 1980s portion of the navigation project, much less of the spoil was deposited on the floodplain, but instead at within-bank sites. Essentially this involves removing sediment from the deeper part of the river to create a sufficiently deep and wide navigation channel, to a generally shallower area on the side of the river. This synthesis estimates that 28.8% of the left bank and 35.6% of the right bank in the study area were permitted as in-channel disposal sites, potentially affecting 64.4% of the channel corridor, but not all permitted within-bank sites were used (Data source: U.S. Army Corps of Engineers, Mobile District, 1986).

Figure 9. Natural and human-altered topography associated largely with floodplain deposition of dredge spoil on LiDAR imagery. (A) Two large dredge spoil floodplain mounds, one on the right bank near RM 40.3 and across from Swift Slough and a second near RM 41.5. These, the largest spoil mounds in the study area, both stand 7-12 m higher than the adjacent floodplain. (B) A reach with minimal deposition of dredge spoil on the floodplain, but some possible within-channel disposal sites. (C) Some smaller dredge spoil mounds between RM 53 and 54 on both sides of the channel. (D) Erosion and sediment on the left bank near Estiffangula Bluff required dredging resulting in numerous mounds and hummocks on the right bank (Fig. 10).

Figure 10. (A) Dredge spoil mounds. (B) Hummocky topography covered with trees and limited understory, due in part to the very sandy nature of the dredge spoil deposits not supporting as wide a variety of riparian vegetation. (C) Estiffangula Bluff in the background and people for scale. (D) Relatively high flows expose and erode some of these dredge mounds near the channel boundary (Photographs taken by Joann Mossa).

Figure 11. Volumetric change analysis of a large dredge spoil mound below Chipola Cutoff on the left bank near RM 41.5, showing rough changes to the dredge spoil mound given disposal and lateral erosion from the river channel.

Figure 12. Volumetric change analysis of a large dredge spoil mound across from Swift Slough, on the right bank near RM 40.3, showing rough changes to the mound over time.

Figure 13. Locations of dredge spoil mounds, flood deposits and point bar sediment samples in the study area shown with the LiDAR map of the floodplain as background. The Apalachicola River floodplain outline approximates the 10-year floodplain boundary and the river miles are from the 1980s topographic maps (Source: Light et al., 1998, shape files courtesy Melanie Darst and Helen Light).

Figure 14. Cumulative frequency curve showing grain-size distribution of two samples collected at similar relative elevations to the river during early March 2016. The dredge spoil mound deposits (dashed lines) are approximately 2 ϕ coarser than the recent flood deposits (solid lines).

Figure 15. Cumulative frequency curve showing grain-size distribution of 28 point bar samples collected at various elevations in August 2016 low water. Some of these bars were sites of within-channel disposal of thalweg materials, explaining the similar coarseness of these deposits to floodplain spoil mounds. Other parts of the bar were finer, especially those near the vegetation line where vegetative resistance induces sedimentation.

Figure 16. Sand bar areas and changes in the study reach. (A) Areas in 1940-41, before the navigation channel was authorized, and in 2004, soon after dredging had stopped. (B) Sand bar areal changes in the study reach between 1941 and 2004 measured at similar flows.

- 1032 Table 1. The purposes and sources of primary and secondary data utilized in this study.
- 1033 Table 2. Volumes and surface area of dredge spoil mounds identified on LiDAR (March 2007
1034 data) in the study area.
- 1035 Table 3. Sources and values of uncertainty for the elevation change analysis.
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Within-Bank Deposition

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