

Cooperating Parties Group

**LOWER PASSAIC RIVER RI/FS
NEWARK, NEW JERSEY**

**APPENDIX M - ATTACHMENT B
BATHYMETRY ANALYSIS OF THE
LOWER PASSAIC RIVER**

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1.0 INTRODUCTION

This report describes an analysis of bathymetrical surveys carried out in the Lower Passaic River (LPR). These comprise the multi-beam surveys of 2007, 2008, 2010, 2011 (post-Irene) and 2012. In addition, information from the 1995 single-beam survey was added, together with information on contaminant concentration in the bed from several data collection programs, data from the physical water column monitoring program, and other historical data and data from literature.

All data have been put into the OpenEarth data base. This data base, which is based on the satellite images within Google Earth, allows for a comparison of the various data sets, establishing the dynamics and evolution of the LPR.

Interpretation of the bathymetrical evolution of the LPR should start from a conceptual picture of the hydro-sedimentological functioning of the LPR, accounting for the hydrograph of the river. This conceptual picture and the relevant background information is presented in Chapter 2. To place the bathymetrical evolutions in perspective, Chapter 3 describes the long-term bathymetrical evolution briefly.

All bathymetrical surveys are subject to errors; a summary of possible sources of errors are summarized in Appendix B of the current document (Lower Passaic River RI/FS, Appendix M - Attachment B). Stochastic errors are filtered out in this method of analysis. However, there were strong indications that the 2008 bathymetrical data were affected by a small systematic error. This systematic error discussed in Section 4.1 and Appendix C, together with an assessment on the required corrections. Chapter 4 also discusses the sediment composition in the LPR, the recent multi-beam bathymetric surveys, and the temporal changes therein. This information is important for the mathematical modeling of the sediment dynamics in the LPR.

The bathymetrical analyses in this report also establish the stability of legacy sediments. The distribution of these sediments within the LPR is presented in Chapter 5, together with a classification of these sediments in the form of four groups, distinguishing between sedimentation rates, i.e. historical bathymetric change, level of contaminant concentration and riverbed features.

A brief summary of the work in the chapters 2 -5 is given in Chapter 6.

2.0 BACKGROUND INFORMATION – SUMMARY OF SYSTEM UNDERSTANDING

This section summarizes the most important background information (system understanding) necessary for the interpretation of the bathymetrical data. Figure 2-1 presents the fresh water river discharge measured at Little Falls, showing that the last five years are characterized by relatively high peaks in river flow as compared to the earlier years of the period under consideration. The long-term median flow measures about 600 cfs and the average flow about 1100 cfs.

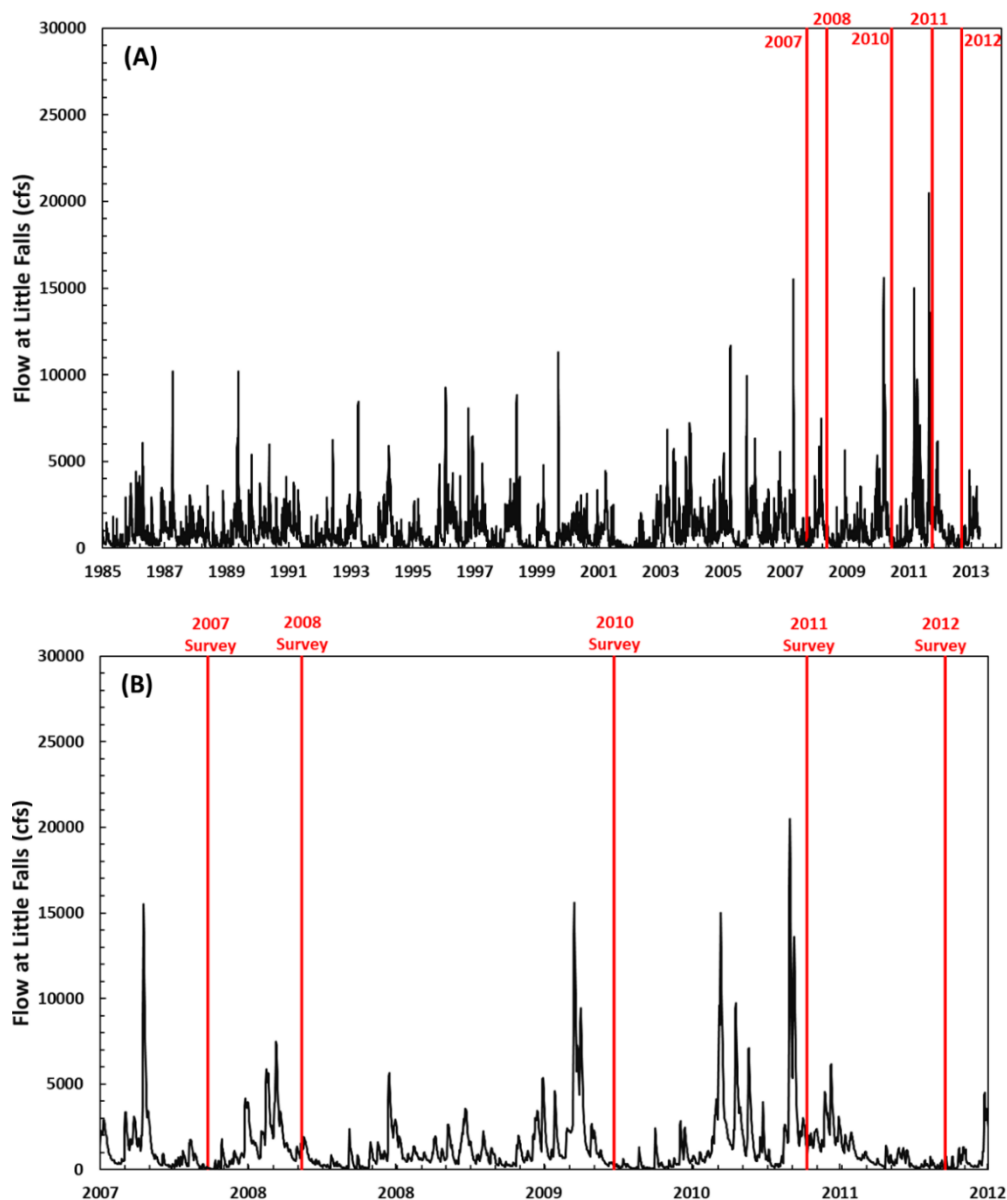


Figure 2-1: LPR river discharge at Little Falls during (A) 1985-2013, and (B) 2007-2012, including times of multi-beam surveys.

Figure 2-1 also shows the time and duration of the multi-beam surveys, where it is noted that the 2008 and 2012 surveys have been executed after prolonged period of low river flow, whereas the other multi-beam surveys were carried out shortly after a high-discharge event. The significance of this observation is further discussed in Chapter 4.0.

Figure 2-2 shows the sediment load over Dundee Dam. Comparison with Figure 2-1 shows that data for run-offs larger than 10,000 cfs are not available, and have to be obtained from extrapolation. Moreover, no data is available on the composition of the sediments brought into the LPR at high discharge. However, from the analyses in Chapter 4, it must be concluded that part of these sediments comprise sand.

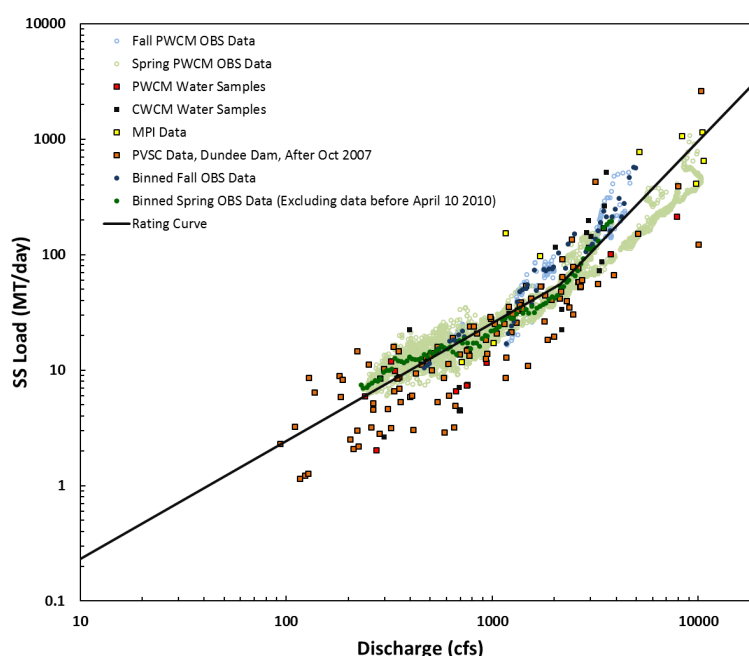


Figure 2-2: Sediment load over Dundee Dam located around RM 18.

Estuarine circulation is an important agent in the fine sediment dynamics in estuaries – this circulation is induced by longitudinal salinity gradients, and is also known as gravitational circulation. Therefore, the salinity distribution is an important parameter in the LPR. There is insufficient data to establish the salinity distribution in the LPR as a function of tidal range and river run-off. Therefore, this relation was obtained with the numerical model of the LPR, calibrated for a variety of conditions (HydroQual 2008). The results are presented in Figure 2-3, and shows that salinity intrusion is a function of river flow, with the extent of salinity intrusion decreasing with increasing river flow. At river flows beyond ~6000 cfs, all salt water is flushed out of the river, i.e. down-estuary of RM 1 beyond which the river widens rapidly. At the average river flow of about 1100 cfs, salt water is expected to penetrate up to and beyond about RM 5, whereas at very low river flow, salt water penetrates well into the upper reaches of the river (e.g. RM 10).

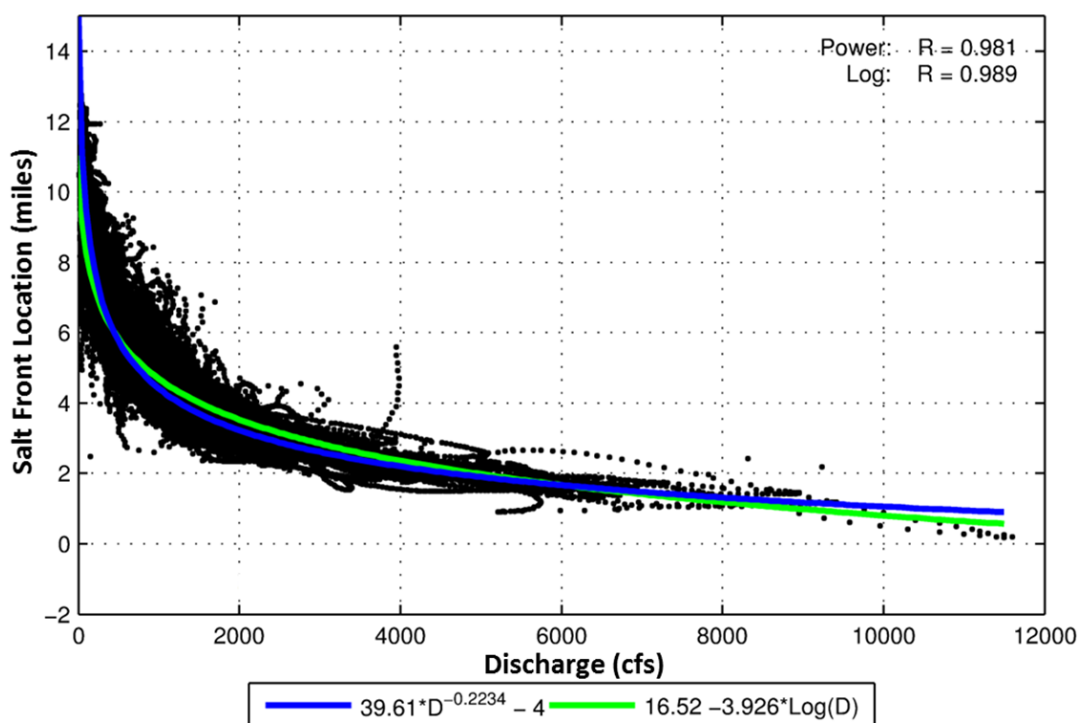


Figure 2-3: Computed variation in salinity intrusion as function of river flow at Dundee Dam. Salt front for purposes of this illustration is defined as the upstream-most extent of the near-bottom 2 ppt isohaline.

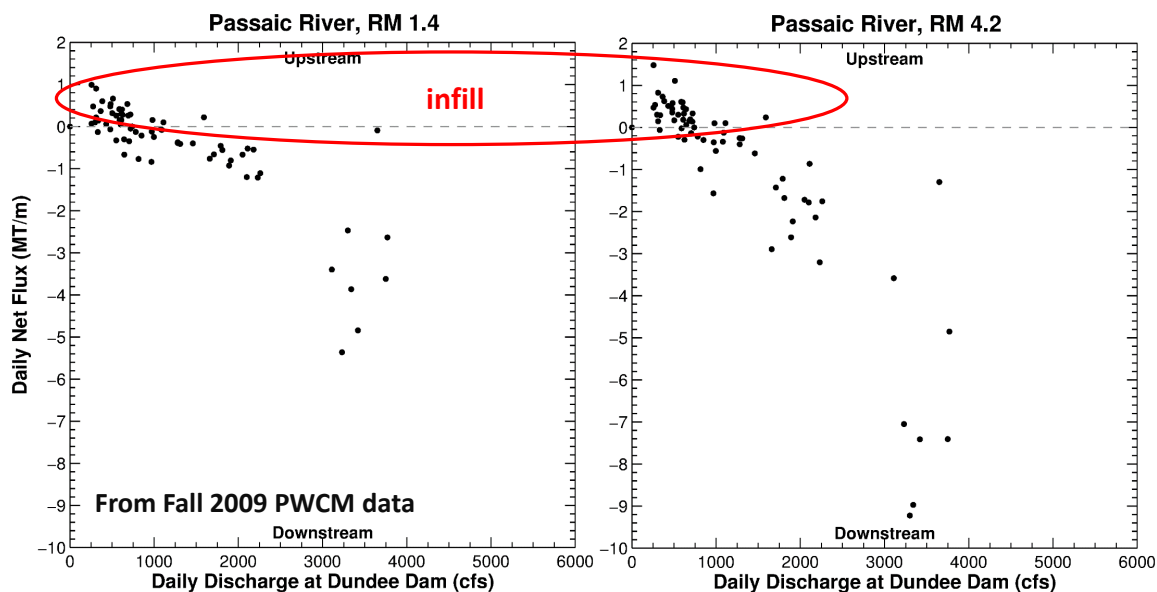


Figure 2-4: Fine sediment fluxes measured in LPR at RM 1.4 and RM 4.2; positive flux is up-estuary – transition in flux direction at $Q_{\text{river}} = 750$ cfs.

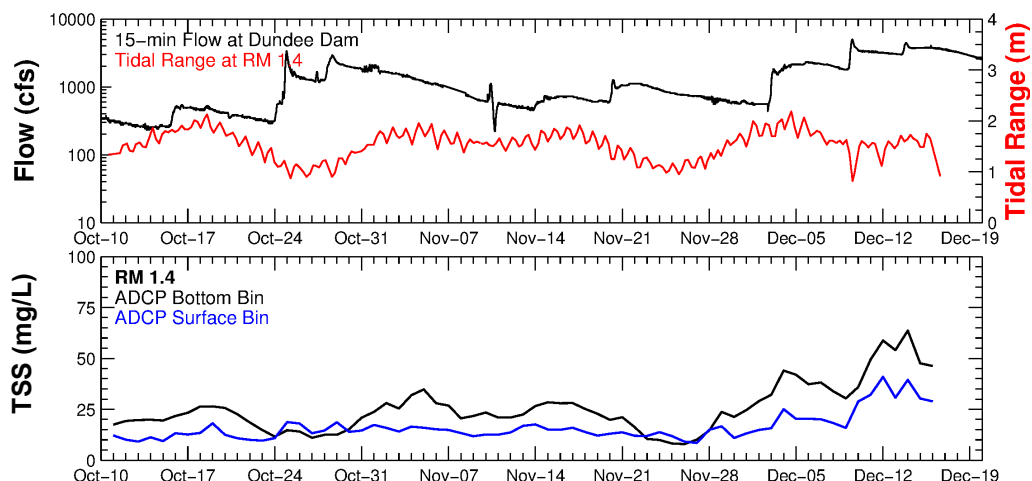


Figure 2-5: Time series of measured daily-average TSS-(lower panel; in mg/L) values at RM 1.4 (from Fall 2009 PWCM).

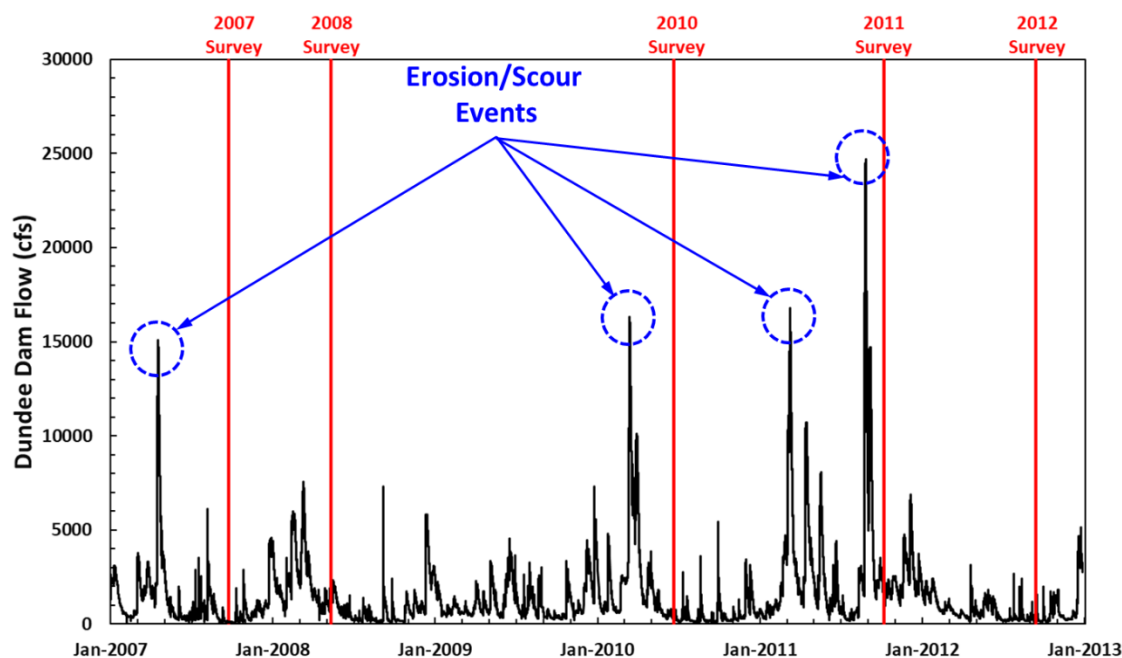


Figure 2-6: Hydrograph and scour events in LPR.

The (daily mean) fine sediment fluxes measured at RM 1.4 and RM 4.2 during the Fall 2009 monitoring program are presented in Figure 2-4. Net down-estuary transport at RM 1.4 is found to occur at river flows between 2000 – 3000 cfs, and net up-estuary transport at lower river flows. Note that salt water still penetrates the river slightly beyond RM 1.4, hence fine sediments may continue accumulating in the lower miles of the LPR.

Figure 2-5 shows a two-month record of the daily-average TSS values measured at RM 1.4 during the Fall 2009 monitoring program, in conjunction with the river flow and tidal

range. During the first 7 weeks, when river flow is less than ~2000 cfs (except for two short-lived spikes in flow during the week of October 24), both surface and bottom TSS is seen to vary over a range of ~10-35 mg/L. The variability during this period is primarily in response to the spring-neap variability in tidal range, with higher TSS during spring and vice versa during neap. TSS tends to higher values only following the high river-flows starting at the beginning of December. Similar trends were noted at other locations up-estuary. These records suggest that elevated TSS-values are to be expected at river flows beyond 2000-3000 cfs only. A similar threshold was also found from other observations (at RM 1.4 using the data collected by Sommerfield and Chant [2010] in 2008-2009; see Section 2.3.5 in the main body of this report).

The general observations of elevated TSS concentrations and net export of sediment, both at high river flows, are in agreement with an analysis of the multi-beam surveys described in Section 4.0. Briefly, as seen in Figure 2-6, over a 5-year period from 2007 through 2012, a total of five multi-beam bathymetric surveys were performed in the LPRSA encompassing a range of flow conditions from extreme low river-flows to extreme high river-flows such as Hurricane Irene (a 1 in 90-year event). Review of bathymetric differencing (using consecutive surveys) showed that on a river-wide aggregate basis, the periods between the 2007-2008 and 2011-2012 surveys were net depositional, and the periods between the 2008-2010, and 2010-2011 surveys were net erosional. Examination of these bathymetric differences relative to the river flows between individual surveys, shows that both depositional periods did not include any river flows in excess of 6000-7000 cfs, whereas both erosional periods correspond to flows in excess of 6000-7000 cfs, thus leading to the conclusion that below 6000-7000 cfs no or little scour/erosion takes place in the river. In other words, river flows higher than 6000-7000 cfs will cause erosion, and therefore elevated TSS and net export of sediment from the river, a general trend similar to the analysis of TSS concentrations and net suspended sediment fluxes.

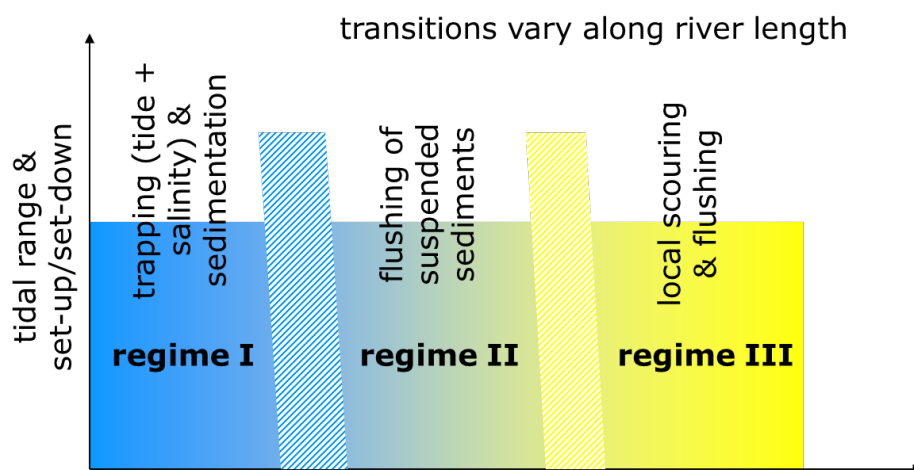


Figure 2-7: Hydraulic regimes in Lower Passaic River.

This conceptual picture is summarized in Figure 2-7, showing that the fine sediment dynamics in the LPR are characterized by three regimes:

Regime I (up to 750-1000 cfs): Net infill with fine sediments, induced by tidal asymmetry and estuarine circulation. On shorter time scales (few tidal cycles), the fines in the water column are in equilibrium with those within a fluff layer on the river bed. Sediments from this fluff layer are slowly “entrained” into the bed by consolidation processes.

Regime II (between about 750-1000 cfs and 7000 cfs): Flushing of the fines in the water column and loose sediments on the bed (fluff layer). TSS concentrations in the water column are still moderate (typical values of 50 – 100 mg/L).

Regime III (beyond about 7000 cfs): (Part of) the consolidated river bed is subject to erosion and local scour; TSS concentrations in the river increase rapidly, depth-averaged values in the lower reaches of the river up to about 200 mg/L have been measured.

3.0 HISTORICAL DEVELOPMENT AND DATA

3.1 History of dredging in the Lower Passaic River

A comprehensive description of the dredging history LPR is presented in USACE (2010). The report describes the federal navigation channel and its different segments with authorized depths. Table 1 of USACE (2010) presents a comprehensive list of maintenance dredging history in the LPR by reach. A review of the available dredging construction charts as well as condition surveys carried out by the USACE in the 20th century (Hydrographic Survey sheets in microfiche from the USACE NY district, obtained in scanned (TIF format) from Tierra Solutions via their consultant Arcadis) indicated that aforementioned Table 1 in USACE (2010) provides a very detail description of the various dredging events. The only exception is the 1976 dredging event, which based on the dredging construction charts covers a larger area than the RM 9.0 to RM 10.2 described in the Table. Figure 3-1 shows the dates of the last dredging events by location in the river mile. It can be observed that some areas were dredged back in 1932, and they have not been maintained since. The last maintenance dredging event took place in 1983 covering the channel segment with an authorized depth of 30 ft in the lower 2 miles of the LPRSA.

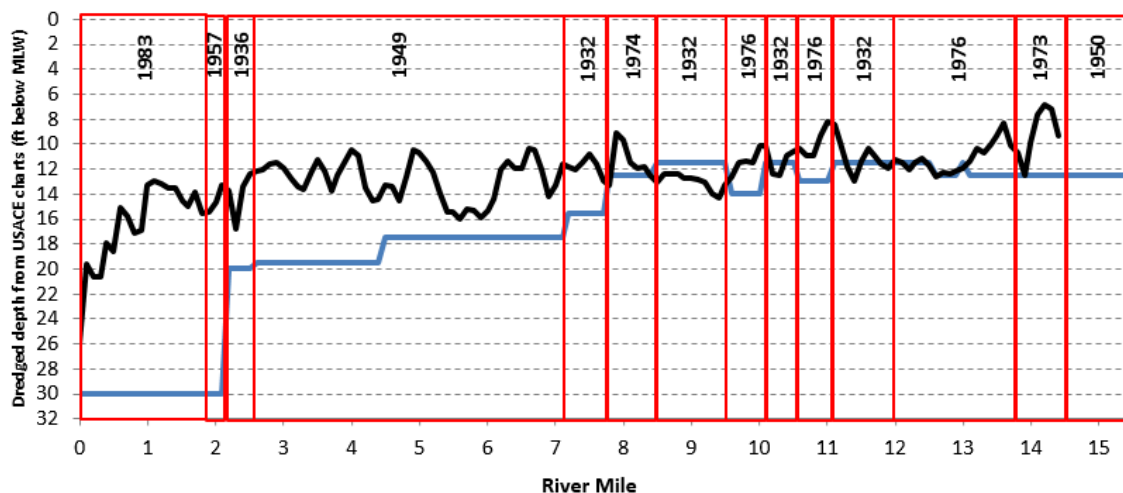


Figure 3-1: Last dredging events in the LPR by location (black line represents the 2007 average cross section depths at the navigation channel and blue line the design dredge depths)

3.2 Analysis of major Historical Infilling

An analysis of the post dredged infill rates was carried out using available historical bathymetric information. Two sources of data were available:

1. Hydrographic Survey sheets in microfiche from the USACE NY district, obtained in scanned (TIF format) from Tierra Solutions via their consultant Arcadis.

2. Prof. Bill Hansen at Worcester State College provided the CPG via email (4/21/2010) with the point shape files of the years 1949, 1966 and 1976 that he has used in his research funded by the Hudson River Foundation. These files were also received by Eugenia Naranjo at EPA, who was the original recipient of the email. The point files contained the digitized depth values obtained from rectified scanned surveys to NJDEP high resolution Ortho photos and Digital Channel data. The horizontal datum of the shape file is NJ State Plane NAD83 in feet, and the depth values are referred to the hydrographic survey datum (MLW)

In addition, the hydrographic survey sheets were rectified to carry out a QA/QC of the positioning of the depth values for the 1949, 1966 and 1976 surveys obtained by Prof. Hansen. Additional pre- and post-dredge bathymetries for 1983 from RM -0.5 to RM 1.4, were created by rectifying the hydrographic survey sheets and digitizing the available depth points. Finally, the original shape file provided by Prof. Hansen for 1966 was corrected due to potential errors in the rectification process. Rectification to the navigation channel alignment was selected over the original rectification to other available locations such as bridges or abutments. Table 3-1 presents the final bathymetries used for the analysis and the extent of the files. As observed from the table two additional more recent bathymetric surveys (1995 and 2007) were also used to estimate more recent sedimentation rates in the lower miles of the LPR. The vertical reference of all these files is the original MLW from each of the Hydrographic Surveys.

Table 3-1: Surveys used in the analysis and their extent.

Date	Chart File No.	Survey Extent
1949	497 5,6; 504	RM (2.5 – 6.8)
1966	675 series	RM (2.3 – 7.8)
1976	710 series	RM (0.75 – 4.35)
March 1983	761	RM (-0.5 – 1.4)
August 1983	768	RM (-0.5 – 0.5)
September 1983	770	RM (0.5 – 1.4)
1995	Tierra Solutions	RM (0.5 – 8.15)
2007	CPG	RM(-0.3 – 14.4)

3.2.1 Analysis of uncertainty

Although the uncertainty in the depth values of the historical bathymetries cannot be quantified, it is probably quite large due to the number of assumptions and transformations that were required to have these data available in a usable format, such as ArcGIS format. Following is a list of potential sources of uncertainty in these data:

- Errors associated with the survey – The uncertainty associated with data collected by surveys conducted 30 to 70 years ago is much larger than that associated to

recent bathymetric survey technology, both in positioning as well as in the value of the water depth.

- Positioning errors associated with the scanning process – Due to the difference in the chart dimensions by stretching or squeezing of the paper chart when scanned.
- Errors in the rectification process – The rectification process produces errors in the horizontal positioning of the depth points.
- Interpretation of the depth values – Depth values are hand written in the hydrographic surveys and are difficult to read due to the quality of the scanned maps. In addition, the depth values are in feet with a single decimal value.

Figure 3-2 depicts an example of the historical survey data. As seen in the figure, the 1966 and 1976 surveys do not follow the same transects, whereas the 1949 was not collected along transects but rather using soundings covering the complete river area.



Figure 3-2: Example of transects from 1949, 1966 and 1979 surveys

As a result, these historic bathymetry data should generally be used to assess broad patterns in the LPR bathymetry and used with caution when evaluating changes at a smaller scale.

3.3 Evaluation of historical sedimentation rates

Table 3-2 presents the results of the volume change calculations using the derived surfaces from each of the surveys considered. Historical surveys were compared using the common extent of the two surveys to be compared. For example, the 1949 and 1966 surveys have the area between RM 2.5 and 6.8 in common, while the 1976 and 1966 surveys have a much smaller common area between RM 2.35 and 4.35. The common area for the three surveys is between RM 2.5 and 4.35. The estimated area-average annual rate of deposition is very similar between the periods 1949-1966 and 1966-1979 since the river was still trying to recover from the large dredge event of 1949 in this area. The estimated area-average annual rate of deposition was in the order of 0.22 to 0.25 feet/year.

The estimated area average annual rate of deposition following the dredge event of 1983 in the lower 2 miles was estimated to be in the order of 0.56 feet/year between 1983 and 1995 in the segment between RM 0.5 and 1.4. The volume that accumulated during this 12-year period is estimated to be larger than the volume dredged in 1983. In the following 12 years between 1995 and 2007, the sedimentation rate is lower, in the order of 0.33 feet/year, as expected as the area moves towards approaching an equilibrium depth. The additional bathymetric analysis of the lower miles presented in Section 4.6 as part of the navigation scour analysis indicates significant sedimentation (up to 20 ft) in the area between RM 0.5 and RM 1.4 after the 1983 dredging event. After 2007, changes are much smaller responding more to the cyclical conditions of accumulation during storm events and erosion due to navigation scour during normal conditions.

Table 3-2: Results of change in volume and average rate of deposition from the comparison of hydrographic surveys.

Date	Extent of comparison	Change in Volume (ft ³)	Average rate of deposition (ft/yr)
1966 - 1949	RM (2.5 – 6.8)	24,500,000	0.22
1976 - 1966	RM (2.35-4.35)	9,500,000	0.25
1966 - 1949	RM (2.5-4.35)	13,700,000	0.24
1976 - 1966	RM (2.5-4.35)	8,300,000	0.25
August 1983 – March 1983	RM (-0.5 – 0.5)	Volume dredged 3,500,000	
September 1983– March 1983	RM (0.5 – 1.4)	Volume dredged 11,700,000	
1995 – September 1983	RM (0.5 – 1.4)	15,000,000	0.56
2007 - 1995	RM (0.5 - 1.4)	8,800,000	0.33

The estimated area average annual sedimentation rate calculated from the analysis of the historical bathymetries has been compared to the annual sedimentation rates obtained from the sediment cores collected in the Lower Passaic River. As observed from Figure 3-3 values obtained from the bathymetric comparison are very similar to the long term averaged net sedimentation rates obtained from Cs137 and Pb210 profiles, considering the uncertainty associated with the analysis.

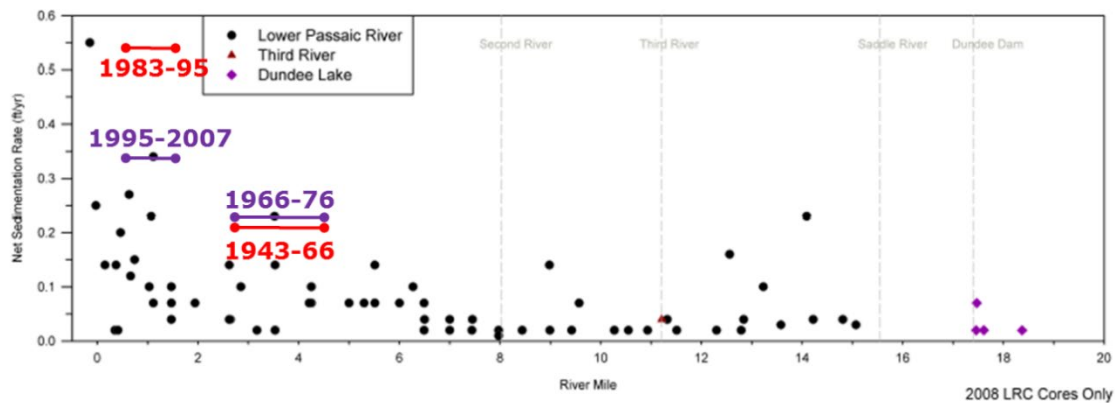


Figure 3-3: Comparison of long-term averaged net sedimentation rate from Cs137 and Pb210 profiles (shown with circles) and estimated from hydrographic surveys (shown using red and purple lines).

3.4 Other anthropogenic changes in the Lower Passaic River

Although the area average sedimentation rates in the in the Lower Passaic River are highly correlated with the dredging history in the river, especially of the navigation channel, local sedimentation rates might be very different from these averages since they depend on the local conditions. Many construction projects that have been done in the 20th century have also affected the river morphology. Some of the most relevant are mentioned below, though detail analysis of the history of these and other project might be necessary to understand the detailed morphological changes in the river at small scales.

- Bridges constructed and removed – For example, historical aerial photographs indicate that a bridge at around RM 5 was removed in the early 1980's.
- Shoreline hardening – Many shorelines along the river has been modified and hardened, in some cases modifying the final location of the shoreline.
- Barges placed and removed in RM 7.5 – Historical aerial photographs show that barges were placed in the late 50's early 60's at the shoal in RM 7.5 promoting the accumulation of sediment. From the late 1990's to early 2000's the barges have almost disappear.
- Construction of Route 21 along the west bank of the LPR in the 1950's and 1960's also affected the location of the west bank in several areas of the LPR.

- Realignment of main river channel at RM 13-14 as part of the Route 21 construction in this area.

4.0 ANALYSIS OF BATHYMETRICAL SURVEYS

4.1 Introduction

In this section, the results of five multi-beam bathymetric surveys are analyzed. The exact dates of these surveys are given in Table 4-1. The data have been uploaded in OpenEarth, a MATLAB-based database superimposed on Google-Earth satellite images. The OpenEarth database allows for a quick, yet detailed analysis of bed level changes over the various survey years, including information on sonar targets and the sediment's chemical data.

Table 4-1: Dates of multi-beam surveys and occurrence of >15,000 cfs river flows

Year survey & floods (>15,000 cfs)	Start date	End date	days betw. surveys	days between survey & flood
2007 flood	04/18/2007			
2007 survey	09/10/2007	09/24/2007		145
2008 survey	11/20/2008	12/5/2008	438	255 ³⁾
2010 flood	03/16/2010			
2010 survey	06/08/2010	06/23/2010	565	84
2011 flood	03/12/2011			
2011 Irene	08/20/2011			
2011 (post Irene) ¹⁾	10/04/2011	11/10/2011	495	35
2012 survey ²⁾	08/29/2012	09/17/2012	290	

¹⁾ In July 2011, also a partial survey between RM 10 and 12.2 was carried out – results are not discussed in this report, as this partial information does not contribute to the overall picture.

²⁾ Single beam: 13-29 September.

³⁾ 438 days after 2007 survey; 255 days after March 2008 flood (7000 cfs, Figure 2-1)

The analysis distinguishes between three spatial scales, e.g. the macro-scale, covering the entire river, the meso-scale, covering morphodynamic elements in the river, such as river bends, and the micro-scale, focusing on local scour events. It is emphasized that a further down-scaling of the analysis may yield spurious results, owing to the inherent limited accuracy of bathymetrical data.

4.2 Comparison of Bathymetries – 2008 Correction

The analysis of the bathymetrical changes in response to river floods requires knowledge of the accuracy of measured bed levels during the individual surveys. A brief general discussion on the accuracy of bathymetrical surveys is presented in Appendix A of the current document (Lower Passaic River RI/FS, Appendix M - Attachment B); suggesting that considering a random (stochastic) in the order of 0.3 ft in a specific survey is good practice. Bathymetrical data are checked on mutual consistency with emphasis on vertical positioning. For this purpose, transects along the river are defined which intersect with stable bed level features. These stable bed features are identified in four segments of the LPR. Furthermore, the presence of car wrecks and sonar targets allow for a comparison of

the bed levels at some other locations for the 2007, 2008, 2010 and 2011 (post-Irene) surveys. Appendix B of the current document (Attachment B) includes a detailed description of this analysis.

Table 4-2: Performance tests of multi beam surveys (calibration).

	2007 [ft]	2008 [ft]	2010 [ft]	2011 [ft]	Criteria (soft depth, depths 15 to 40 ft) [ft]
Maximum outlier	0.5	1.05	0.76	0.78	1.0
Mean bias	-0.12	-0.24	-0.07	-0.05	±0.2
Elevation accuracy	0.55	1.07	0.44	0.41	± 1

Table 4-3: Average difference between 2008 and 2007; and 2010 and 2011-post Irene bed levels for segments A, B, C and D, car wrecks and sonar targets.

Item	2008-2007 [ft]	2008-2010 [ft]	2008-2011 [ft]	2011-2010 [ft]
Segment A ¹⁾	-0.35			
Segment B	-0.24	-0.28	-0.21	-0.07
Segment C	-0.24	-0.20	-0.15	-0.05
Cars	-0.26	-0.20	+0.03	-0.23
Sonar	-0.27	-0.14	-0.13	-0.01
Segment D ¹⁾	≈ -0.3			
Average	-0.3	-0.2	-0.1	-0.1

1) Based on 1x1 ft² resolution of bathymetric grid.

The accuracy of the 2008 survey has been subject of discussion, as the calibration for this survey was considerably less accurate than for the other surveys. The accuracy of the 2007 survey calibration was a bit less than the 2010 and 2011 (post-Irene) surveys as well, but better than the 2008 survey calibration. The results of the calibration are presented in Table 4-2. The results from the detailed analyses described in Appendix B of the current document are summarized in Table 4-3 and presented graphically in Figure 4-1. This analysis confirms that the 2008 bathymetry is systematically low compared to the 2007 and 2010 bathymetries, i.e. 0.2 to 0.3 ft too low. Furthermore, the 2011 bathymetry appears about 0.1 ft lower than the 2007 and 2010 bathymetries. In the latter case differences are actually quite small, and in the range of the specified accuracy of the measurements (see the ‘mean bias’ parameter in Table 4-3); therefore the 2011 data were not corrected.

Since the analysis presented here involves bathymetric differences, any relative correction of the various bathymetries is possible in theory. However, Table 4-2 suggests that the 2008 survey is the most inaccurate. It is therefore reasonable to only correct the 2008 bathymetry. Therefore, only the 2008 bathymetry was corrected by adding systematically 0.3 feet to the observed bed levels. Moreover, the analyses presented in Appendix B of the current document shows that this 0.3 ft correction should be applied over the entire river, as all sections of the river reveal more or less the same bias. It can be shown (e.g. Figure 4-2) that a 0.3 ft correction of the 2008 data would imply a net infill of the river in the

2007-2008 period, in conjunction with net erosion in the 2008-2010 period, which is in line with the river response expected on the basis of the hydrograph (see Figure 2-1 and arguments in Chapter 2.0). If no correction would be applied, the bathymetrical data would suggest net erosion in the 2007-2008 period and net sedimentation in the 2008-2010 period, which is highly unlikely, given the hydrograph (e.g. Figure 2-1). A 0.6 ft correction of the 2008 data would imply that in the period 2010-2008 more erosion would have occurred than in the period 2011-2010, which is also highly unlikely, as the latter includes the effects of Hurricane Irene.

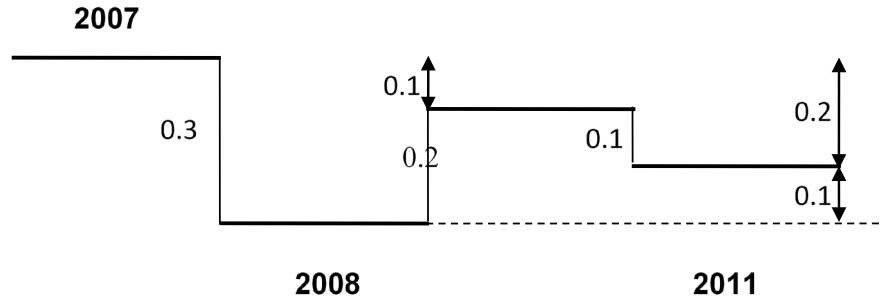


Figure 4-1: Average differences [ft] between multi beam measurements for 2007, 2008, 2010 and 2011 (post-Irene). Based on average values in Table 4-3.

The remainder of the analyses only include the corrected 2008 bathymetry. Note that the applied corrections amount to less than 1% of the maximum water depth in the river. The bathymetric differencing analyses presented in the remainder of this report are based on a 5×5 ft² resolution grid.

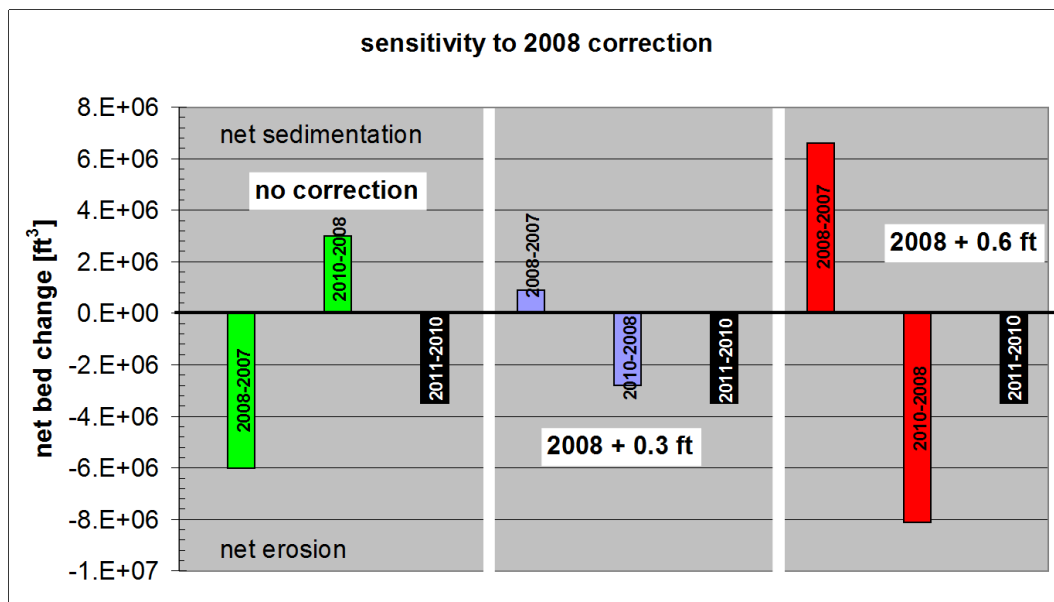


Figure 4-2: Sensitivity of LPR overall sediment balance to 2008 correction.

4.3 Large Scale Behavior

First, the large-scale response of the LPR, as deduced from the multi-beam surveys is analyzed. Figure 4-3 presents this large-scale response. Each sub-plot represents the difference between two subsequent multi-beam bathymetries, integrated along the entire LPR (e.g. from RM 14 to RM 0), with a division at RM 2, where the river widens rapidly.

Figure 4-3 shows that the upper 12 miles of the LPR experienced net accretion in the periods 2007-2008 and 2011-2012, whereas in the lower two miles, erosion took place. During the periods 2008-2010 and 2010-2011 (post-Irene), the opposite trends were found, e.g. erosion in the upper miles of the river, and sedimentation in the lower miles of the LPR. The response of the river over these periods is in line with the hydrograph in Figure 2-1 showing that the 2007-2008 and 2011-2012 periods are characterized by small to moderated river flows, whereas within the other two periods substantial river floods such as Hurricane Irene occurred.

It should be noted that the multi-beam survey in the river mouth did not cover the entire width of the river, hence one may not draw too detailed conclusions with respect to the sediment balance in the LPR from these graphs. Yet, Figure 4-3 suggests that at least part of the sediments eroded in the 2007-2008 and 2011-2012 periods from RM 14-2 are deposited in the lower two miles, whereas at least part of the sediments deposited in the 2008-2010 and 2010-2011 periods in RM 14-2 originate from the two lower miles. This speculation is further elaborated upon in Section 4.4 and 4.5.

Figure 4-4 shows TSS values measured during the March 2010 flood, revealing depth-averaged concentrations of about 200 mg/L, with near-bottom values of about 500 mg/L at the mouth of the river.

Figure 4-3 suggests net erosion between 2008 and 2010 of about $3 \cdot 10^6$ ft³. It is assumed that this entire bed level change is attributed to the March 2010 flood (see Figure 2-1 hydrograph for justification). Since the data do not indicate when most of the erosion occurred, the following two cases are evaluated: 1) the entire erosion took place during the first flood period of about 8 days, or 2) the entire erosion took place during the entire 23 days of river flows larger than 6,000 cfs. Thus, the equivalent TSS can be determined by dividing the measured erosion volume (e.g. bed level changes) by the total amount of fresh water discharged during these 8 or 23 days, while assuming a bulk density of the bed of either 75 or 87 lb/ft³. This assessment yields the TSS values presented in Table 4-4.

During the March 2010 flood, sediments were also imported from Dundee Dam. Figure 2-2 shows that no data are available for flow rates of 16,000 cfs (450 m³/s), and the rating curve has therefore to be extrapolated, yielding an import from over Dundee Dam between about 50 and 150 mg/L, depending on the method of extrapolation. Unfortunately, the composition of the imported sediments from over Dundee Dam is unknown. Finally, it is

noted that the 2010 survey was executed about three months after the March 2010 flow event. Therefore, some sediments may have been imported into the LPR during the intervening period after the March 2010 flow event. However, the volume involved is unknown.

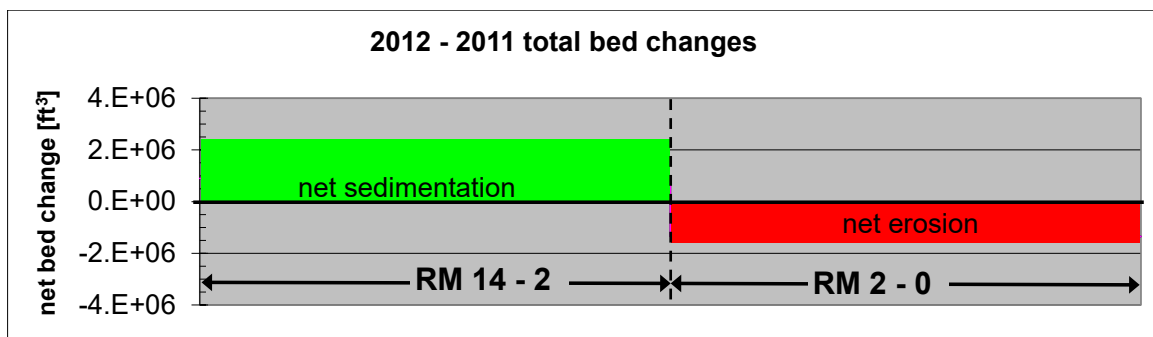
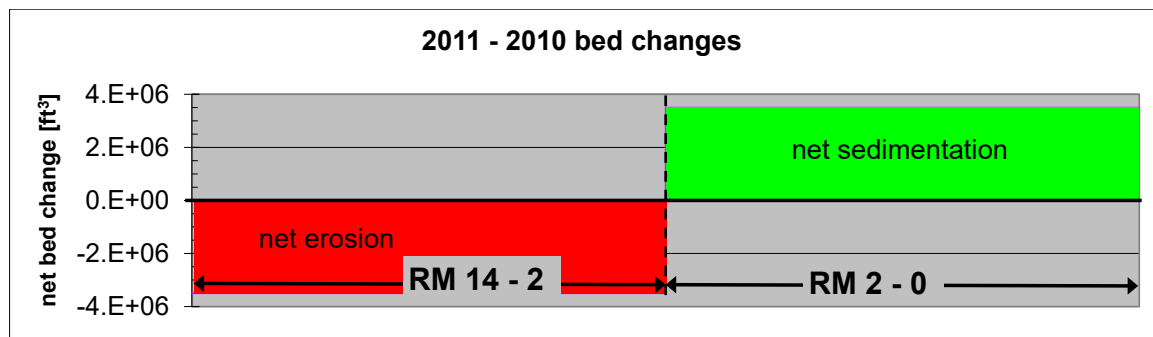
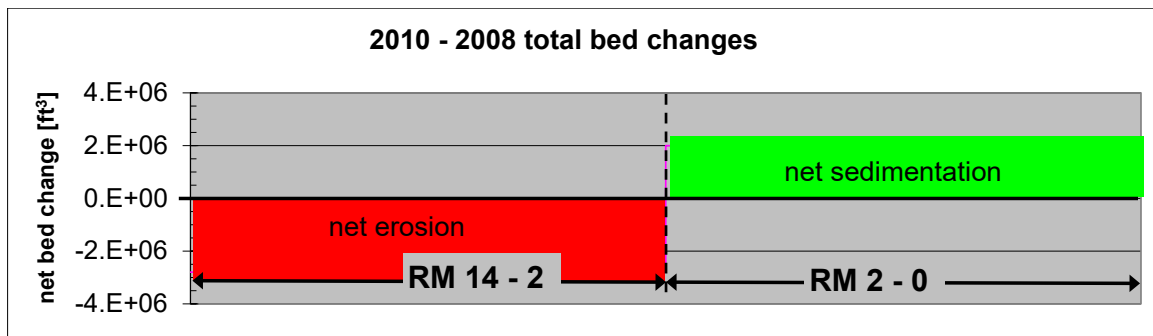
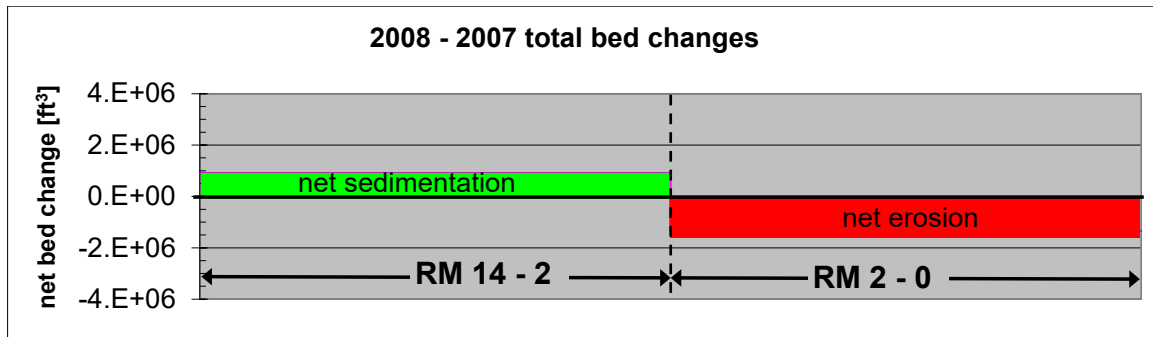


Figure 4-3: Bed level changes cumulative over RM 14-2 and RM 2-0 from the five multi-beam surveys.

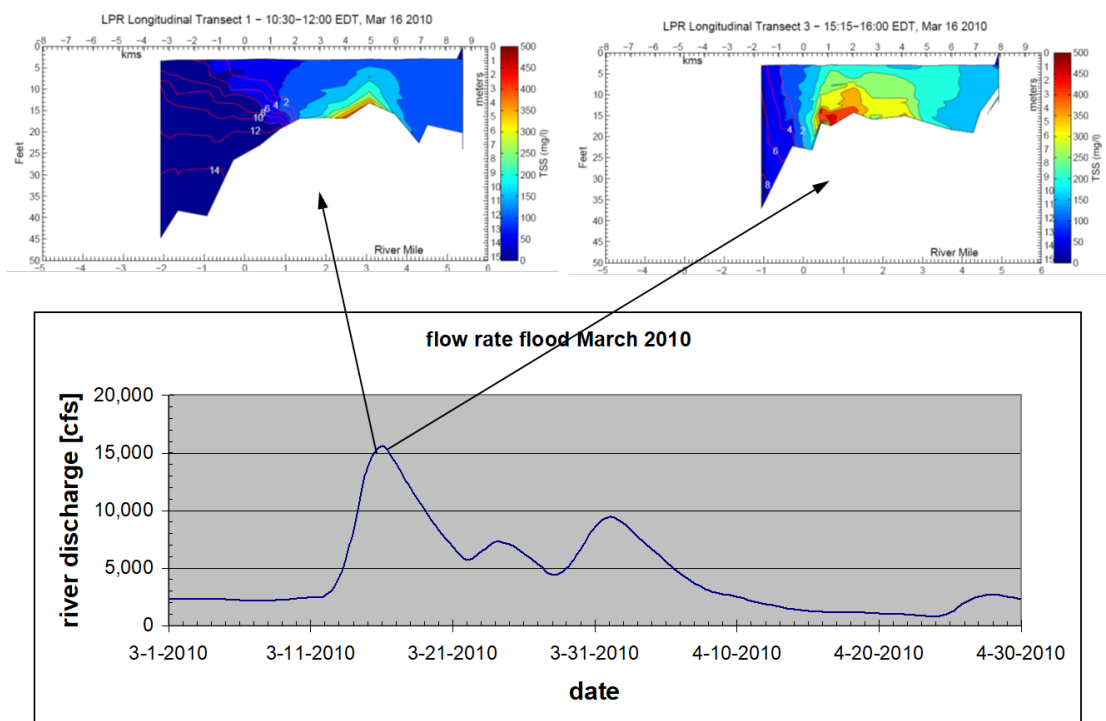


Figure 4-4: TSS concentrations measured during the March 2010 flood and March 2010 hydrograph.

Table 4-4: Assessment of characteristic TSS values during March 2010 flood, based on a net erosion (bed level changes) of $3 \cdot 10^6$ ft³.

	ρ_{bulk}		
	75	87	lb/ft ³
8 days flood	123	261	mg/L
23 days flood	51	108	mg/L

In spite of these inaccuracies and uncertainties, the TSS value of about 200 mg/L measured in March 2010 (Figure 4-3) matches the characteristic TSS values of 100 – 200 mg/L, assessed in Table 4-4, accounting for a Dundee Dam import of 50 – 150 mg/L. Therefore, it was concluded that measured TSS values and bathymetrical response are qualitatively consistent. Moreover, the March 2010 flood most likely was the major erosion event in the period 2008-2010, shaping the difference in bathymetries measured by the multi-beam surveys.

4.4 Meso-Scale Behavior

Next, the changes in bathymetry at the meso-scale are discussed. Bathymetrical differences are integrated in the down-estuary direction starting at Dundee Dam for this purpose. The results are presented in Figure 4-5 through Figure 4-7; as discussed, the 2008 bathymetrical data have been raised by 0.3 ft over the entire river. This integration can be interpreted as net transports of sediment. For instance, the red curve in Figure 4-5 (2010 – 2008) depicts a positive slope down-estuary; i.e. the transport in down-estuary direction increases, owing to the net erosion between the 2008 and 2010 surveys. The first part of the analysis in this section assumes zero net transport at Dundee Dam.

Figure 4-5 shows that in between RM 14 and RM 2 (varies a bit between RM 1 and RM 3) net down-estuary transport (hence, net erosion) is observed for the survey periods 2008-2010 and 2010-2011 (post-Irene), whereas net up-estuary transport in the same river stretch is observed for the survey periods 2007-2008 and 2011-2012. These observations are in agreement with the conceptual picture of Section 2.

In the lower 1 – 3 miles (around RM 2 to the mouth of the LPR), Figure 4-5 shows the opposite trend, i.e. up-estuary transport when the major part of the river depicts down-estuary transport (2008-2010 and 2010-2011), and vice versa for the other periods. This picture suggests an exchange of sediments between the lower 1 – 3 miles and the rest of the river. However, these trends must be taken with caution, as the survey in the lower miles did not cover the entire river cross section, and it is not known if the same sediments are involved.

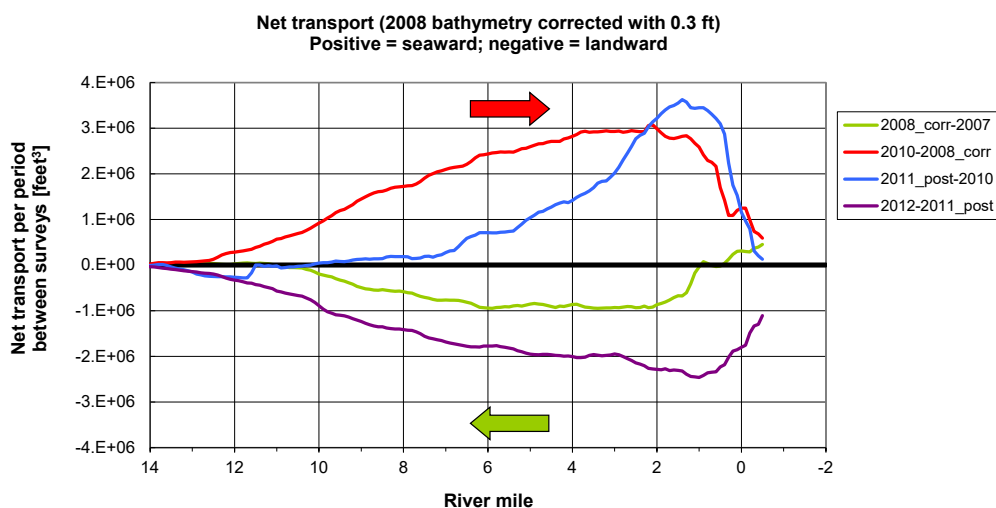


Figure 4-5: Net sediment transport in between periods of multi-beam surveys; positive slope of curves (e.g. red line over RM 14-4) implies down-estuary transport, a negative slope (e.g. purple line over RM 14-1) yields up-estuary transport.

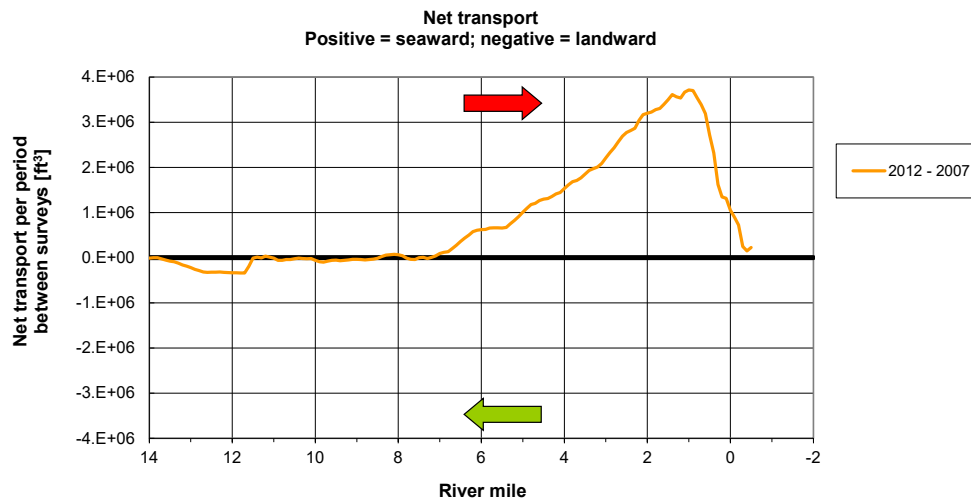


Figure 4-6: Net sediment transport between September 2007 and September 2012 (including three >16000 cfs events).

Figure 4-6 presents the net sediment transport over the entire survey period, i.e. 2007 – 2012, showing that net transports in the upper 7 miles is almost zero for that period, whereas in the stretch RM 7 – RM 1, net erosion took place, and in the lower miles, net sedimentation. If this erosion would be homogeneously distributed over the riverbed between RM 7 and RM 1 (yielding a projected area of about $1.5 \cdot 10^7 \text{ ft}^2$), the $3.7 \cdot 10^6 \text{ ft}^3$ would be the equivalent of 0.2 ft lowering of the entire river between RM 7 and RM 1. Since during the 2007-2012 periods more numerous and larger flood events (in terms of river flow) occurred than in the decades before, this 0.2 ft yields a measure of the variability of the mean bed level around the morphodynamic equilibrium towards which the LPR is developing. Note that this river stretch filled in on average by about 0.07 ft in the period 2011-2012, e.g. Figure 4-5.

This variation around the morphodynamic equilibrium is further illustrated in Figure 4-7, showing net variations smaller than 0.5 ft in general. The spike around RM 11.5 in the 2011-2010 curve is to be attributed to engineering works on a bridge at that location, blocking a major part of the river.

Next, the various bathymetrical responses are discussed sequentially. Three months prior to the 2007 survey, a 16,000 cfs flood occurred. From that survey, up to the 2008 survey, no major flood was recorded. Figure 4-5 shows up-estuary transport between RM 11 and RM 2. As no net bed level changes occurred over RM 14 – RM 11, the infill in the 2007-2008 period must have originated from:

- Input of sediments from over Dundee Dam, and/or
- Up-estuary transport of sediments deposited in the LPR mouth, and/or
- Up-estuary transport of sediments from Newark Bay (and beyond).

It is not possible to quantify either of these three sources quantitatively, as detailed data are not available. However, Figure 4-8 suggests that the Dundee Dam sediment input is quantitatively insufficient to explain the whole infill. Moreover, this input likely contains a considerable amount of very fine material (wash load), which does not contribute to bed level changes in the LPR.

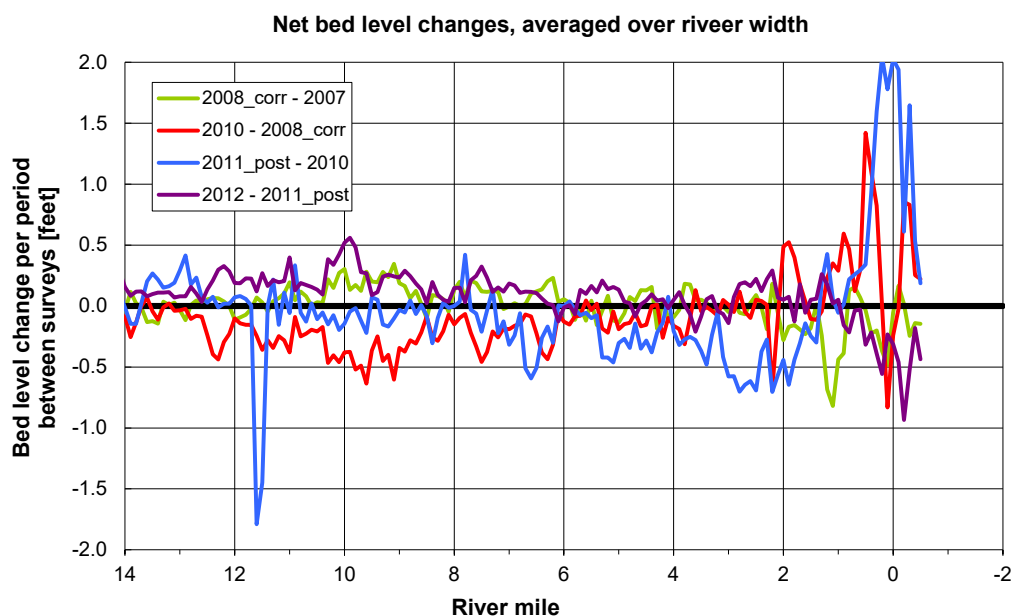


Figure 4-7: Short term net bed level changes, averaged over river width.

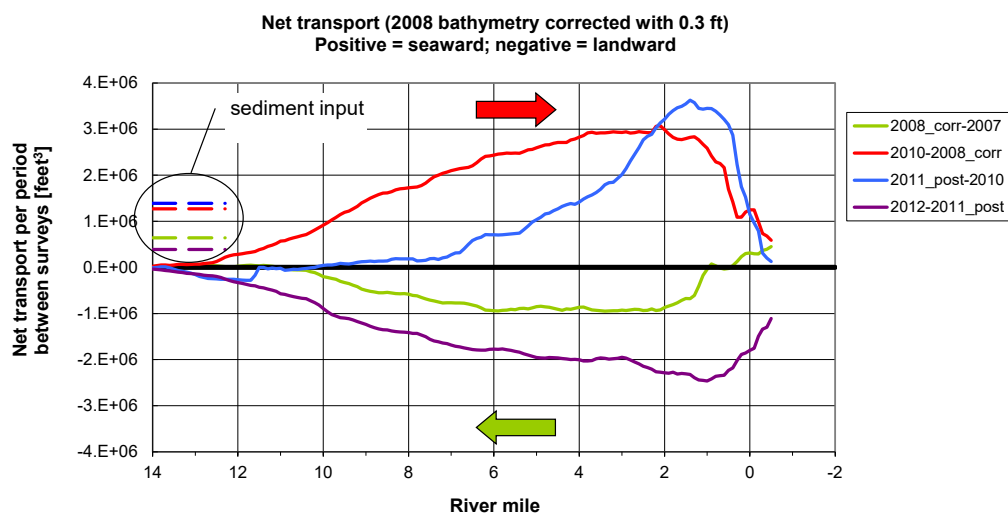


Figure 4-8: Same as Figure 4-5, including estimated cumulative input of sediments from Dundee Dam (e.g. Figure 2-2 and extrapolation).

Finally, it was observed (e.g. Figure B-2 and Figure B-3) that the bed in the upper reaches of the river was characterized by pronounced bedforms (20 ft long and 0.5 ft high), which disappeared in 2008. The bed in this part of the river therefore must contain mainly sand, as bedforms cannot form from fine suspended sediment.

A careful inspection of the differential bathymetrical maps reveal that all maps show bedforms up-estuary of RM 9 sometimes, with some locations more pronounced than at other times/locations.

As an example, Figure 4-9 shows bedform developments around RM 13.3, induced by the Irene flood. The similarity between the differential maps 2010-2011 and 2010-2012 suggests that during the calm hydrodynamic conditions of 2011-2012, the bedforms by Irene are not really modified. These bed forms have similar dimensions as the bedforms presented in Figure B-3, e.g. less than 32 ft length, and a height of 1 ft maximal. The reason for this similarity in bed forms can be found in Van Rijn (1994). The critical shear stress for erosion of sands of a few 100 μm yields a few Pa, i.e. of the same order of magnitude as the bed shear stresses computed with the hydrodynamic LPR model for a river flow of 24,000 cfs. At smaller river flows, bed shear stresses decrease of course, and only smaller sand particles can be transported. However, according to Van Rijn, the river stays in the same bed form regime, with more or less similar bed form dimensions, though formed by grains of different diameter.

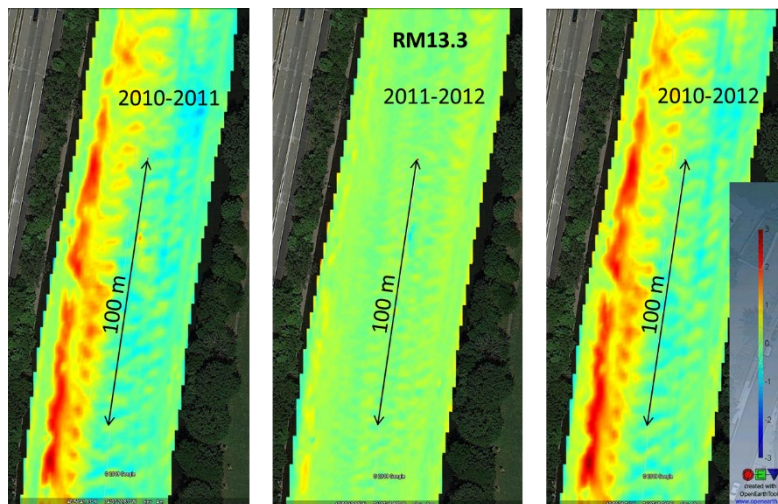


Figure 4-9: Bed form development around RM 13.3 by Irene floods

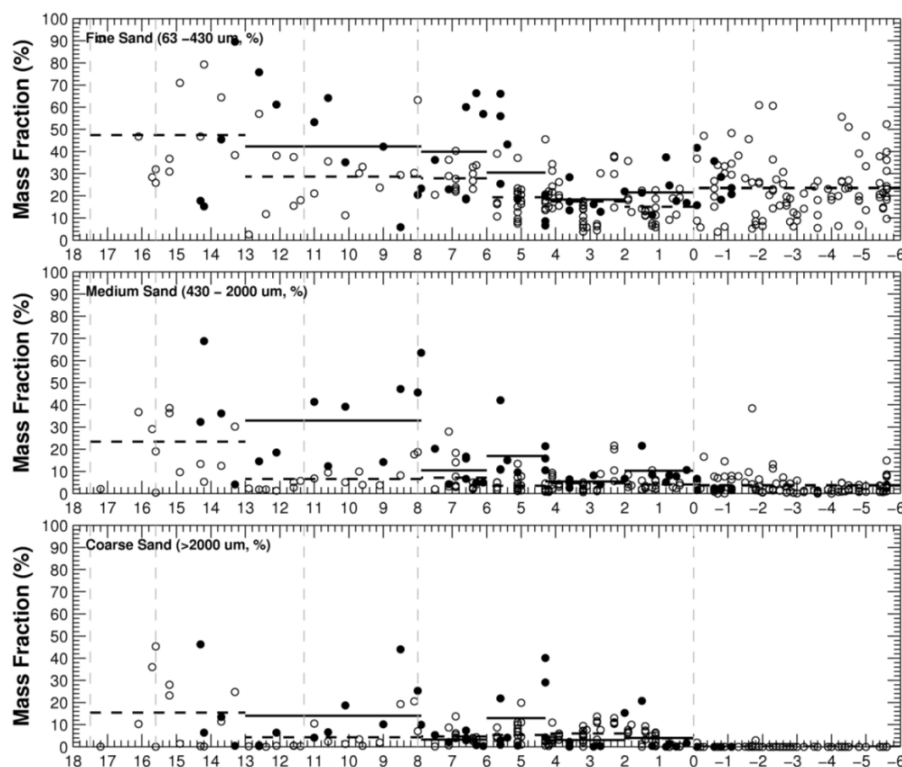


Figure 4-10: Sand content in LPR (grab samples); solid dots: within navigation channel, open dots: outside navigation channel. The horizontal lines indicate average values for given reach (dashed lines outside navigation channel, and solid lines inside navigation channel).

The existence of bedforms indicates bed load transport of sandy material. This down-estuary transport of sands explains the relative high sand content in the overall muddy bed of the LPR bed below RM 8, e.g. Figure 4-10. These sands enhance the erosion resistance of the bed, and induce the armoring accounted for in the numerical model.

It is important to appreciate that Dundee Dam was built in the 1850s, hence more than 150 years ago. Thus, it can be argued that sands must flow over Dundee Dam, at least occasionally during floods. If not, the riverbed down-estuary of Dundee Dam would have been seriously degraded by now. This argument adds to reasoning in Section 4.3 on the overall sediment balance in the LPR in the sense that not all sediments flushed over Dundee Dam contribute to TSS values measured in the lower reaches of the river.

4.5 Small-Scale Behavior and Cyclical Response

In this section, the small-scale response of the LPR is discussed by analyzing the multi-beam surveys presented above. The results are also related to the results of the pilot dredging experiment at the end of this section

Figure 4-11 shows four differential maps for the period 2008-2007; 2010-2008 (2008 bathymetry corrected by 0.3 ft); 2011-2010; and 2012-2011. As discussed, the first and fourth period should be characterized by net, large-scale infill, as no major floods occurred, whereas the second and third period are characterized by net, large-scale erosion due to the March 2010 and two 2011 (amongst which was Hurricane Irene) floods. Yet, Figure 4-11 suggests a more complicated picture – both periods reveal areas with erosion and with sedimentation. Moreover, Figure 4-11 also suggests that where the first period reveals erosion at a specific location, the following period depicts sedimentation, and vice versa. This picture is characteristic for almost the entire river, and for all periods, e.g. 2008-2007/2010-2008; 2010-2008/2011-2010; and 2011-2010/2012-2011. Erosion in the 2010-2008 period and the 2011-2010 period (both periods characterized by river floods) are mainly found around bridge pillars, bank irregularities, etc. In the subsequent low-river flow periods, these scour holes are filled in again. Part of the sediments scoured from the bed during flood events is deposited down-estuary of that scour, and is subsequently eroded during low-river periods. This cyclic behavior is clearly visible in Figure 4-11.

Instead of presenting all cyclic variations along the entire river for the four periods, this behavior has been quantified. As an example, the erosion/deposition patterns around RM 2.5 for the survey periods 2008-2007 and 2010-2008 are compared in Figure 4-12 by defining five classes. Considering the uncertainties in the bathymetric measurements and in the correction for apparent datum bias applied to the 2008 survey, as discussed in Appendix B of the current attachment and in Appendix A of the main RI report. Bed level changes smaller than a threshold of ± 6 inches (± 0.5 ft) during each of these periods as well as overall are ignored as being within the accuracy of the datasets (yellow regions in Figure 4-12). Dark and light blue regions indicate areas that experienced erosion exceeding the threshold in one period and deposition exceeding the threshold in the other, or vice versa, i.e., characterized by cyclic behavior. Areas characterized by deposition exceeding this threshold in at least one period and no erosion exceeding the threshold in the other period are indicated as depositional areas (sedimentation dominant; green regions). Similarly, erosion exceeding the threshold in at least one period and no deposition above the threshold in the other are shown as erosional areas (erosion dominant; red regions).

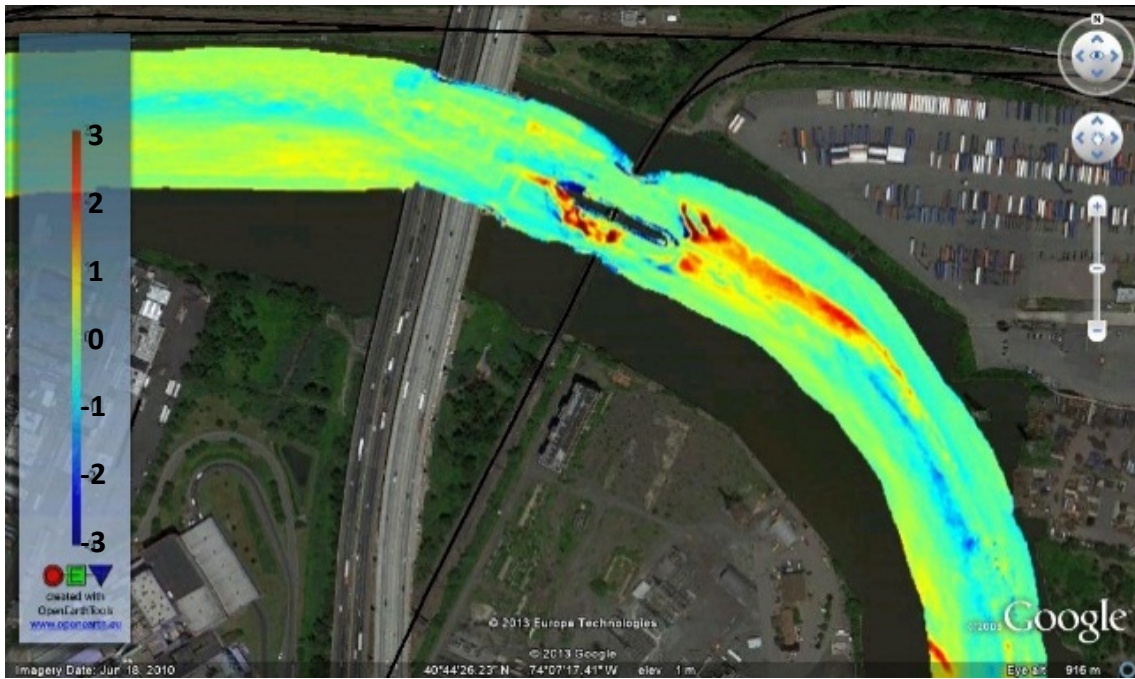
Additionally, these five categories were evaluated using a smaller bed-change threshold of 3 inches (0.25 ft; a lower bound on the measurement uncertainty between multibeam surveys per the discussion in Appendix A of the main RI report) to obtain a qualitative estimate of potential additional areas that might exhibit cyclical behavior that cannot be reliably captured due to the measurement limitations of the existing datasets. From the bottom panel of Figure 4-12, which shows the same bathymetric change categories evaluated using the lower threshold, a coherent pattern is evident in that areas that were already classified as cyclical using the 0.5 ft threshold now grow larger (dark and light blue regions). This suggests that the relatively large uncertainty in the measurements may be obscuring certain trends and that the extent of cyclical behavior in the river is likely larger than the area estimated in the analysis with the 6 inch threshold.

Next, the surface areas of these bathymetric classes are determined for longitudinal stretches of 0.1 mile, covering the longitudinal extent of the multibeam bathymetric

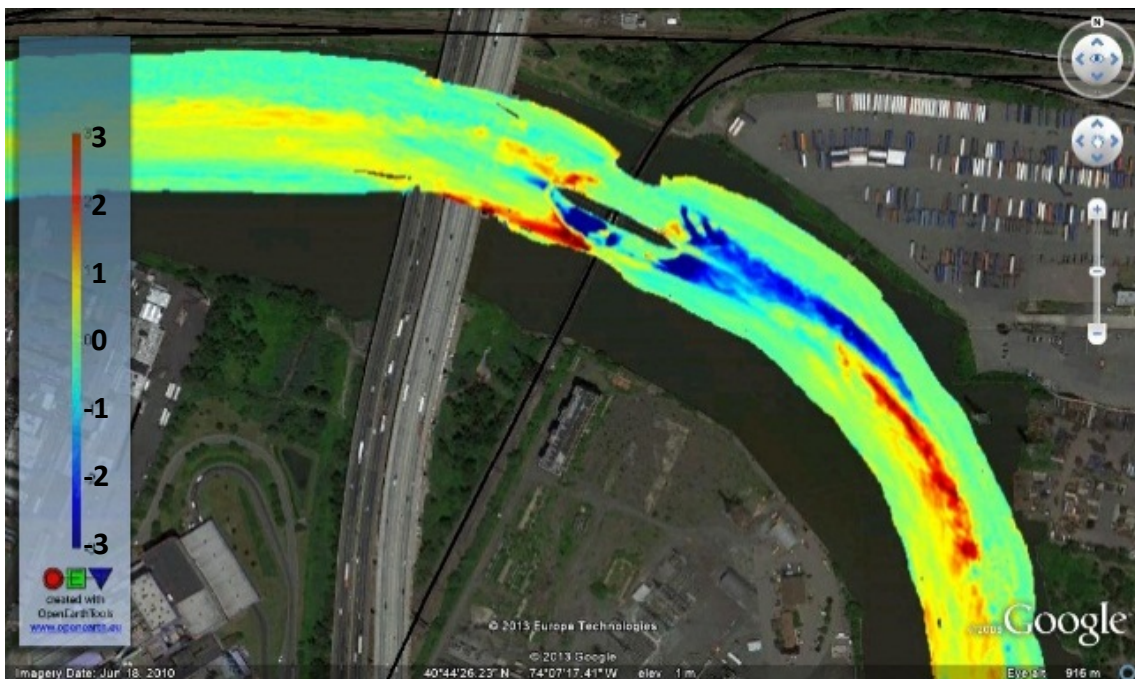
surveys for the 2007-2008-2010, 2008-2010-2011, and 2010-2011-2012 periods (approximately RM 0 to RM 14.3, depending on the survey pair analyzed). The results are presented in Figure 4-13, Figure 4-14 and Figure 4-15 respectively. For each set of periods, the areas falling under each bathymetric category are evaluated using both the 0.5 ft change threshold (Figure 4-13a, Figure 4-14a, and Figure 4-15a) and the 0.25 ft change threshold (Figure 4-13b, Figure 4-14b, and Figure 4-15b). The areas within each category are also shown on a cumulative basis in Figure 4-16 (i.e., the integration along the LPR of the 0.1 mile bins in Figure 4-13, Figure 4-14 and Figure 4-15) and summarized in Table 4-5. Note that these figures and Table 4-5 characterize only the portion of the river width covered by the multibeam surveys, which did not fully extend into the shoals due to depth limitations.

The patterns in the 2007-2008-2010 and 2010-2011-2012 inter-survey evaluations (Figure 4-13 and Figure 4-15 as well as the top and bottom panels of Figure 4-16) are qualitatively similar in that the majority of the bed level changes (>50%) is within survey accuracy and cyclical regions represent 8 to 10% of the total area when a 0.5 ft threshold for detectable change is applied (Table 4-5). Reducing the threshold to 0.25 ft increases the area of cyclical behavior to about 20% of the total (Table 4-5). Overall, a minority portion of the river depicts erosion dominated (14 to 30% of total depending on the change threshold used, Table 4-5) or sedimentation dominated (13 to 25% of total) trends in these two inter-survey periods.

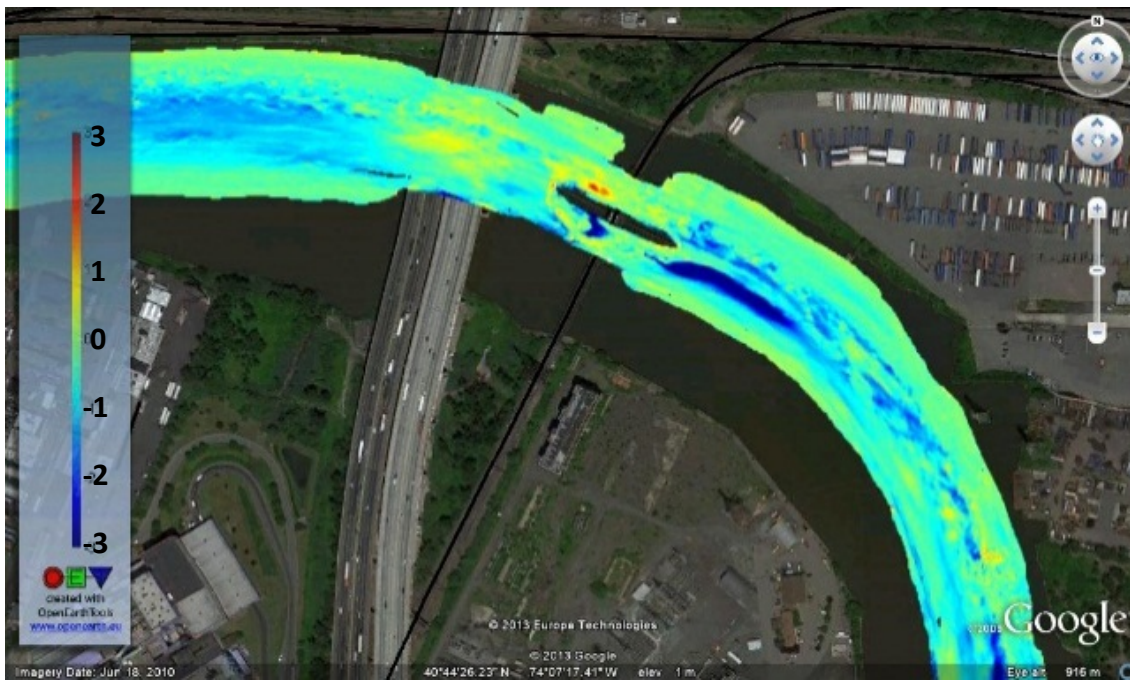
The 2008-2010-2011 inter-survey period depicts an erosion dominated trend in a larger portion of the LPR (Figure 4-14 and middle panel of 4-16), covering 30 to 42% of the river areas surveyed depending on the detection threshold used for classification. By comparison, cyclical behavior and a deposition dominated trend represented only 5 to 12% and 19 to 24%, respectively, of the total area (Table 4-5), with the lower 1.5 miles contributing a large fraction of the deposition dominant areas (Figure 4-14). The explanation for this different behavior must be sought in the hydrograph of Figure 2-1, showing that the 2008-2010-2011 evaluation period is characterized by three major floods in 2010 and 2011.



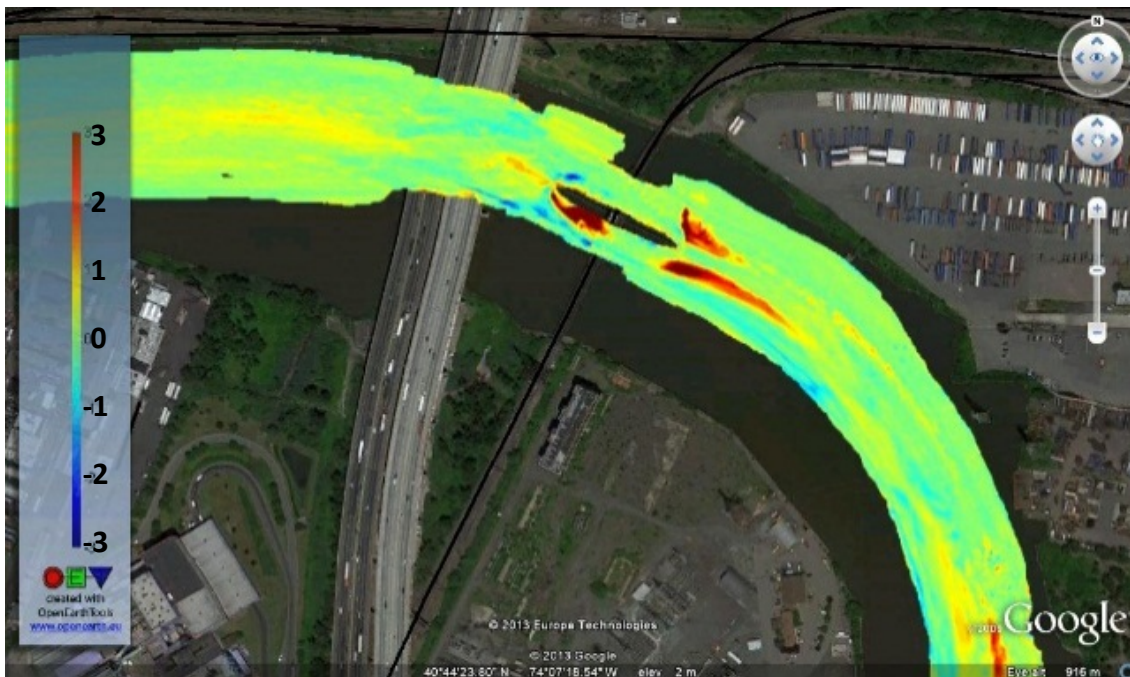
a: Differential map around RM 2.5 for 2008-2007



b: Differential map around RM 2.5 for 2010-2008



c: Differential map around RM 2.5 for 2011-2010



d: Differential map around RM 2.5 for 2012-2011

Figure 4-11: Differential maps around RM 2.5 for different years. Negative values indicate erosion and positive values indicate deposition.

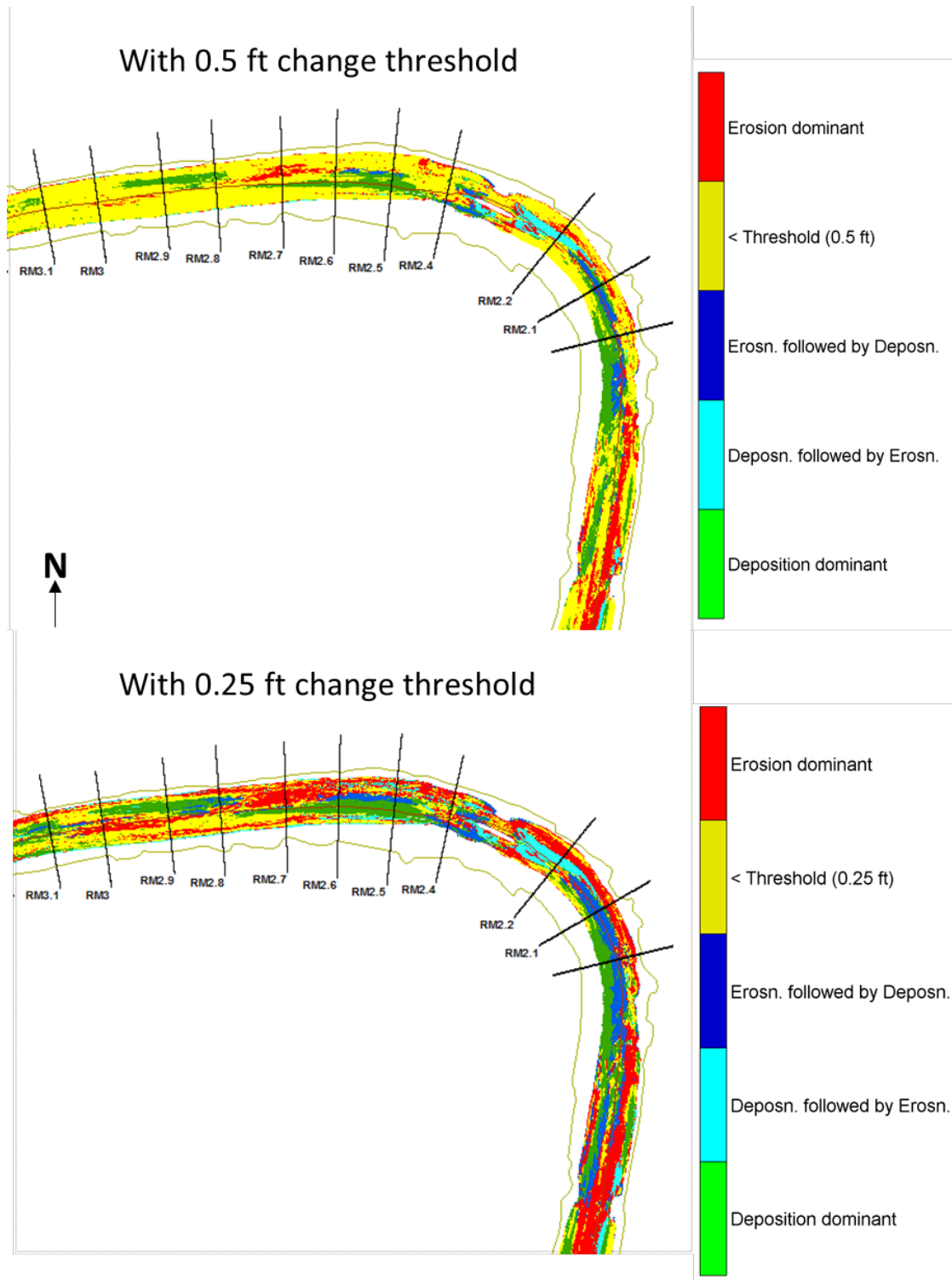
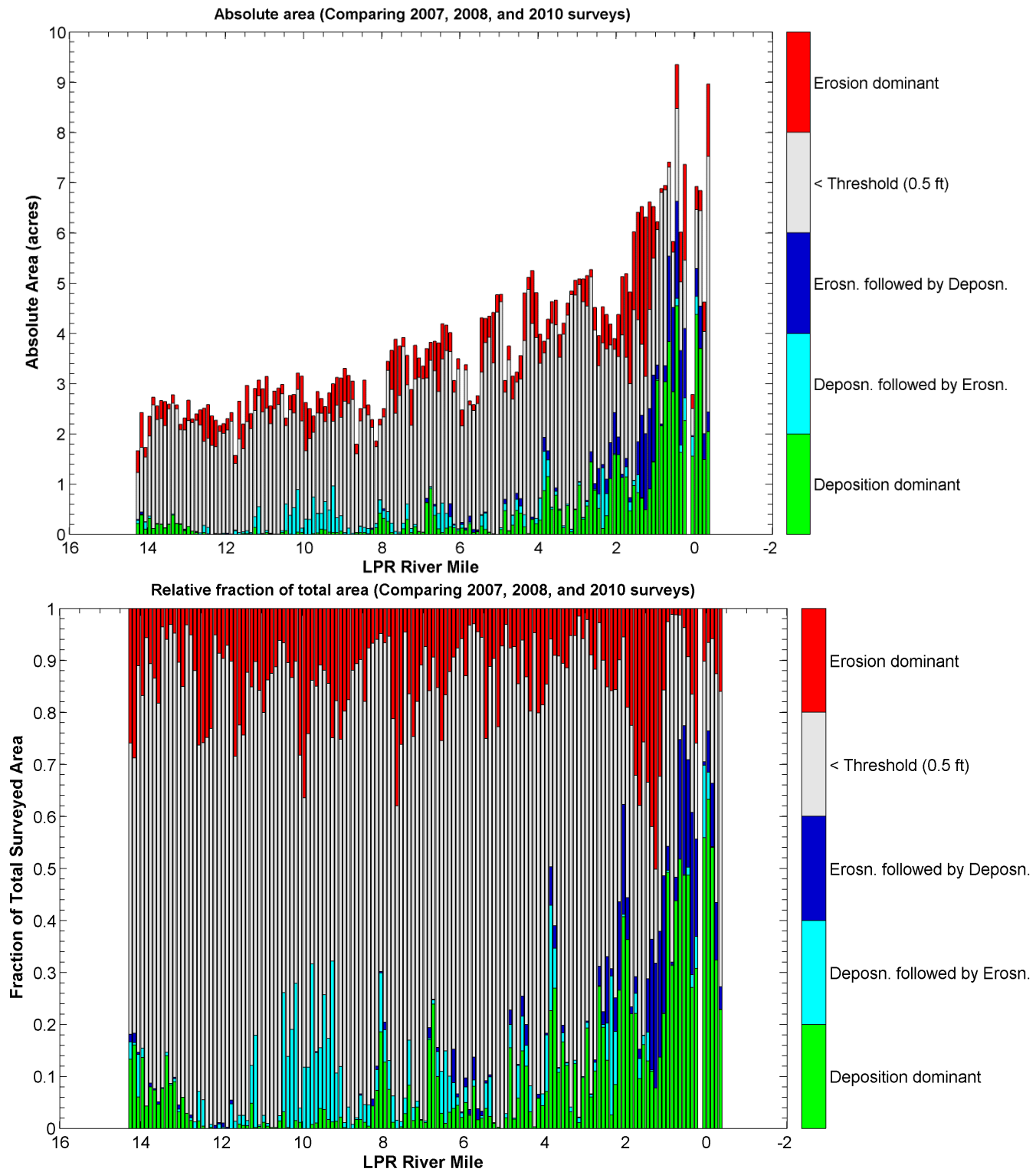


Figure 4-12: Comparison of erosion/deposition patterns around RM 2.5 for the LPR bathymetry survey periods 2008-2007 and 2008-2010.



a: Comparison of bathymetric changes using a 0.5 ft significance threshold

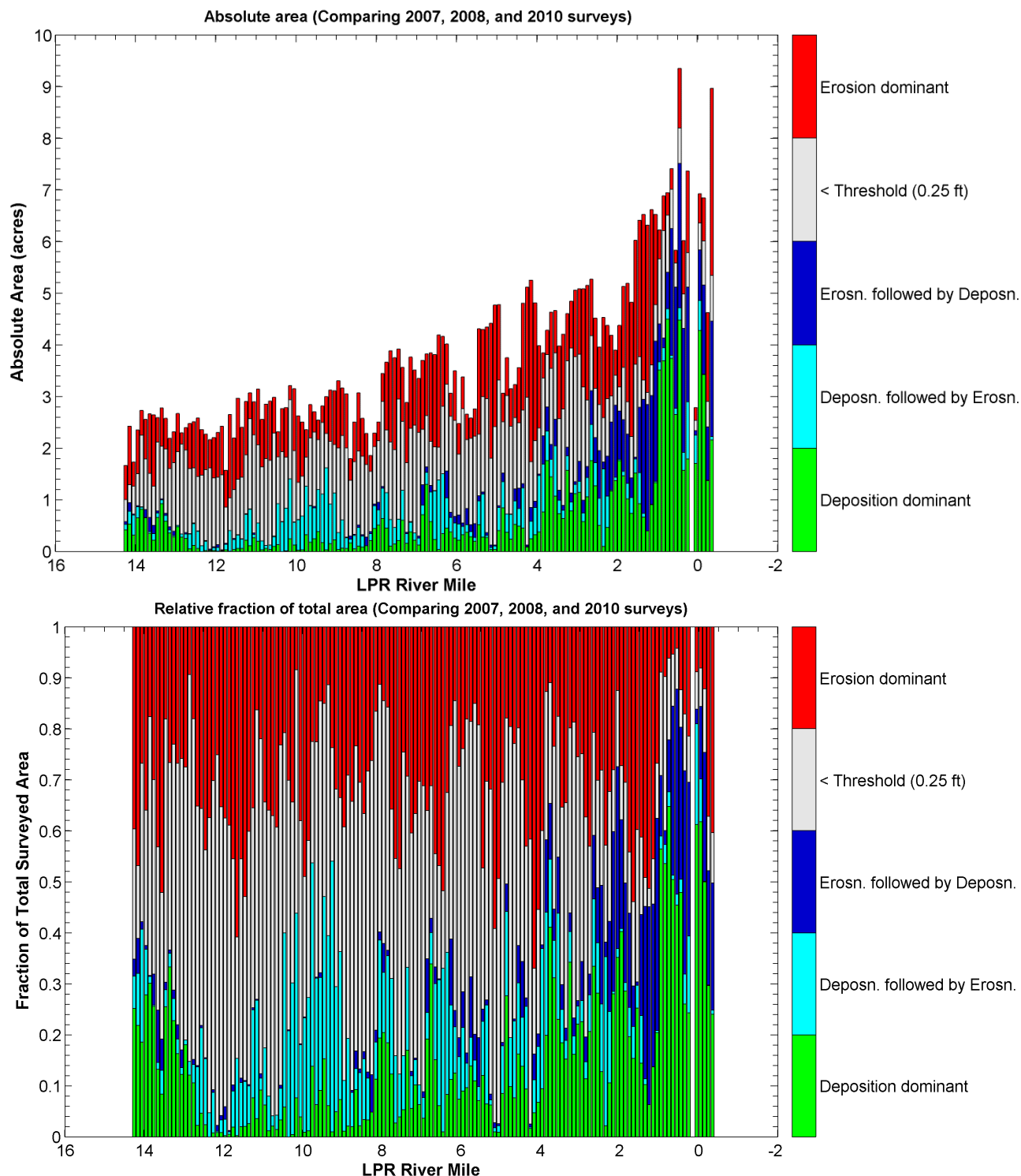
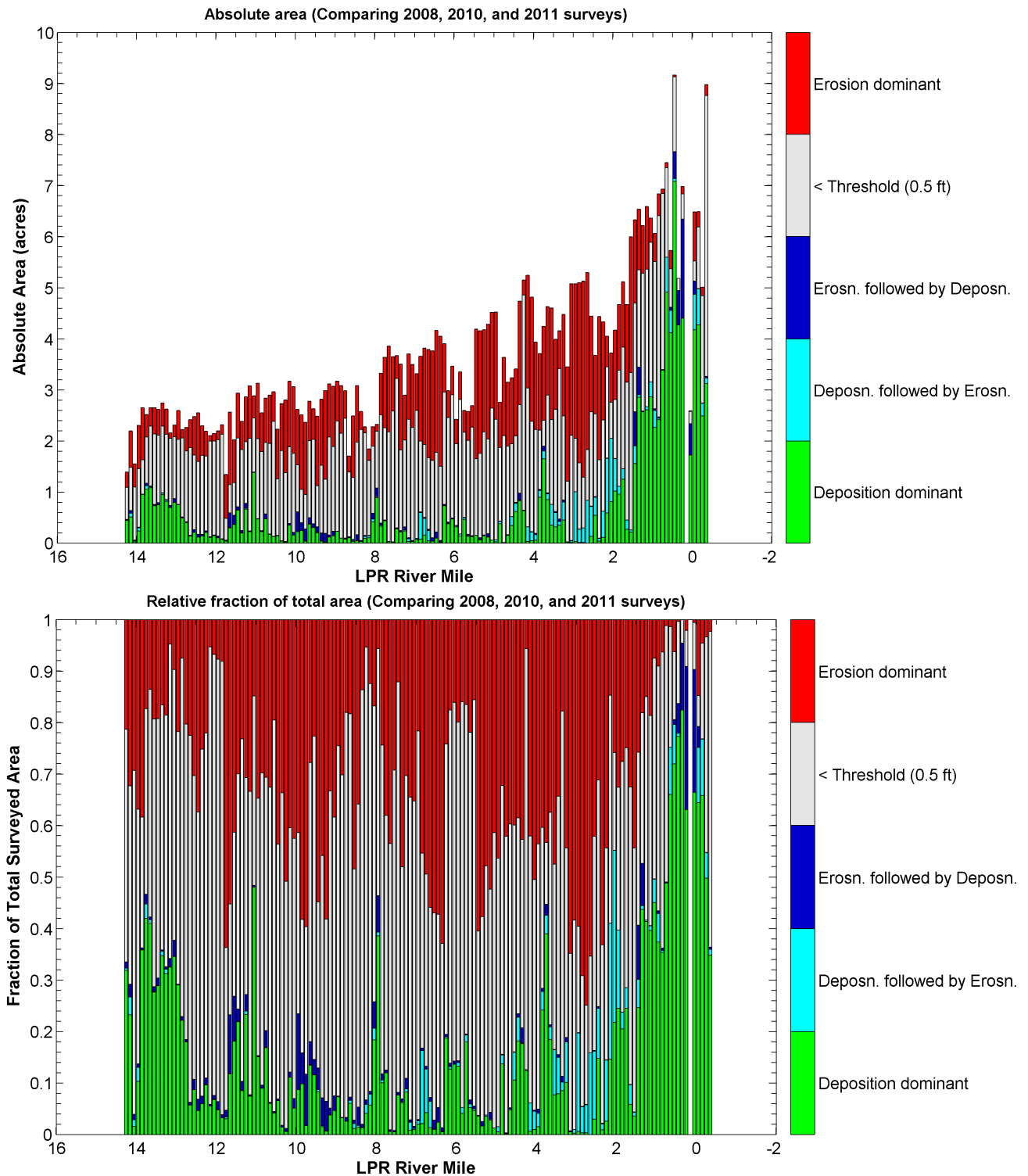
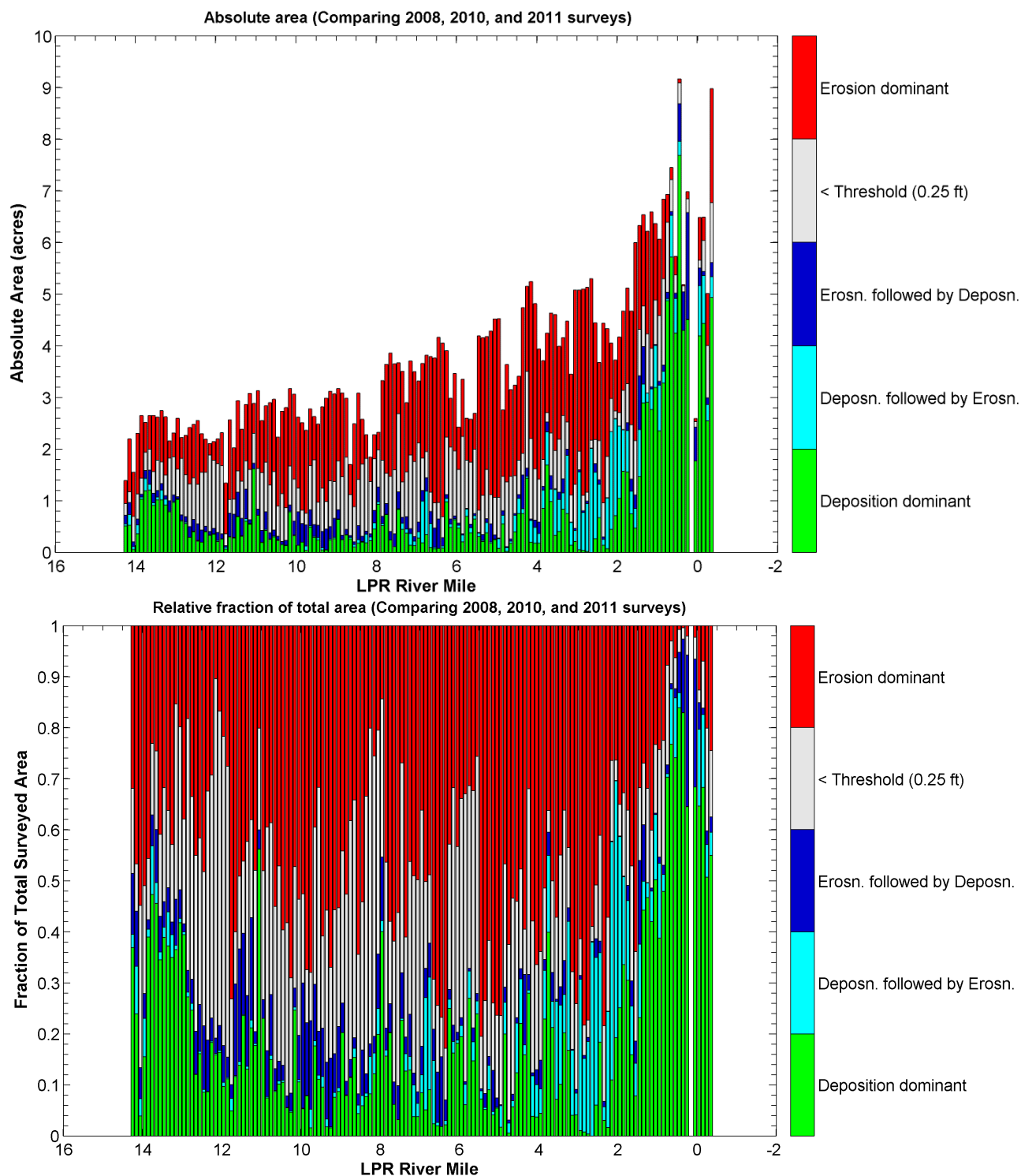


Figure 4-13: Longitudinal variation of cyclicity in absolute and relative terms for the LPR bathymetry survey period 2008-2007/2010-2008.

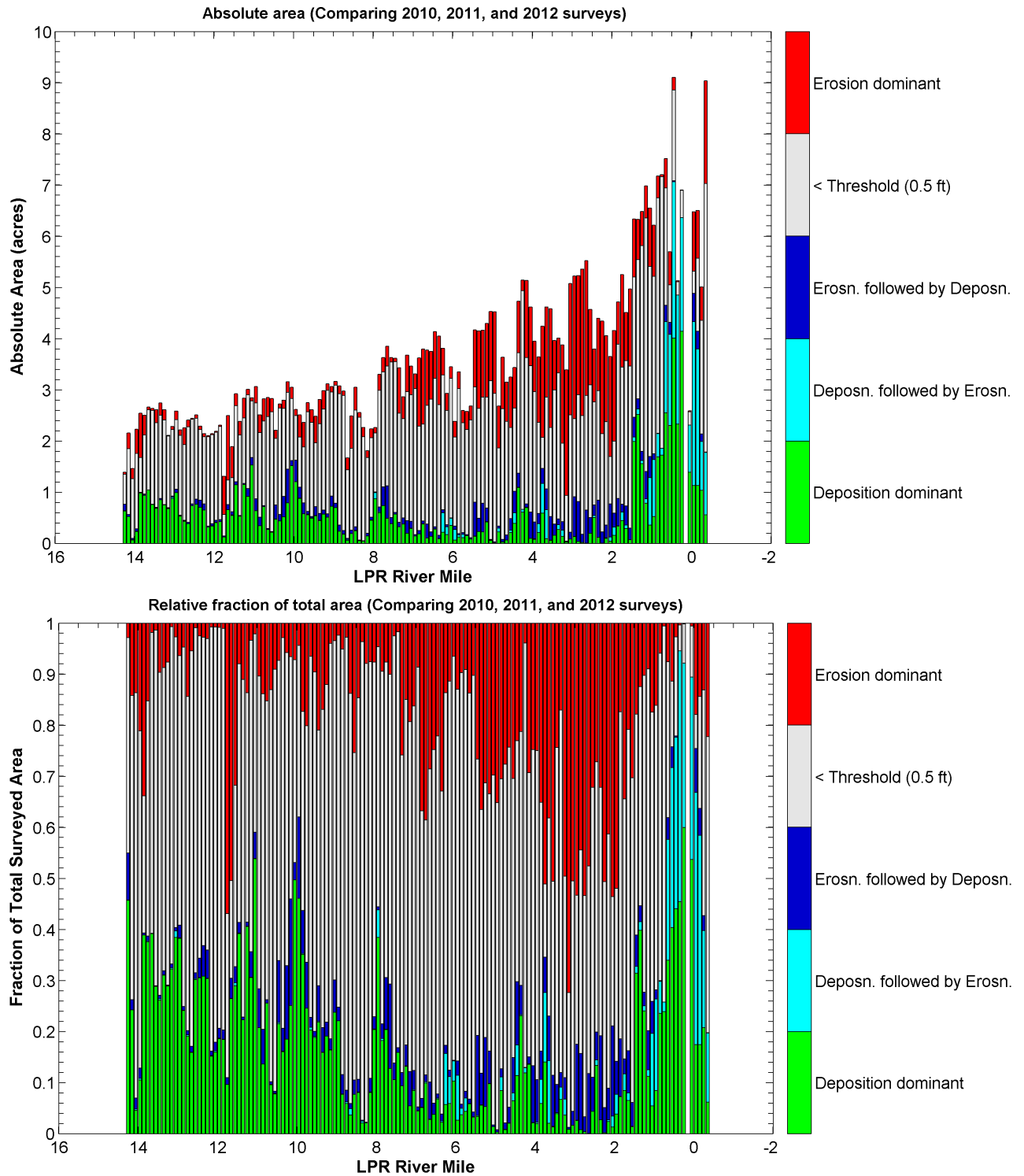


a: Comparison of bathymetric changes using a 0.5 ft significance threshold

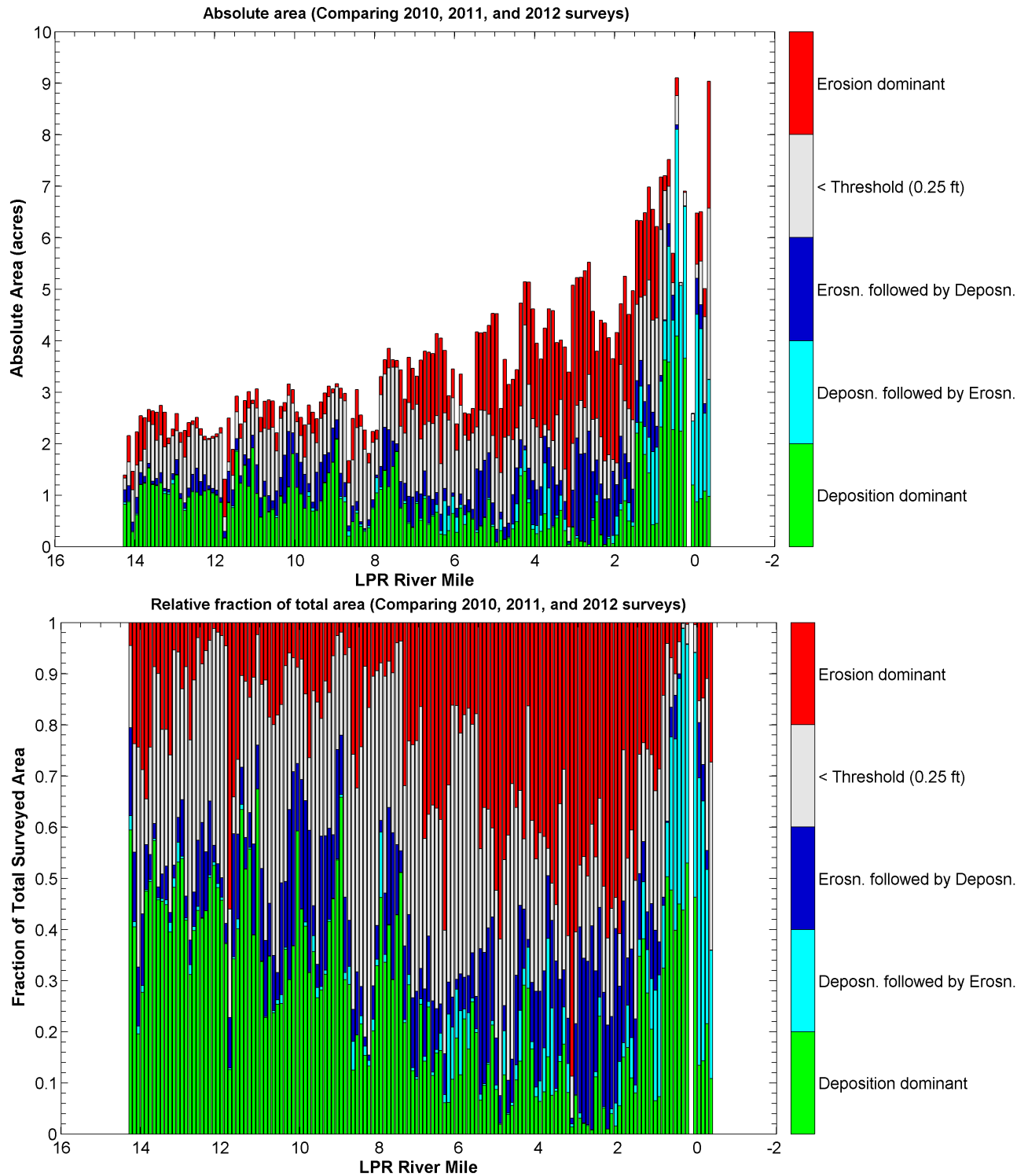


b: Comparison of bathymetric changes using a 0.25 ft significance threshold

Figure 4-14: Longitudinal variation of cyclicity in absolute and relative terms for the LPR bathymetry survey period 2010-2008/2011-2010.



a: Comparison of bathymetric changes using a 0.5 ft significance threshold



b: Comparison of bathymetric changes using a 0.25 ft significance threshold

Figure 4-15: Longitudinal variation of cyclicity in absolute and relative terms for the LPR bathymetry survey period 2011-2010/2012-2011.

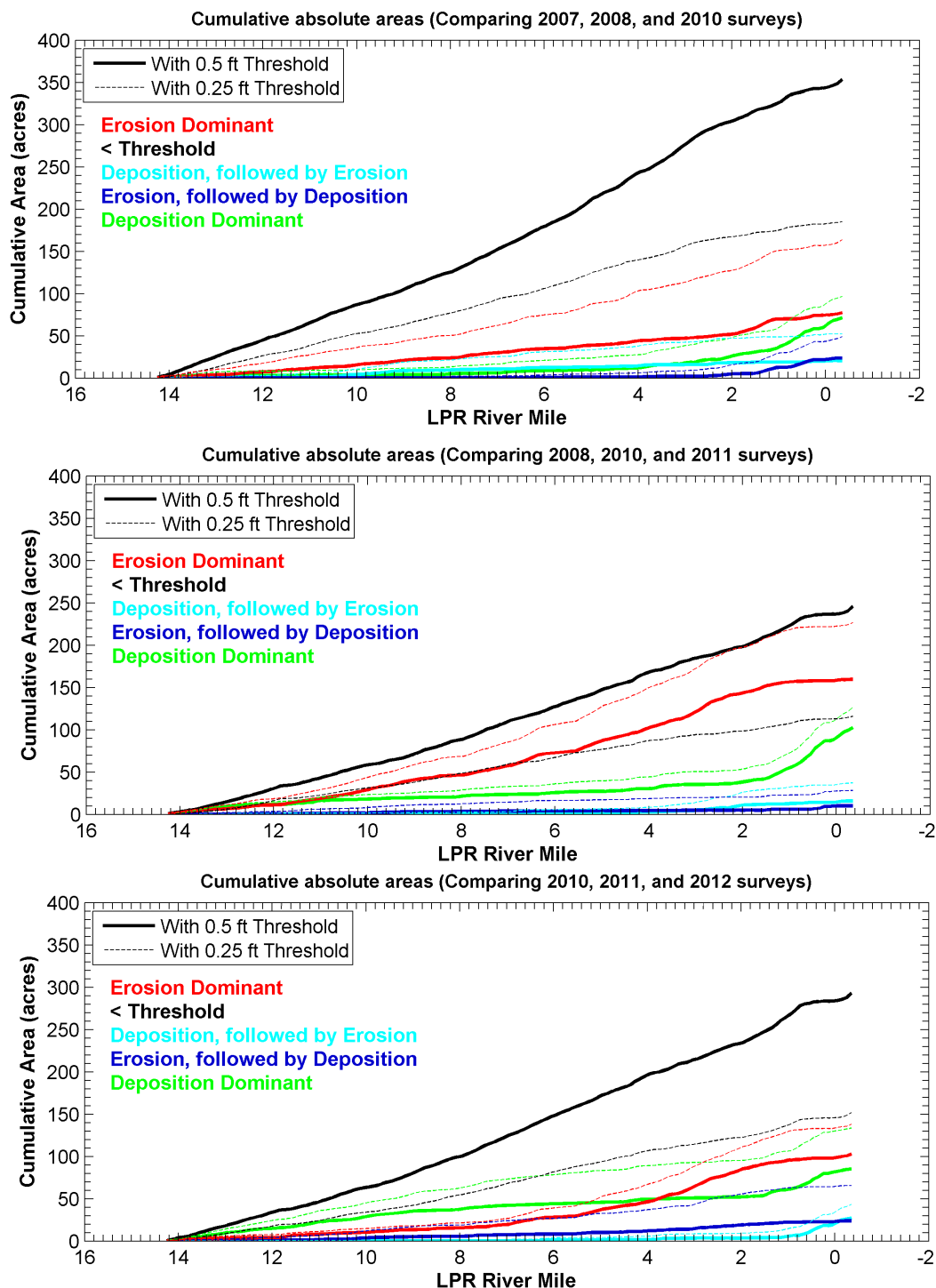


Figure 4-16: Cumulative relative surface area of LPR affected by cyclical behavior or ongoing erosion/deposition for the three inter-survey periods.

Table 4-5: Summary of relative surface area LPR affected by cyclical behavior

Using 0.5 ft change threshold	08-07/10-08	10-08/11-10	11-10/12-11
Sedimentation dominant	13%	19%	16%
Sedimentation, followed by erosion	4%	3%	5%
Erosion, followed by sedimentation	4%	2%	5%
hence cyclical behavior	8%	5%	10%
Non-detectable (below threshold)	65%	46%	55%
Erosion dominant	14%	30%	19%
Using 0.25 ft change threshold	08-07/10-08	10-08/11-10	11-10/12-11
Sedimentation dominant	18%	24%	25%
Sedimentation, followed by erosion	10%	7%	8%
Erosion, followed by sedimentation	9%	5%	12%
hence cyclical behavior	19%	12%	20%
Non-detectable (below threshold)	34%	22%	29%
Erosion dominant	30%	42%	26%

A pilot dredging pit was excavated close to RM 3 (location shown in Figure 4-17) in December 2005, removing about 112,000 ft³ of sediment at an average removal depth of 2 ft over about 68000 ft² of riverbed. The re-infill of this pit with sediments was measured twice in the four months following the dredging. Figure 4-18 shows various pre- and post-dredge bathymetry measurements for a lateral transect located within the dredge footprint. In addition, hydro-chemical parameters were measured, but these are not relevant for the analysis below. For details on the pilot dredging, the reader is referred to the Environmental Dredging Pilot Report (Malcolm Pirnie, 2007).

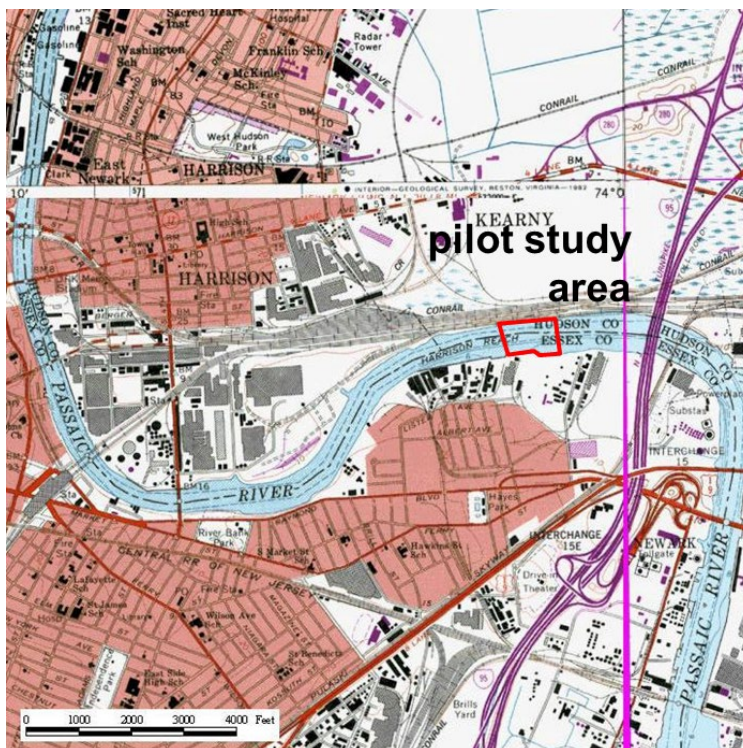


Figure 4-17: Location of the pilot dredging experiment in 2005. Reproduced from Malcolm Pirnie (2007).

Table 4-6: Infill rates pilot dredging excavation; the excavated area was sub-divided into three cells, each with an area of 22475 ft²

	Survey Feb 15, 2006			Survey April 18, 2006			Survey April 18, 2006		
	# days = 65 (Dec 11)			# days = 62 (Feb 15)			# days = 127 (Dec 11)		
	Infill	Infill	Infill rate	Infill	Infill	Infill rate	Infill	Infill	Infill rate
	ft ³	ft	ft/d	ft ³	ft	ft/d	ft ³	ft	ft/d
Cell 11	15444	0.69	0.0105	10503	0.46	0.0075	25947	1.15	0.0092
Cell 13	7992	0.36	0.0056	5373	0.23	0.0039	13365	0.59	0.0046
Cell 15	15633	0.69	0.0105	9018	0.39	0.0066	24651	1.08	0.0085
Total	39069	0.59	0.0089	24894	0.36	0.0059	63963	0.95	0.0075

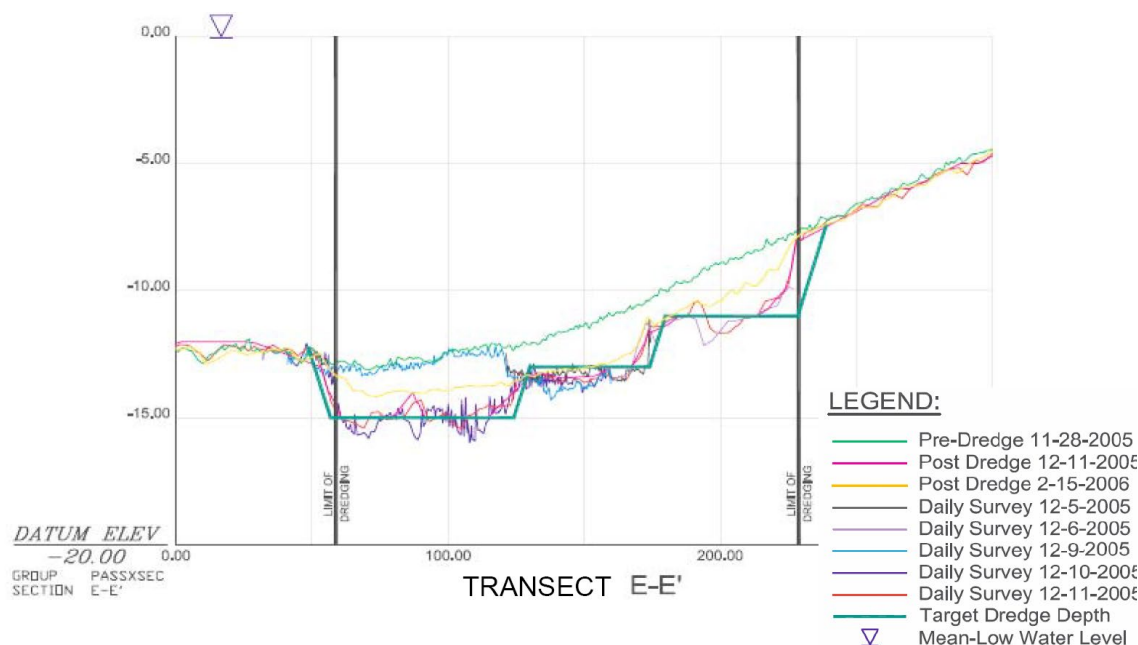


Figure 4-18: Cross section of dredged pilot pit with soundings prior to, directly after and two months after excavation. Reproduced from Malcolm Pirnie (2007).

The measured infill rates are summarized in Table 4-6. Both intra-survey periods are of about similar length, e.g. 65 and 62 days. Note that siltation rate in the first period (0.59 ft) is larger than during the second period (0.36 ft). These siltation rates can be conveniently analyzed with the so-called “Volume of Cut” method, which describes infill rates through an exponential function:

$$h(t) = h_{eq} + (h_0 - h_{eq}) \exp \left\{ -\frac{\nu t}{h_0 - h_{eq}} \right\} \quad (1)$$

in which h_{eq} = morphodynamic equilibrium depth, h_0 = initial over depth by dredging, $h(t)$ = the over depth after time t , and ν = infill rate per time unit (days).

Using the data of Table 4-6, the exponential infill rate ν can be calculated, the results of which are given in Table 4-7. These values are a bit larger than the linear infill rates of Table 4-6.

Table 4-7: Infill rates computed with Volume-of-Cut method

	#days	h_{eq} [ft]	h_0 [ft]	$h(t)$ [ft]	ν [ft/d]
period Dec 11 – Feb 15	65	14.1	15.75	15.16	0.0112
period Feb 15 – Apr 18	62	14.1	15.16	14.80	0.0072

The infilling in the two periods can be compared using the exponential infill rates of Table 4-7. For the second period, starting with the bed level measured at the second survey, hence 65 days after excavation, Figure 4-20 shows that the two lines for $v = 0.01$ ft/d starting at $t = 0$ and for $v = 0.0066$ ft/d starting at $t = 65$ days agree. This implies that the infill processes during the two periods are identical. This is remarkable, as flow rates during that first period were considerably larger, including a peak of 6,000 cfs (though at neap tide conditions), which is close to the transition from Regime II to Regime III (e.g. Figure 2-7). Moreover, the head of salinity intrusion, hence the estuarine turbidity maximum is around RM 3 for most of this period, as the river flow was around 3,000 cfs (e.g. Figure 4-19 and 2-3). Hence, the hydrodynamic conditions during the two periods are largely different. The fact that the infill processes in these so different periods are identical suggests a very robust mechanism controlling the sediment transport processes in the river likely related to sediment flux induced by estuarine circulation resulting in net up-estuary flux towards the turbidity maximum.

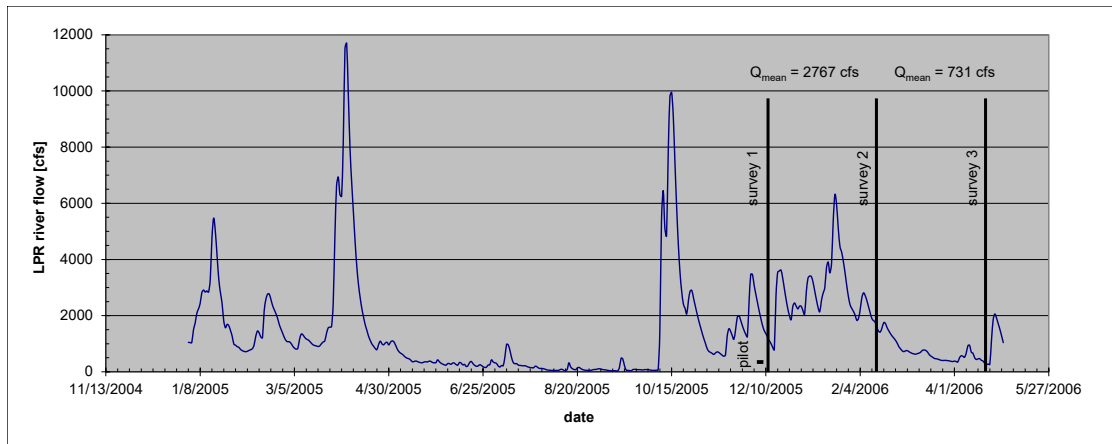


Figure 4-19: Hydrograph prior to pilot dredging experiment, during excavation and the survey periods.

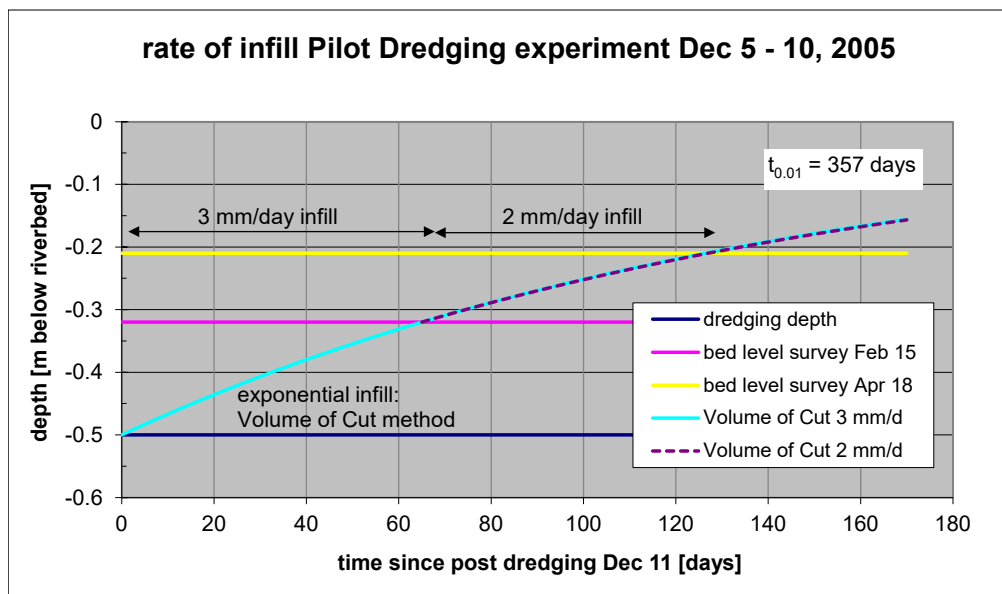


Figure 4-20: Schematic infill diagram of pilot dredging excavation, including results of Volume of Cut method.

Next, infill rates observed for the pilot dredging experiment, as given in Table 4-6 are compared to the infill rates during the inter-survey periods of 2007-2008 and 2011-2012 (e.g. Figure 4-8). The infill of the scour holes after a flood period (e.g. the dark blue lines of Figure 4-16) is compared to the infill of the pilot dredging excavation. The results are summarized in Table 4-8.

Table 4-8: Comparison of infill rates during post pilot dredging surveys and multi-beam inter-survey periods

	surface area [ft ²]	total infill [ft ³]	infill time [days]	infill rate [ft/d]
Pilot dredging excavation	68,000	63,500	127	0.0077
Pilot dredging excavation, with full infill after 1 year	68,800	113,000	360	0.0047
Multi-beam, 2008-2007	$3.8 \cdot 10^6$	$35.3 \cdot 10^6$	438	0.0007
Multi-beam, 2008-2007	$3.8 \cdot 10^6$	$35.3 \cdot 10^6$	225 ¹⁾	0.0010
Multi-beam, 2012-2011	$6 \cdot 10^6$	$84.7 \cdot 10^6$	290	0.0013

¹⁾ accounting for March 2008 flood

Table 4-8 shows that the mean infill rate for the inter-survey period 2011-2012 is about 30% larger than for period 2007-2008 accounting for the March 2008 flood, maybe even twice as large (e.g. 0.0013 ft/d vs 0.0007 ft/d). However, given the inaccuracies of this analysis, infill rates over the river during low river-flow conditions are estimated at the order of 0.0007 – 0.0013 ft/d. However, infill rates following the pilot dredging excavation are substantially larger, i.e. around 0.0077 ft/d. Even if using the Volume of Cut method to

extrapolate to a 99% filling of the excavation (which would take about 1 year), the infill rate of the excavation would amount to 0.0047 ft/d.

However, the infill surface (cyclic infill after scour) in the inter-survey period 2007-2008 is about 60 times larger than the surface area of the pilot dredging excavation, whereas for the 2011-2012 period, the infill surface is even about 90 times larger. From these numbers the following conclusions can be drawn:

- Only part of the sediment flux passing the pilot dredging excavation is trapped within the excavation – the remainder of the transported fine sediments probably has settled elsewhere in the river,
- The infill rates during low river-flow periods is supply limited – the infill of the “excavations” by scouring is much smaller than for the pilot dredging experiment,
- The larger infill rates in the 2011-2012 may be indicative of the fact that the river must be further off its equilibrium after the two severe 2011 floods than in the 2007-2008 period. The higher deviation from equilibrium implies a larger trapping efficiency.

The source of the sediments, which fill the scour and excavation holes is not known. However, from the system understanding analyses presented here it can be concluded that:

- Relatively small sediment loadings enter the LPR over Dundee Dam during low flow periods, in particular, during periods following severe river floods,
- The various bathymetrical differential maps suggest that the lower parts of the LPR (between about RM 1 and RM 0) are an important source for the sediment. However, flow-induced bed stresses in this part of the river are too low for substantial remobilization of deposited sediments, and therefore it is hypothesized that local shipping activities play a role (e.g. Section 4.6),
- Sediments from Newark Bay, and further away, brought in through the Kill van Kull and Arthur Kill are likely to be transported towards, hence possibly into the LPR by estuarine circulation and tidal asymmetry,
- Likely, also redistribution of sediments takes place within the LPR – coarser sediments scoured from the bed in the upper part of the river during high river flow periods may be deposited down-estuary.

4.6 Navigation Scour

As noted in Section 4.3, the lower-most two miles of the river underwent net sedimentation in the high-flow periods of 2008-2010 and 2010-2011, and net scour in the low-flow periods of 2007-2008 and 2011-2012. However, while the net infill in this reach during the high-flow years could likely be explained by the hydrodynamics associated with high-flow

events that cause erosion in RM 2-14 and deposition downstream, the phenomenon of net erosion during the low-flow years cannot be explained by normal hydrodynamic stresses. Examination of shear stresses in the lower miles of the river during high-flow conditions similar to the flood events in 2010 and 2011 show higher shear stresses during these conditions than during the flow conditions of 2007-2008 and 2011-2012. It is highly unlikely that a sediment particle deposited under high shear stress conditions would be eroded during a subsequent low shear stress conditions. Therefore, the observed erosion during 2007-2008 and 2011-2012 is unlikely to be caused by hydrodynamic shear-stresses (due to currents). Furthermore, shear-stresses due to waves are also unlikely to be the cause given the relatively deep water-depths in much of the area apparently subject to scour.

	Tug#1	Tug#2
Company/name	Comet Towing company	Franklin Reinauer
		
Rated horsepower (per propeller)	2305 (1718 KW)	2360 (1760 KW)
Number of propellers	2	2
Propeller Diameter (inches)	116 (2.95)	104 (2.64)
Type of Propeller	Nonducted	ducted
Rudder	-	-
Maximum vessel draft (feet)	16.4 (5)	9.85 (3)

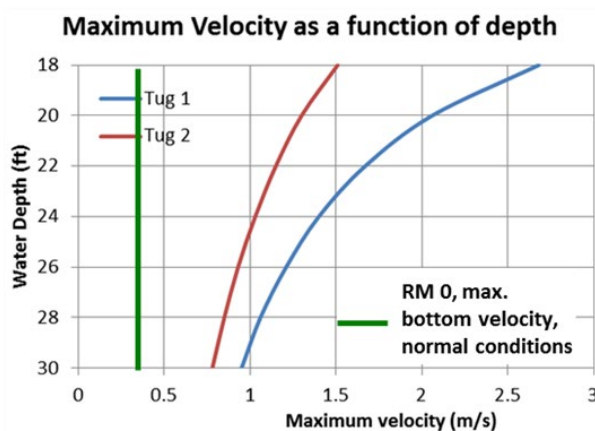


Figure 4-21: Specifications for a pair of tug-boats commonly operating in the lower miles of the LPR, and calculated velocities due to propeller motion as a function of distance (in the vertical) from the propeller.

The lower miles, especially between RM 0 and RM 1.4, are characterized by the presence of several shipping terminals, some of which see vessels with drafts up to 34 feet (MLW; USACE 2010) – drafts comparable to the available water depths at several locations in the lower miles of the LPR. The deep-draft vessels berthing in these terminals, as well as the

tug-boats which operate at a high torque especially while maneuvering these vessels and barges into the berths can potentially cause resuspension of mud and other soft sediments from the river bed. An analysis of currents due to propeller-motion (following the methods of Schokking, 2002) for two different tug-boats that frequent this section of the river presented in Figure 4-21 indicates velocities in the range of 0.75 - 1 m/s at 30' depth, which is about a factor of two higher than maximum tidal velocities in this section of the LPR. The factor of two higher near-bottom velocity translates to a factor of four higher shear-stress when compared to normal tidal conditions, which is high enough to cause erosion in the bed. This suggests that propeller-motion induced bed shear-stresses are a plausible cause for the scour observed in the lower two miles of the river.

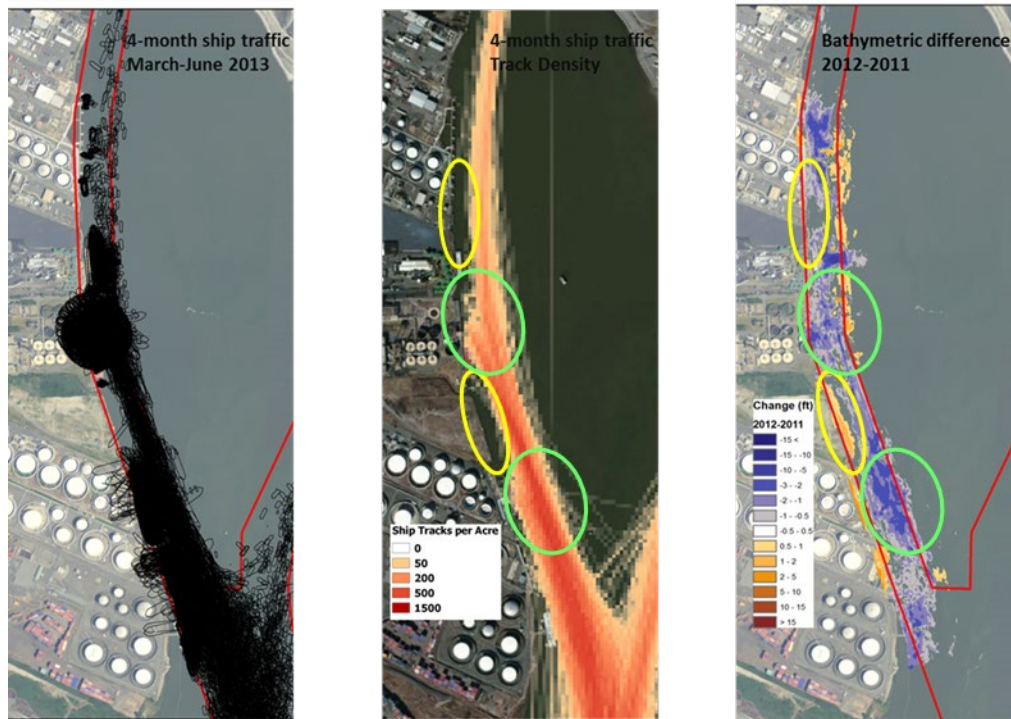


Figure 4-22: Reported ship locations, ship tracks and frequency of passage, and bathymetry difference between the 2011 and 2012 surveys. Negative values for bathymetric difference indicates erosion and positive values indicate deposition.

An analysis of vessel traffic data as shown in Figure 4-22 suggested that the spatial coverage of ship tracks and the frequency of ship passage corresponds with the spatial extent of scour observed in the bathymetric data. The left panel of the figure shows reported ship locations based on the Automatic Identification System (AIS) data transmitted by ships operating in the LPR over a period of 4 months (March-June 2013 in this case). The analysis assumes that the traffic frequency and patterns during this period are similar to the period of the 2011-2012 bathymetric surveys. Such assumptions are standard practice in traffic analysis for waterfront/maritime infrastructure and the conclusions resulting from the analysis of the AIS data over March-June 2013 are not expected to impact its comparison to the bathymetric data over 2011-2012. The ship locations were converted to tracks and used to estimate the frequency of passage shown in the middle panel. The third

panel shows the bathymetric difference during the low-flow period bounded by the 2011 and 2012 surveys as an example for comparison to the ship traffic data. In general, the ship track and frequency maps show good correspondence with the areas of observed scour, with high scour typically in front of the terminals, somewhat lower in the channels, and net deposition or no change in areas that do not show evidence of shipping. A few examples illustrating the correspondence between traffic and erosion/deposition are shown with green and yellow polygons on the middle and right panels – green polygons are examples indicating areas of relatively high navigation traffic and coinciding with erosion, whereas yellow polygons are examples indicating areas of relatively low to no navigation traffic and coinciding with deposition. The consistency between the extent of observed scour in the lower two miles and the areas of the bed directly influenced by ship traffic points to navigation induced shear-stresses as the most likely cause of the scour.

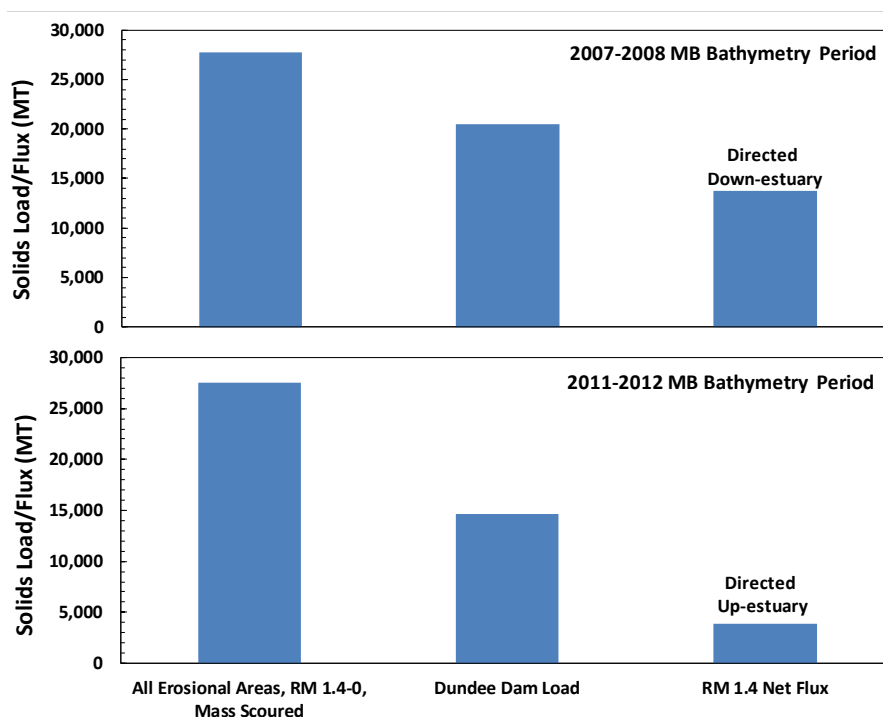


Figure 4-23: Solids mass eroded due to navigation scour compared to Dundee Dam solids load and model results for water column net solids flux at RM 1.4

In order to assess the significance of navigation scour within the larger scope of sediment transport processes in the LPR, the solids flux associated with navigation scour was compared to solids loads from other sources. The volume change purportedly associated with navigation scour in RM 0-1.4 i.e. all areas exhibiting net erosion in RM 0-1.4 in the two low flow periods surveyed, was converted to mass by assuming a dry density of 500 kg/m³, and compared to the upstream solids load at Dundee Dam which was computed based on a rating curve with river-discharge, as well as to an ECOM-SEDZLJS -predicted solids flux at RM 1.4 over the same period (using a model version otherwise considered to be calibrated). Figure 4-23 shows the resulting comparisons, suggesting that the solids loads from navigation scour is comparable to or even larger than the solids contribution

from Dundee Dam as well as the solids flux at RM 1.4. This suggests that the sediment scour and water column loading associated with navigation scour is significant relative to other sources of sediments entering the LPRSA, e.g from Dundee Dam and from exchange with Newark Bay.

The long-term evolution of bathymetry was also examined in areas subject to navigation scour to better understand the conditions under which navigation scour may occur. Navigation scour was hypothesized as an equilibrium process, with potential for scour as a function of bathymetric accumulation above an equilibrium depth, which is a water depth that is in dynamic equilibrium with the existing local ship traffic. Any sediment accumulation above the equilibrium-depth would be subject to scour to navigation induced stresses. A qualitative analysis of the evolution of bathymetry from 1983 through 2012 (single-beam bathymetries in 1983, 1989, and 2004, LPRSA multi-beam bathymetries from 2007, 2008, 2010, 2011, and 2012, and NBSA multi-beam bathymetry from late 2012) was performed to look for any convergence patterns over time that might indicate the existence of such an equilibrium-depth. Figure 4-24, Figure 4-25, and Figure 4-26 show the temporal evolution of bathymetry at four different transects located at the mouth of the LPR from 1983 through 2012. This analysis which was repeated for other transects in this reach, showed the depth at most locations tending approximately to the 2008 bathymetry, with notable exceptions being in locations of dredging events (for instance location 11 which shows a dredging event between the 2010 and 2011 surveys) or locations exhibiting deposition during Hurricane Irene in 2011 (for instance locations 12 and 13) and subsequently showing a continuing increase in water depths through 2012. This analysis suggests that the equilibrium-depth may correspond to the corrected 2008 multi-beam survey.

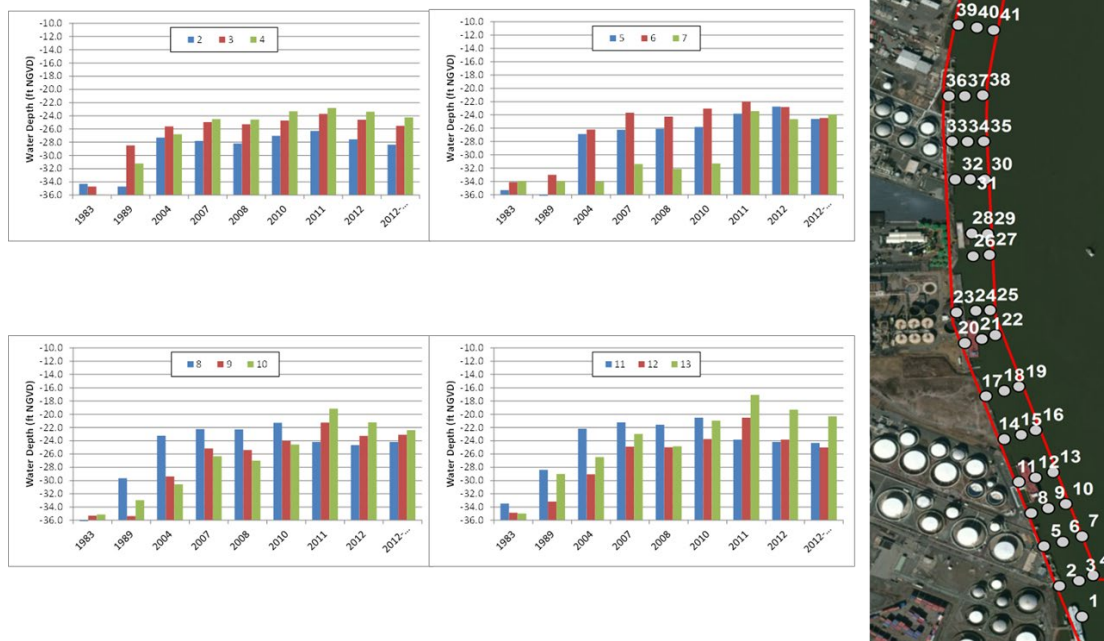


Figure 4-24: Evolution of bathymetry from 1983 to 2012 at four different transects near RM 0, with location of the observation points identified in adjoining map

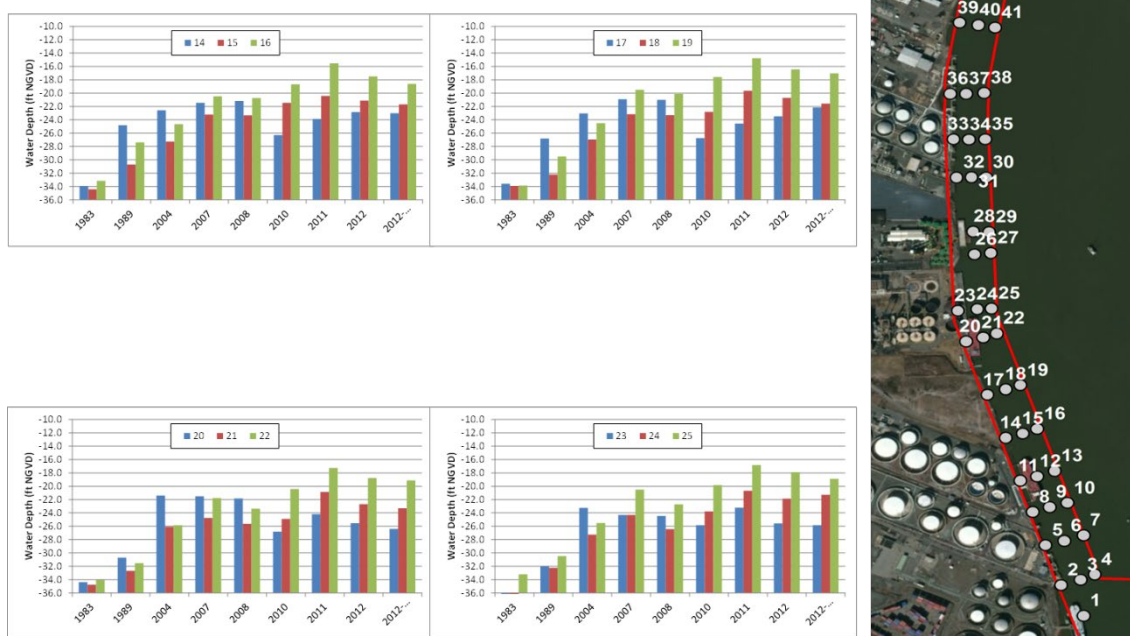


Figure 4-25: Evolution of bathymetry from 1983 to 2012 at four different transects near RM 0.25, with location of the observation points identified in adjoining map

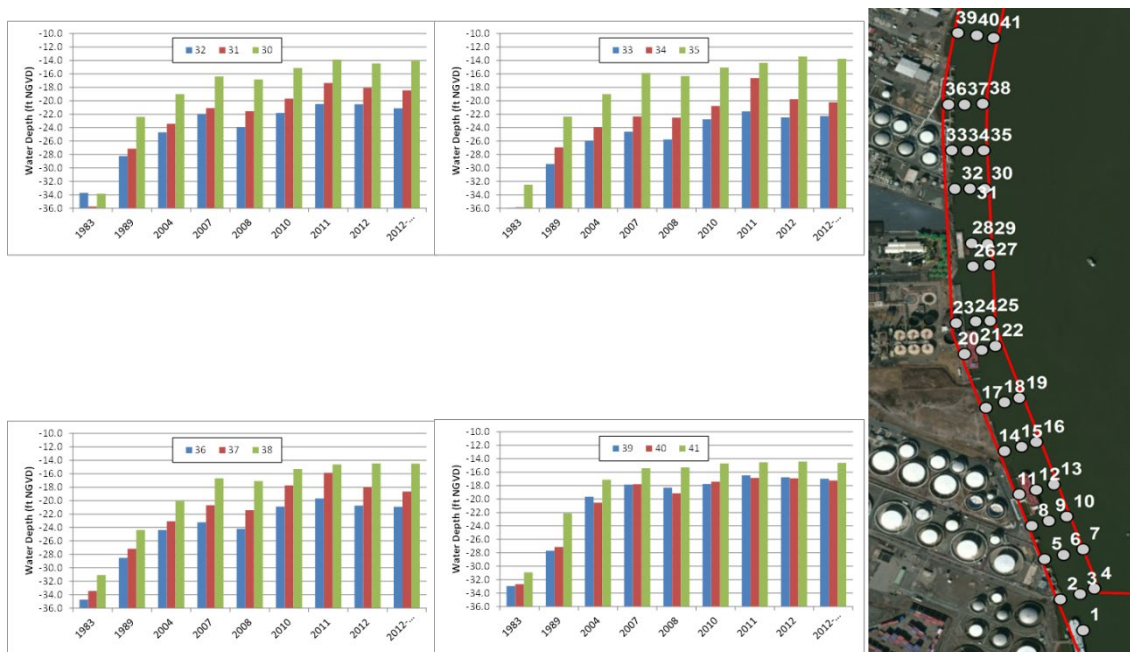


Figure 4-26: Evolution of bathymetry from 1983 to 2012 at four different transects near RM 0.5, with location of the observation points identified in adjoining map

In summary, several independent data sources such as the various multi-beam bathymetries, propeller-induced velocities, and ship-traffic data suggest the role of navigation scour within the LPRSA. Review of the historical and recent bathymetry data

in the areas subject to navigation scour also suggest that these areas are in a state of dynamic equilibrium, with the exact equilibrium bathymetry a function of the traffic and vessel types prevalent in the given area. The scoured sediment mass attributable to navigation scour is a significant source of solids to the lower miles of the LPR, and is a significant internal source of solids within the LPR that needs to be accounted for within the process-based modeling framework used for the LPRSA RI/FS. Navigation scour has therefore been included within the CPG's ST modeling framework.

5.0 ANALYSIS OF CHEMICAL DATA

The historical bathymetries presented in Section 3.0 are derived from digitized historical maps showing water depths (relative to MLW) measured along regular transects. As mentioned previously, the 1949 survey was collected after a dredging event, whereas the 1966 survey was conducted for mapping the existing water depths primarily for navigation purposes. There is no available information on the survey methodology and protocols, or the uncertainty associated with these measurements. Moreover, being derived from interpolating transect measurements, the interpolated surfaces can be subject to errors as well, an issue especially relevant in comparing the historical surveys to each other as well as to more recent multi-beam bathymetry surveys which reflect relatively precise measurements.

5.1 Historical Bathymetric and Morphological Change

Figure 5-1 shows a map of the historical bathymetric evolution calculated as the range between the 1949, 1966, and the 2010 multi-beam survey, or the accumulation from 1949 to 2010. The data show accumulation ranging between 0 to as much as 18 ft in the lower miles, with the accumulation on average decreasing with distance up-estuary. The data also show lateral trends in accumulation, especially within the S-bend at RM 3.5, with more accumulation on the inner bend than on the outer bend.

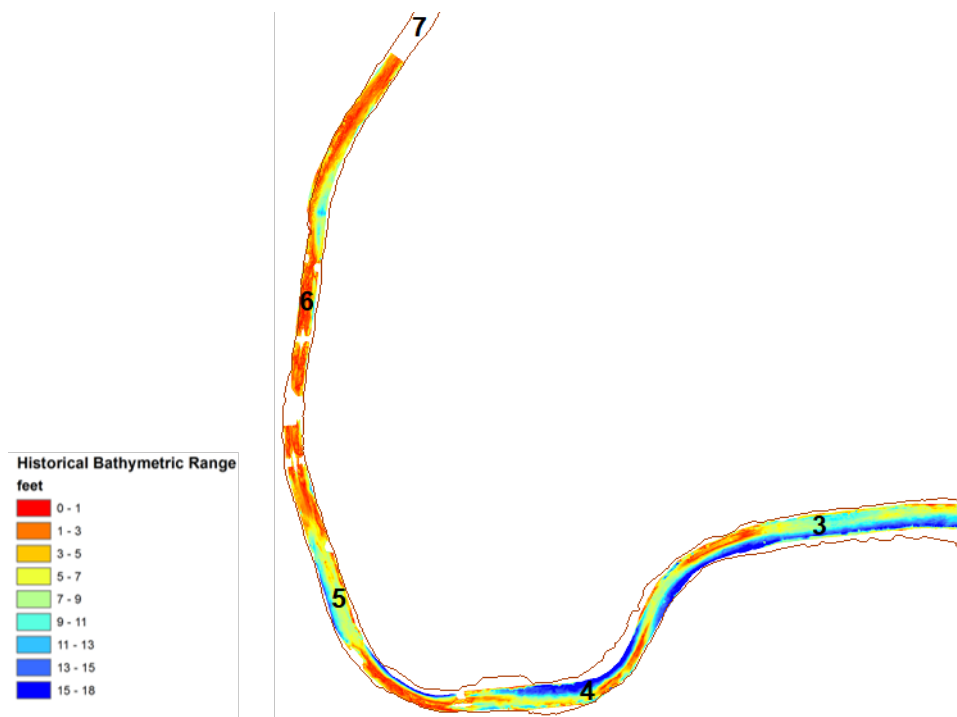


Figure 5-1: Bathymetric evolution following the last dredging event in 1949

5.2 Morphological Change, Cs-137 Sedimentation Rates and Bed Contaminant Data

In an attempt to validate the morphological (depositional) features noted in comparing the historical and recent bathymetries, sediment contaminant and radionuclide data collected in the LPR were analyzed. The datasets analyzed in this context include a sediment sampling program conducted by Tierra Solutions in 1995 (Erickson et al., 2007), and the Low Resolution Coring (LRC) program conducted by the CPG in 2008 (AECOM 2010). The Tierra survey was conducted in RM 1-7, with sediment cores collected mostly within the former navigation channel whereas the coverage of the CLRC surveys extended over the entire LPRSA. Both datasets included Cesium-137 based radio-dating from which sedimentation rates were calculated. The analysis reported here used sedimentation rates calculated from the depth of the Cesium-137 peak in the sediment bed. Contaminant measurements from the datasets used in this analysis include the surficial (top 6" of bed) measurements of 2,3,7,8-TCDD, mercury, and total PCBs. Figure 5-2 shows surface contaminant concentrations measured in these surveys, relative to their spatial location in the river. These survey data indicate about three orders of magnitude variability in 2,3,7,8-TCDD concentrations and about two orders of magnitude variability in mercury and total PCB concentrations within the lower 8 miles, with a decreasing trend in concentration observed upstream of RM 11.

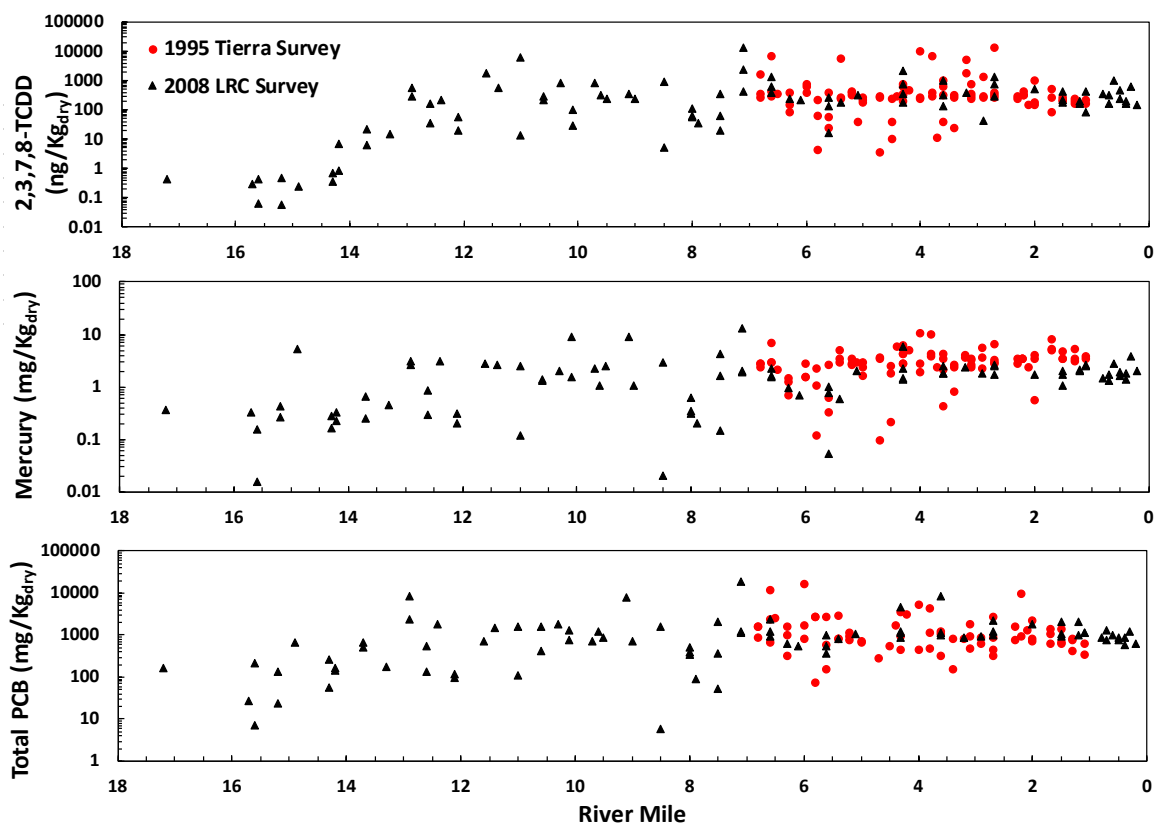


Figure 5-2: Spatial plot of bed-surface contaminant concentration data in LPR.

The morphological evolution of the sediment bed was plotted relative to the depth of the Cesium-137 peak (shown relative to the 2010 bathymetry for plotting purposes), surficial contaminant concentrations from both datasets, the 1949, 1966, and 2010 bathymetric cross sections. Figure 5-3 shows an example of such a plot, in this case including measurements from the 2008 LRC dataset (AECOM 2010), for a set of samples taken along a transect in the S-bend at RM 3.6 and plotted looking up-estuary. The morphological evolution from the 1949, to 1966, to 2010 with sedimentation decreasing from the left to right bank, is comparable to the trend seen in the depth of the Cesium-137 peak, i.e. the Cs-137 peak is covered with more sediment on the left bank than on the right bank. Furthermore, the depth of the Cesium-137 peak, which reflects the location of the 1963 depth horizon (since the Cesium-137 peak is considered to be associated with the peak atmospheric fallout rates recorded in 1963), is similar to the 1966 bathymetry (within +/- 2-3 ft). The trends noted in the morphological evolution and Cesium-based sedimentation rates are also seen in the contaminant concentrations, with near-surface concentrations increasing as the sedimentation decreases from the left bank to the right bank.

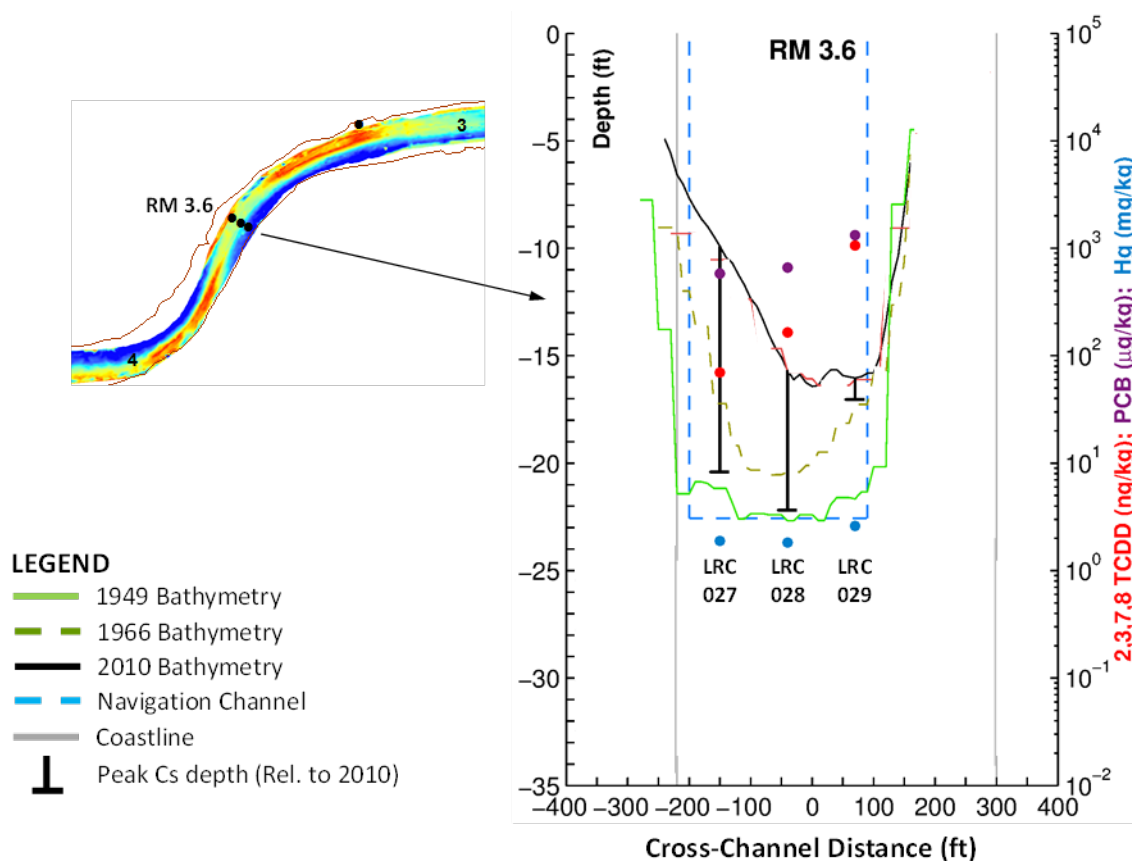


Figure 5-3: Transect plot-of surficial contaminant concentrations (2008 LRC data), depth of Cs peak, and the historical and recent bathymetries at RM 3.6 with Federally mandated navigation channel - looking up-estuary.

5.3 Cs-137 Sedimentation Rates and Bed Contaminant Data

The correlations between bathymetric evolution and the Cesium-137 sedimentation rate and surficial contaminant concentrations discussed in the preceding section are also apparent in the overall dataset. Figure 5-4, Figure 5-5, and Figure 5-6 show plots of the surficial 2,3,7,8 TCDD, mercury, and total PCB concentrations versus the Cesium-137 sedimentation rates for both datasets. In general, the highest concentrations are associated with low sedimentation rates, with near-surface concentrations declining to relatively average values as sedimentation rates increase. Samples with little to no sedimentation tend to contain the lowest concentrations, a reasonable finding given the lack of historical sedimentation at these locations. Note that in addition to low concentrations, there are also some relatively average as well as high concentrations associated with low sedimentation rates (contaminant concentrations span up to four orders of magnitude in range). Although the trend with sedimentation rate does not explain all the variability apparent in the contaminant concentrations, it does help explain an appreciable portion of the orders of magnitude variability in surficial contaminant concentrations. It should be noted that the Cesium-137 sedimentation rates are also possibly subject to artifacts and limitations associated with the identification of the location of the peak, the sampling interval (for instance the LRC 2008 data included Cesium-137 measurements on sediment slices up to 2 ft thick, whereas the Tierra 1995 data included Cesium-137 measurements over thinner slices; however, the latter dataset did not include continuous measurements with depth).

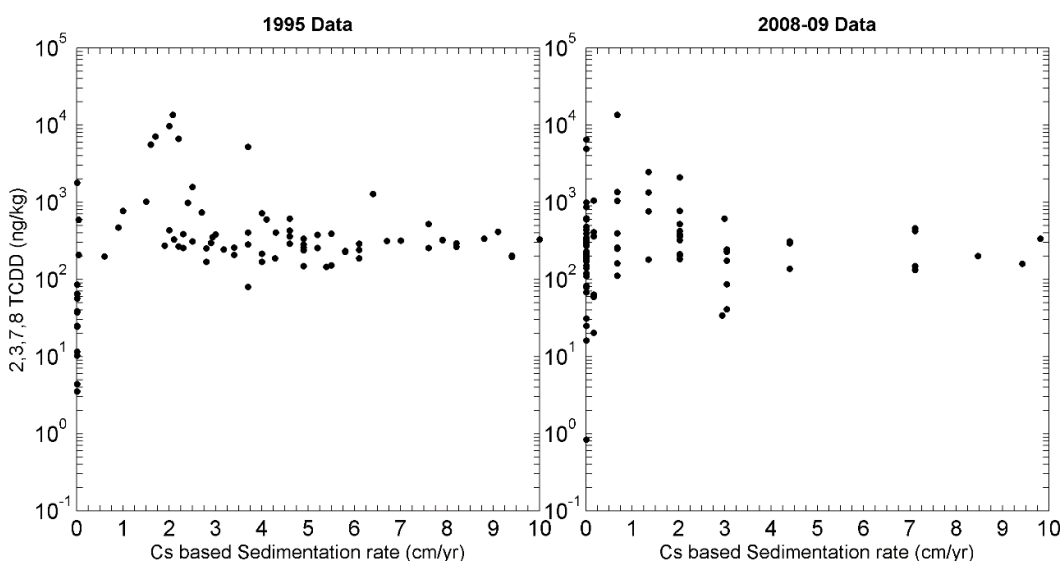


Figure 5-4: Surficial 2,3,7,8 TCDD concentrations versus sedimentation rate for the 1995 Tierra and 2008 LRC datasets

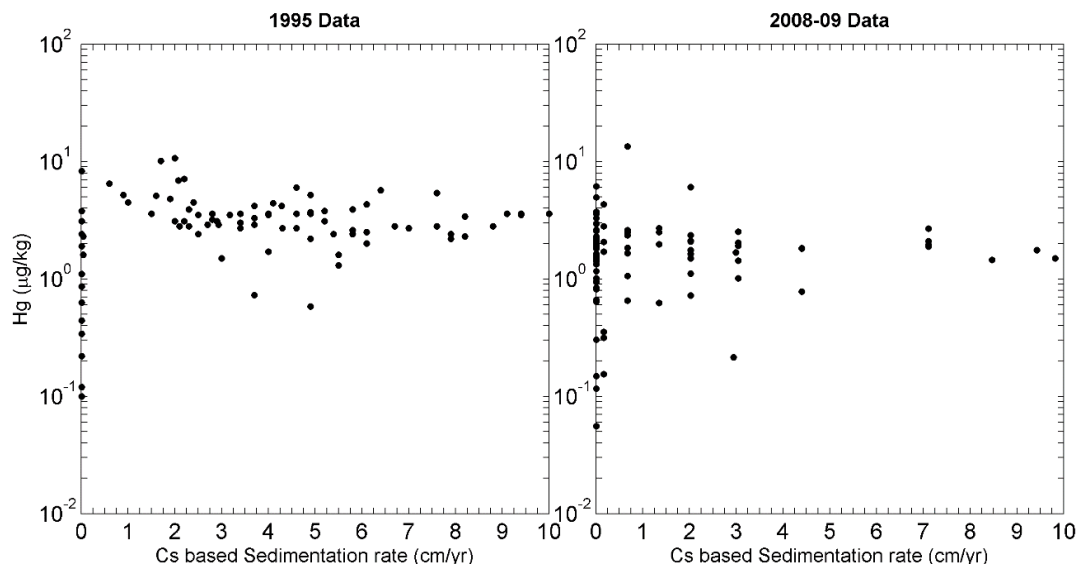


Figure 5-5: Surficial mercury concentrations versus sedimentation rate for the 1995 Tierra and 2008 LRC datasets

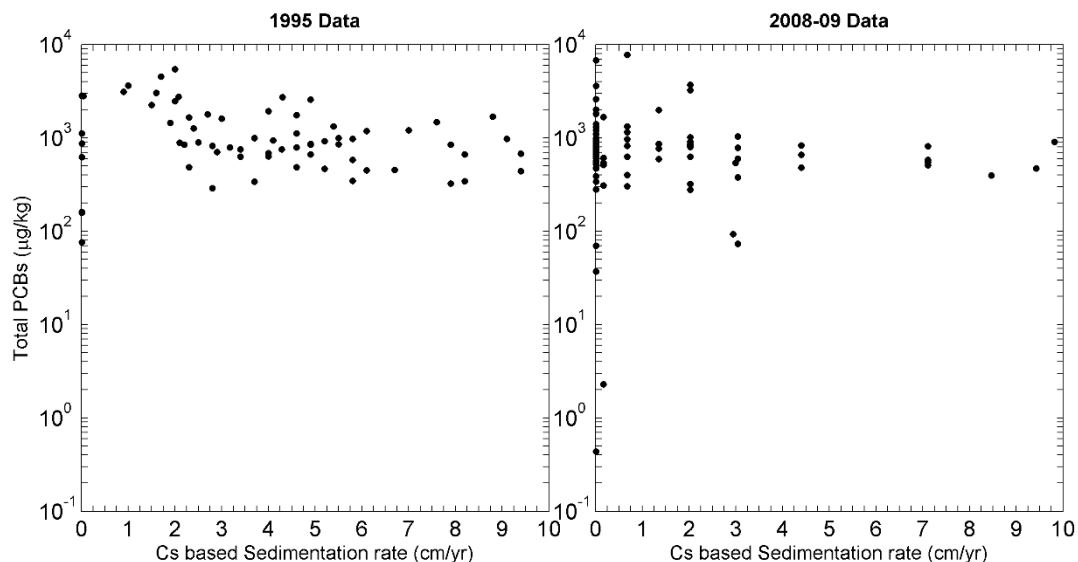


Figure 5-6: Surficial total PCB concentrations versus sedimentation rate for the 1995 Tierra and 2008 LRC datasets

5.4 Validation of Historical Bathymetries

Figure 5-7 shows comparisons of sedimentation rate from the bathymetric data (calculated using the bathymetric range from 1949 to 2010) and the Cesium-137 sedimentation rate. On average, the sedimentation rates from the bathymetry data are positively correlated with and track the Cesium-137 sedimentation rates over a wide range of values. However, there are some consistent differences in this comparison – for instance, the comparison using the 1995 data show the bathymetry-based sedimentation rate biased low by about 1 cm/year.

This might be explained by lower sedimentation rates between 1995 and 2010 compared to 1963-1995 which would bias the bathymetry-based sedimentation rate lower. In contrast, similar comparisons for the 2008 data are more favorable and do not show such a bias. The biases noted in the Cesium-137 sedimentation rates are applicable in this comparison as well. Nonetheless, the comparison in Figure 5-7 can be considered as a validation of the historical bathymetries and the morphological evolution inferred from comparing the historical bathymetries to recent multi-beam bathymetries.

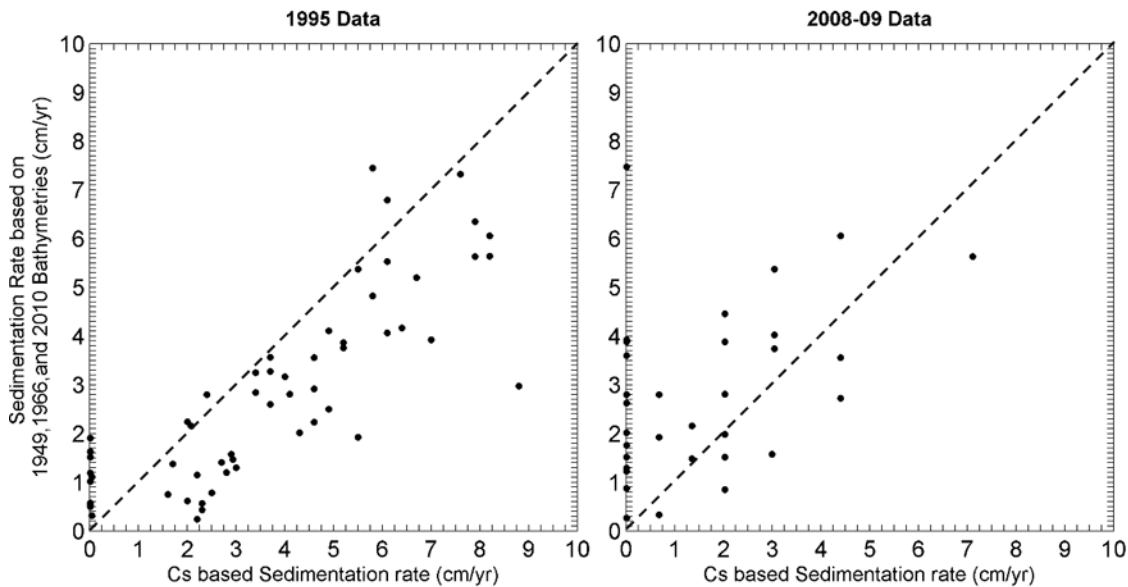


Figure 5-7: Sedimentation rates computed from historical bathymetries versus sedimentation rates derived from Cesium-137 dating. Dashed line indicates perfect agreement between the two measures of sedimentation rate.

5.5 Surficial Contamination Patterns

The comparisons and analyses presented in the preceding discussion suggest that the historical bathymetries and the morphological evolution described by comparing them to more recent bathymetries are consistent with Cesium-based sedimentation rates (and morphological change), and also correlated with contaminant distribution patterns. This implies that the historical bathymetric data are reliable and may be used as a reasonable predictor of the historical sedimentation rate and surficial contaminant patterns. The historical data were therefore used as the basis for classifying the lower miles of the river (area with historical bathymetry coverage) into four distinct zones or groups based on historical bathymetric change and also representative of the expected contaminant concentrations. Since the analysis with the historical bathymetries described in Section 2.0 focused on the footprint of the former navigation channel, the groupings provide more delineation inside than outside the former navigation channel. The various groupings and the criteria used to delineate them are listed below:

- Group 1: Areas outside the former navigation channel, and inside the shoals and margins identified by Region 2 as part of their FFS model (Louis Berger Group, 2014) and characterized by variable concentrations.
- Group 2: Areas within the channel where the range in the 1949, 1966 and 2010 bathymetries was less than 2 ft, and also found to be associated with low-average surficial contaminant concentrations. This zone includes areas that have experienced little to no sedimentation since the last dredging event in 1949.
- Group 3: Areas where the range of variability in the in the 1949, 1966 and 2010 bathymetries was between 2 and 7 ft, and also found to be associated with average-high surficial contaminant concentrations. This zone includes areas with a low historical rate of sedimentation.
- Group 4: The remainder of the areas within the river after outlining Groups 1-3, and consisting of areas with relatively high sedimentation rates and characterized by relatively average surficial concentrations.

Figure 5-8 shows a map of the range of the historical bathymetries and the derived classification of contaminant zones.

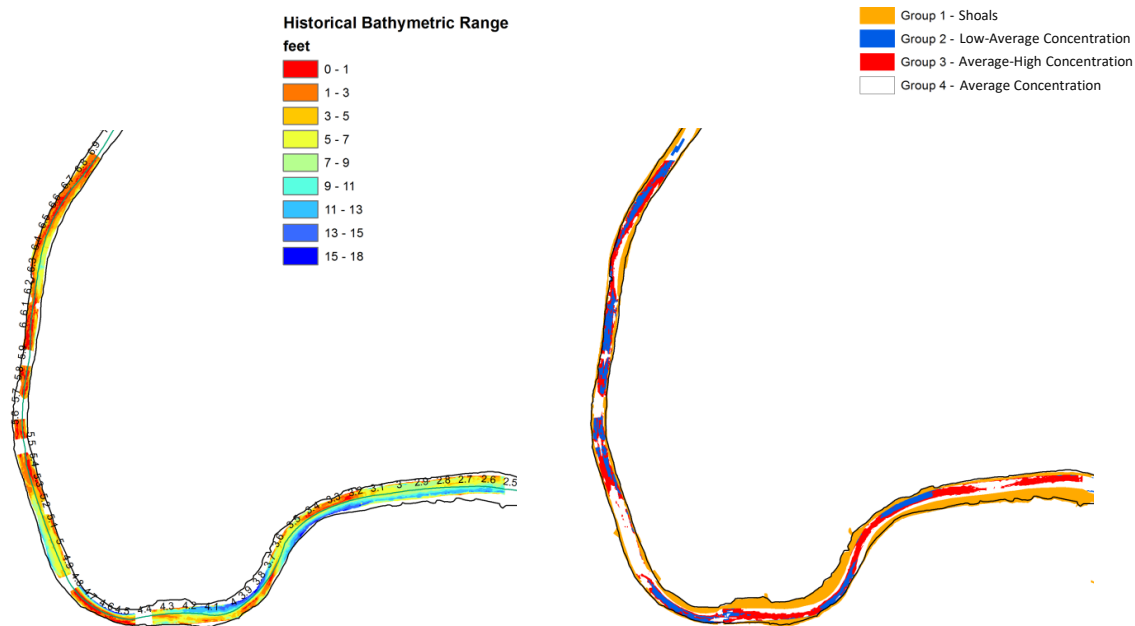


Figure 5-8: Historical (1949-2010) bathymetric change and classification to zones representative of expected contaminant concentrations.

6.0 CONCLUSIONS

This report describes the analyses of five multi-beam acoustic surveys in the Lower Passaic River carried out in September 2007, November 2008, June 2010, October 2011 and September 2012. The 2007, 2010 and 2011 surveys were carried out shortly after major river floods (>16,000 cfs in April 2007, March 2010, and March 2011, and Hurricane Irene with >24,000 cfs in August 2011), whereas the period in between the surveys of 2007 and 2008, and 2011 and 2012 were characterized by low river flows. Hence, the analyses in this report are organized around the low-river flow period 2008-2010 and 2011-2012 and the high-river flow event periods 2007-2008 and 2010-2011.

For reasons unknown, the 2008 survey data are less accurate than the other data, containing a systematic error, as has been identified by comparing the levels of permanent features in the river (rock outcrop, wrecks, etc). Therefore, the 2008 data had to be corrected by adding 0.3 ft to all data points, leading to consistent patterns for all the surveys.

The analysis of the data focused on the entire river (large-scale behavior), the processes around bridge pillars, etc. (small-scale behavior), and the meso-scale in between. At the large scale, the LPR beyond RM 2 is characterized by erosion/scour in the periods 2007-2008 and 2010-2011, while below RM 2, the mouth of the LPR shows infill. Likely, sediments eroded during high river flows up-estuary of RM 2 can settle in the LPR mouth. In the periods 2008-2010 and 2011-2012, when no high river flows occurred, the opposite picture was observed, i.e. sedimentation beyond RM 2 and erosion below RM 2. This different behavior can be understood from the effect of intensive shipping in the lower miles of the river, as a result of which this part of the river cannot become in equilibrium with the natural hydrodynamic stresses.

The meso-scale analysis reveals a redistribution of sediments in the LPR and the memory of the river. An important feature is the down-estuary transport of sand, likely imported over Dundee dam. While the upper part of the LPR (> RM 8) is characterized by bed forms, indicative of bed load of this sand, the sand enhances armoring of the river bed in its lower stretches. The meso-scale analysis also shows that Hurricane Irene only induced very small erosion in the upper reaches of the river (>RM 8). This small effect of this 1 in 90 year flood can only be explained by armoring of the bed during the 2010 floods. Further downstream, more sediments are mobilized, but not much more than during the relatively smaller 2010 floods.

At the smaller scale, cyclic scour and infill around bridge pillars, bank irregularities and river banks is an important feature in the system, accounting for about 20 – 40% of the bed surface area. About 15 – 30% of the river bed is characterized by either erosion or deposition during two subsequent surveys, while the remainder being uncertain with net changes smaller than 0.5 ft.

In addition to the analysis of the recent bathymetric surveys, the long-term bathymetric and morphologic evolution of the LPR using bathymetric surveys from 1949, 1966, and 2010 (as a measure of the current bathymetry) has also been analyzed. The historical

bathymetric evolution has been analyzed in relation to bed contamination data and sedimentation rates derived from peak Cesium-137 radionuclide measurements. The various datasets and metrics show consistent trends and patterns. For instance, the sedimentation rates inferred from bathymetric measurements have been found to be generally consistent with the Cesium-137 derived sedimentation rates. Similarly, the surficial contaminant concentrations also correlate with the Cesium-137 derived sedimentation rates and the historical bathymetric change. This has resulted in the development of an approach that outlines areas within the LPR based on patterns and magnitudes of historical bathymetric change (sedimentation), and associated with varying surficial contaminant concentrations.

We conclude that the analyses described above are in line with the three regimes defined earlier, i.e.:

- I. At river flows less than 750–1000 cfs, infill of the LPR beyond RM 1.5 – RM 2, while erosion in the lower miles of the river (<RM 1.5); this erosion is likely induced by intensive shipping.
- II. At river flows larger than 750–1000 cfs and less than 6000–7000 cfs, flushing of the suspended sediments in the river, accompanied by break-up of the fluff layer, but no considerable erosion/scour of the river bed.
- III. At river flows larger than 6000–7000 cfs, scour and erosion of the river bed. Though erosion/scour rates are limited if averaged over the entire river (e.g. around 10 cm lowering of the bed), much higher values are found around bridge pillars and the like, and in river bends – these areas are characterized by a cyclic scour at high river flows and infill during low river flows.

The data suggest that the bathymetry of the LPR beyond RM 2 currently fluctuates around its morphodynamic equilibrium, whereas the mouth of the LPR (<RM 2) is too deep owing to the erosional effects of navigation. Sediments eroded from the LPR during high river flow can therefore be buffered in the LPR mouth, available for re-infill of the LPR during periods of low river flows.

7.0 REFERENCES

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APPENDIX A: POSSIBLE SOURCES OF ERRORS IN MULTI-BEAM SURVEYS

The major error components of both single beam and multi beam surveys are:

- Tidal Modeling Errors (Phase lag, Range model)
- Acoustic System Linear Errors (Draft, Index, Squat)
- Positional Errors (pre-DGPS, pre-RTK, Latency)
- Bottom Reflectivity Variations (Acoustic frequency)
- Speed of Sound Variations (Salinity, Temperature)
- Vessel Motion Errors (Roll, Pitch, Yaw, Heave)
- System Components (Eccentric Offset Biases)
- Data Processing Biases (thinning, biased depths)
- Others

These errors are very difficult to quantify. Multibeam Accuracy Test were carried out by the USACE in the Lock Chamber of the Poe Lock, Detroit District (Sault Ste. Marie, MI) together with HYPACK, Inc. Results presented in Figure A-1 tend to indicate that even when most of the afore mentioned errors are eliminated, because it is a known surface elevation (concrete sill) and the vessel is dead in the water, results show a ± 0.2 foot variance across the entire sweep, which might be considered as the “best case” accuracy assessment the multi-beam procedure.

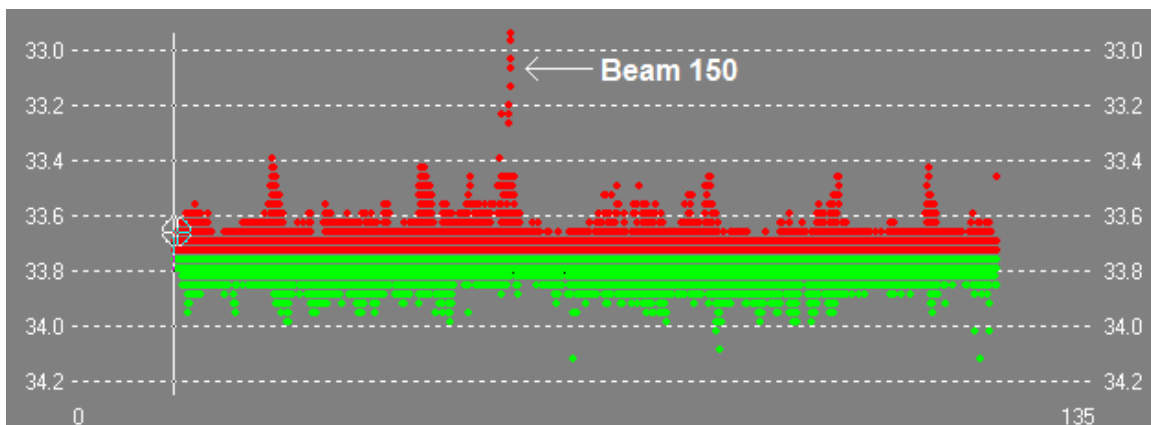


Figure A-1: Results from the Multibeam Accuracy Test were carried out by the USACE in the Lock Chamber of the Poe Lock, Detroit District

APPENDIX B: CORRECTION OF 2008 MULTI-BEAM SURVEY BY 0.3 FOOT

Stable bed features in four segments of the river were selected to assess the correction for the bed levels of the 2008 bathymetry. The four segments A, B, C and D are shown in Figure B-1 which stems from an analysis of the 2007 and 2008 multi-beam bathymetrical surveys on the basis of a $1 \times 1 \text{ ft}^2$ resolution. Note that the bathymetric differencing analyses presented in the main body of this attachment are based on a $5 \times 5 \text{ ft}^2$ resolution. A higher resolution was adopted to assess the correction for the 2008 bathymetry in order to more accurately resolve various small-scale features used to quantify the magnitude of the correction.

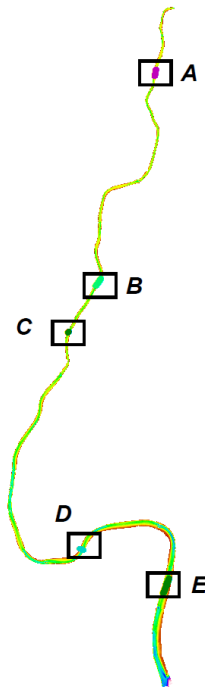


Figure B-1: Selected segments A, B, C and D with assumed stable bed features for comparison of bed levels.

Segment A

The center of this river stretch is located at RM 13.25. Figure B-2 shows the Google Earth image and the 2007 bathymetry with a $5 \times 5 \text{ ft}^2$ resolution, the surficial sediment map (Aqua Survey Inc., 2006) and a detailed bathymetric map with a $1 \times 1 \text{ ft}^2$ resolution.

Segment A is located 0.25 mile north of Union Avenue Bridge (RM 13.0). Over this river stretch the bed surface in the central part along the river axis consists of silt and sand. Near the river banks the bed composition is gravel and sand. The detailed bathymetry of 2007 shows bed forms (sand waves) with a length of 30 feet and a height of approximately 0.5 feet. The 2008 bathymetry (not shown) does not exhibit these features.



Figure B-2: Segment A: upper window: Google Earth image with 2007 bathymetry; lower left window: surficial sediment map (Aqua Survey Inc., 2006); lower right window: detailed bathymetry of 2007 with transect at RM 13.25.

A transect with a length of 700 ft parallel to the river axis is shown in the lower right window of Figure B-2. The 2007 and 2008 bed levels along this transect, as derived from the bathymetry on a 1x1 ft² grid, are given in Figure B-3 showing that the river bed in 2008

is approximately 0.35 ft lower. The periodic fluctuation reflects the presence of the sand waves in 2007. The sharp peak (mound) at a distance of about 170 ft from the transect's northern end is probably caused by a local rock outcrop, hence should not respond to erosion/sedimentation events. In particular, from this rock-outcrop in Figure B-3 it is concluded that the 2008 bed level at the location of the mound is approximately 0.3 ft too low.

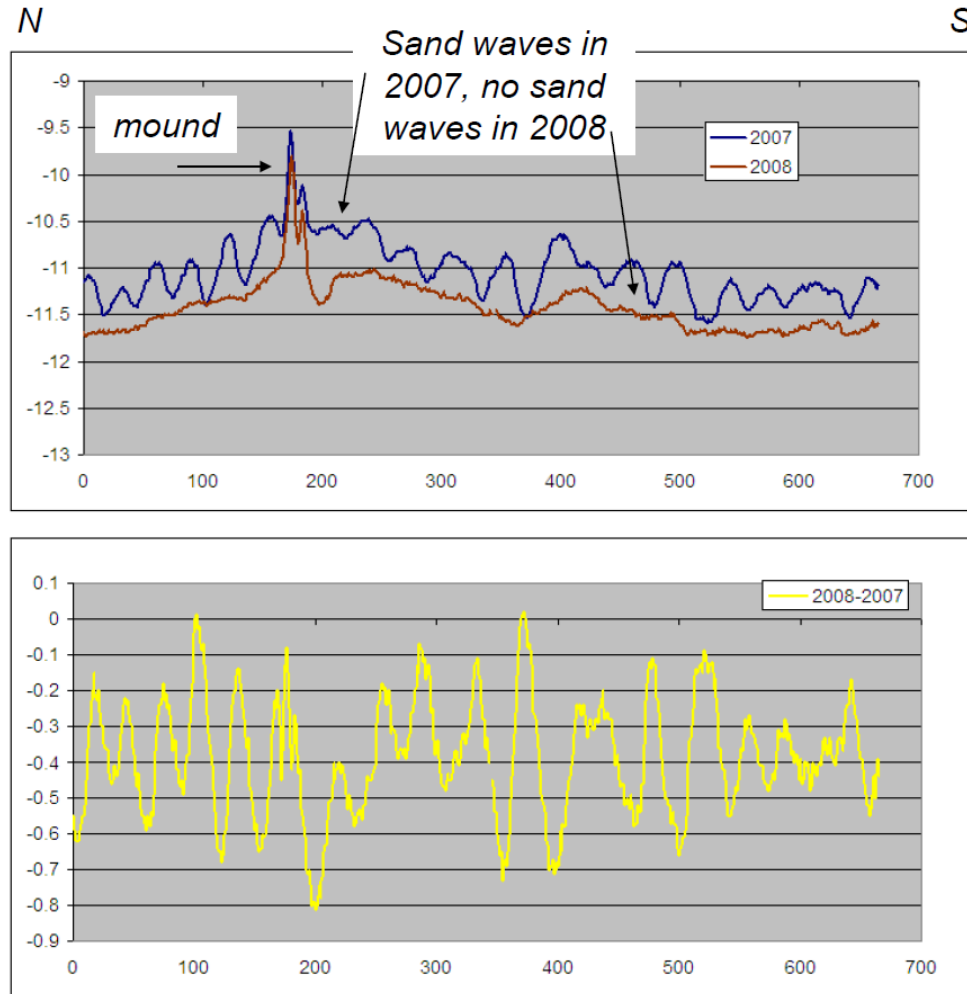


Figure B-3: Segment A: bed levels in 2007 and 2008 (upper window) and difference between 2008 and 2007 bed levels (lower window) along transect for 1x1 ft² bathymetries.

A similar analysis was performed using the 5x5 ft² bathymetries of 2007 and 2008. Figure B-4 shows the bed levels along a transect parallel to the river axis and across the mound (upper window) and the bed level differences between both bathymetries.

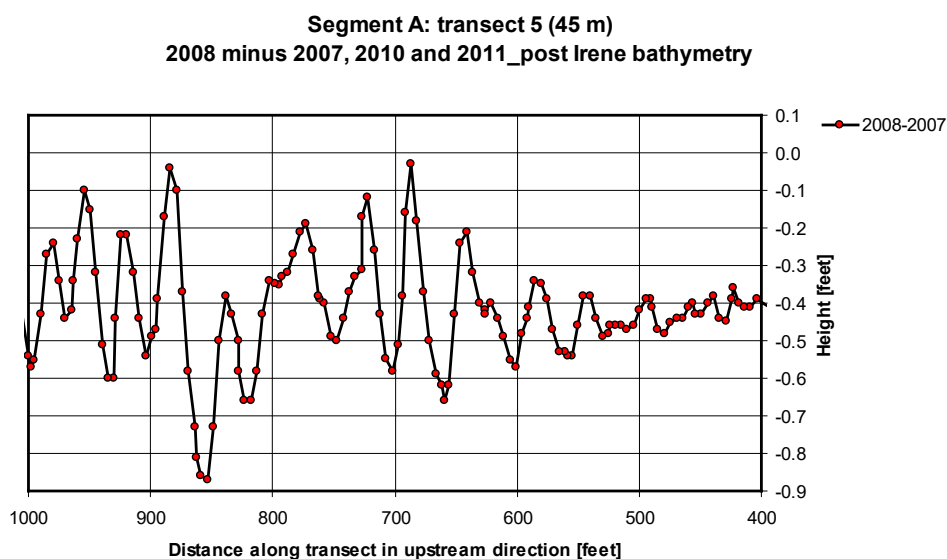
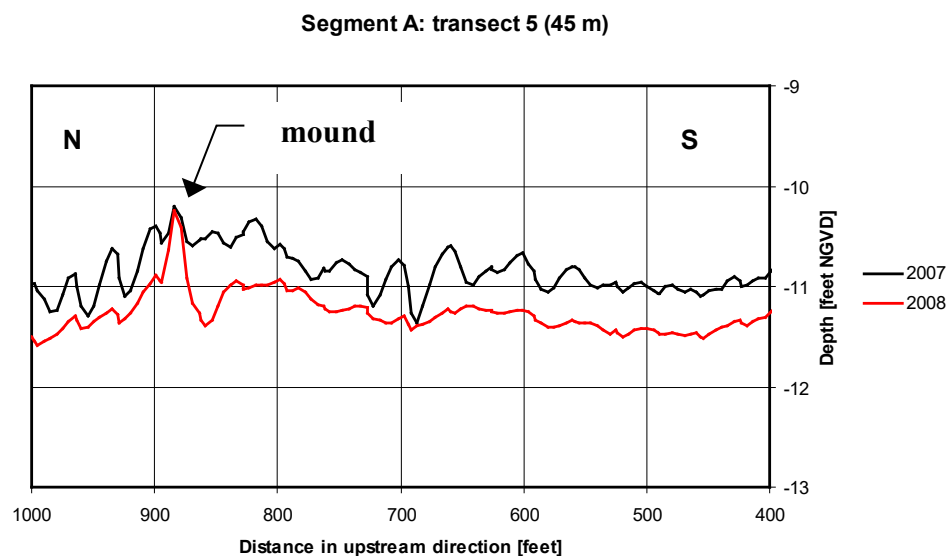


Figure B-4: Segment A: bed levels in 2007 and 2008 (upper window) and difference between 2008 and 2007 bed levels (lower window) along transect for 5x5 ft² bathymetries.

Using the bathymetrical data on a 5x5 ft² grid no evidence was found for a systematic difference between the 2007 and 2008 bed levels as was shown in Figure B-3 for the 1x1 ft² resolution data. Furthermore, for both bathymetries the bed level at the mound on the coarse grid appears to be lower than the bed level on the fine grid. The reason for this discrepancy is probably that the peak cannot be fully resolved on the coarse grid so that the average bed level within one grid cell becomes lower than the average bed level from the

grid with a high resolution. As such the mound is a too small feature to assess the accuracy of the 2008 bathymetry using a $5 \times 5 \text{ ft}^2$ grid resolution.

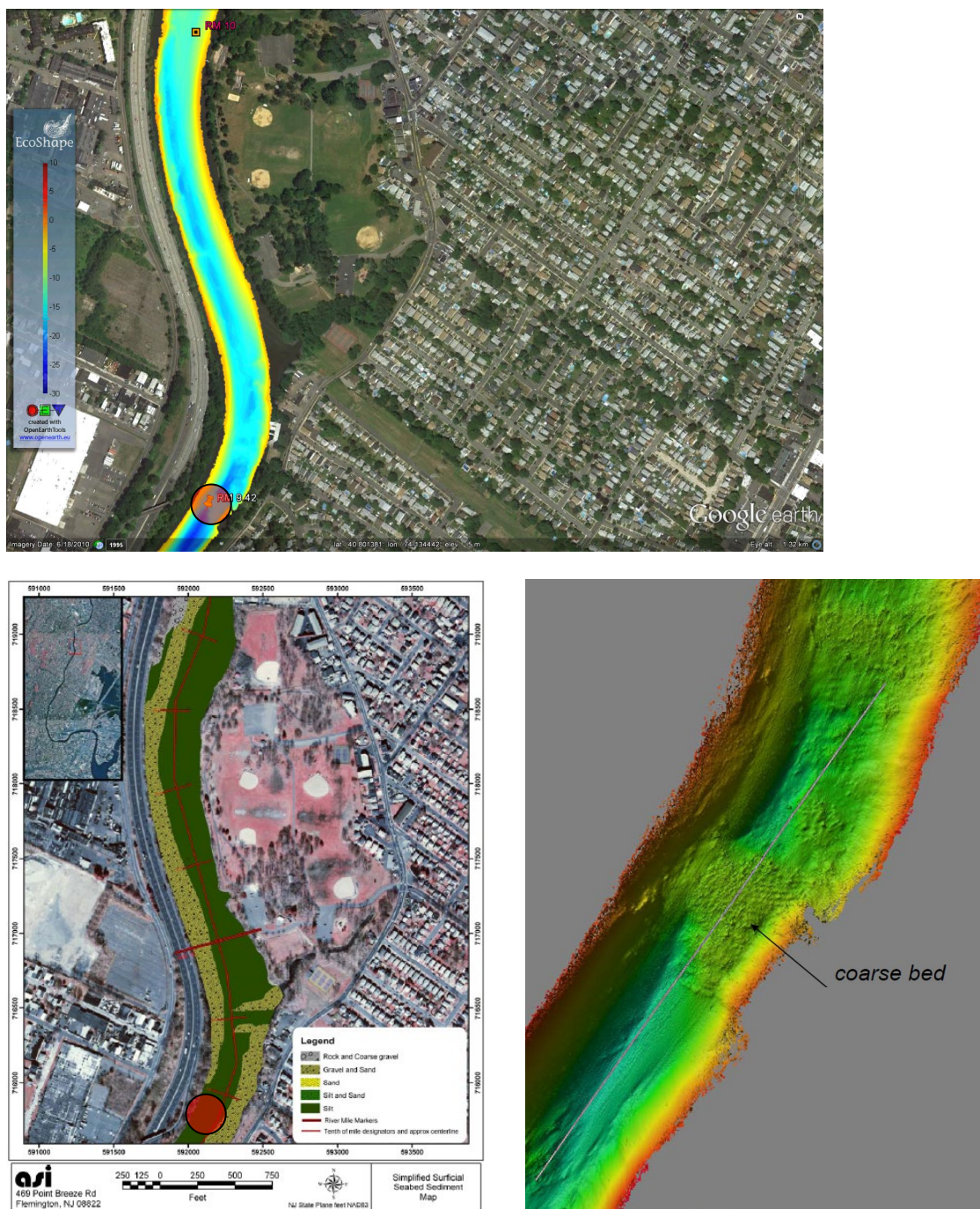


Figure B-5: Segment B: upper window: Google Earth image with 2007 bathymetry; lower left window: surfacial sediment map (Aqua Survey Inc., 2006); lower right window: detailed bathymetry of 2007 with transect at RM 9.42.

Segment B

The centre of this river stretch is located at RM 9.42. Figure B-5 shows the Google Earth image and the 2007 bathymetry with a $5 \times 5 \text{ ft}^2$ resolution, the surfacial sediment map (Aqua Survey Inc., 2006) and a detailed bathymetric map with a $1 \times 1 \text{ ft}^2$ resolution.

Segment B is approximately halfway between Bell Pike Bridge and the Jessa Memorial Bridge. In this segment, the bed consists of silt while a mixture of gravel and sand is present along the left bank (when looking in downstream direction).

Five transects parallel to the river axis with mutual distances of 20 ft are defined, see Figure B-6. Bed levels along centre transect 1 for 2007, 2008, 2010 and 2011 (post Irene) are shown in Figure B-7 (upper window). The transect crosses a section of the river with coarse, presumably non-erodible sediment (see Figure B-5), lower right window). The depth of the river bed varies 7 ft over a distance of 100 ft. It is not affected by a peak discharge such as during the Irene event suggesting that the bed is immobile. Also shown in Figure B-7 (lower window) are the differences between the 2008 bathymetry and the 2007, 2010 and 2011 (post Irene) bathymetries along the transect. In the latter figure, negative values indicate that the 2008 bed levels are below one of the other bathymetries. The non-erodible river stretch between 450 and 580 feet is indicated with solid orange vertical lines. Results show that the 2008 bed levels for this stretch are systematically lower than those measured during the other surveys. For transect 2 (20 ft to the right of transect 1) and transect 3 (40 ft to the right) similar results are obtained (not shown here) whereas transects 4 (20 ft to the left) and 5 (40 ft to the left) do not exhibit an immobile bed. As such the stable bed covers an area of $130 \times 40 \text{ ft}^2$ equivalent with $26 \times 8 = 208$ grid cells.

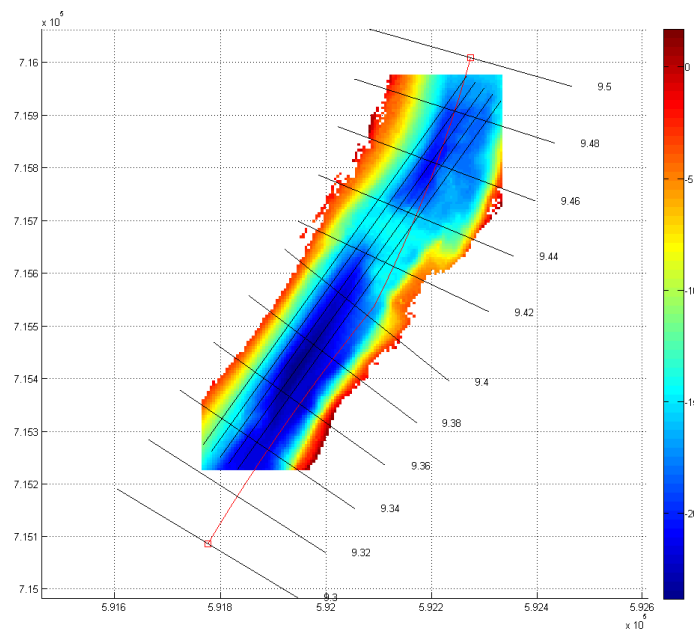


Figure B-6: Segment B: locations of transects. Centre transect 1 is at 0 m, transects 2 and 3 to the right at 20 and 40 ft and transects 4 and 5 to the left at -20 and -40 ft.

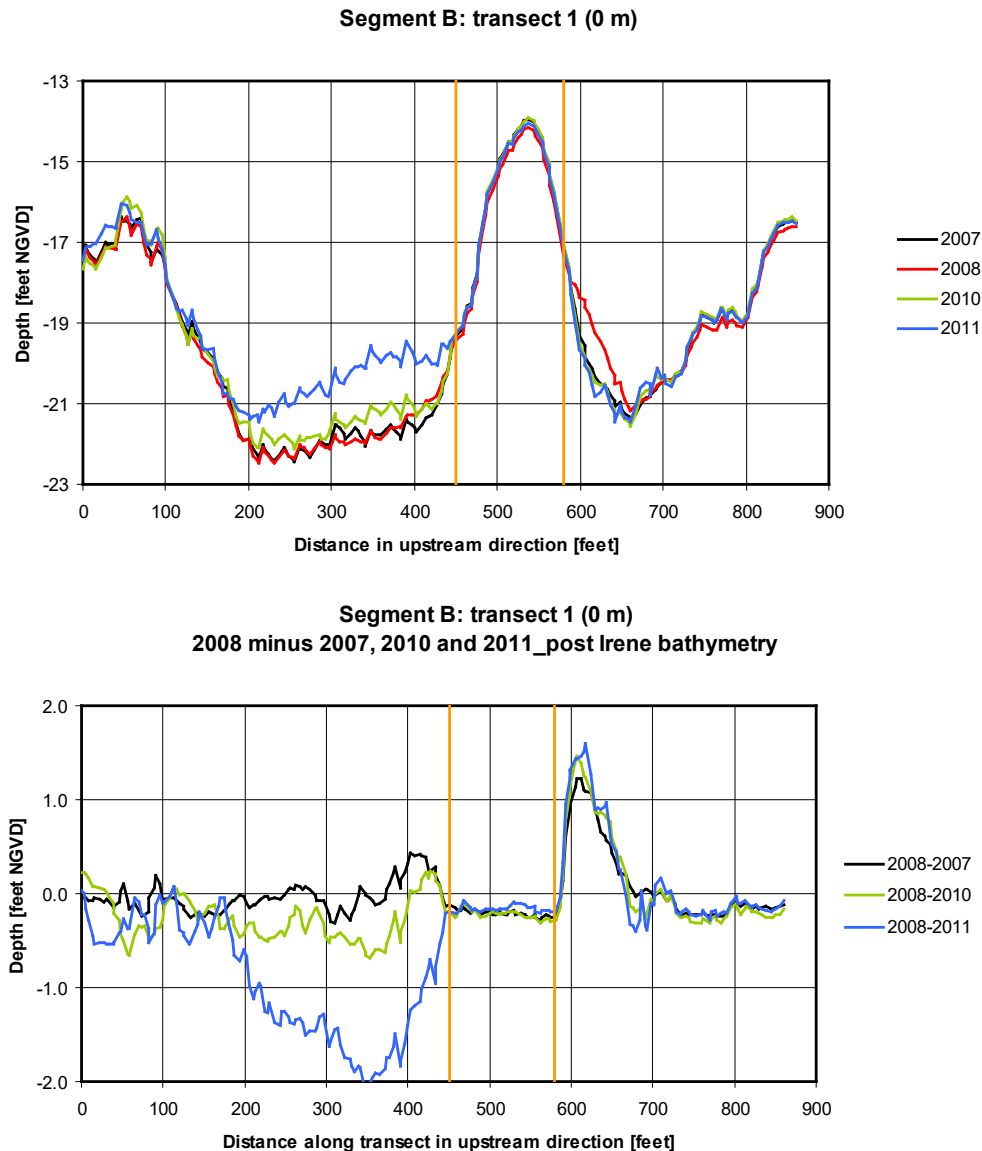


Figure B-7: Segment B: bed levels along transect 1 from 2007, 2008, 2010 and 2011-post Irene surveys (upper window) and differences relative to 2008 bathymetry (lower window) from 5×5 ft bathymetry.

Close inspection of the bed levels along transect 1 between 450 and 580 ft shows, see Figure B-8, that the 2007 and 2010 results are almost identical which confirms the hypothesis that the river bed is largely immobile. The Irene river flood results in a slight lowering of the bed with 0.1 ft so that during these conditions some erosion may have occurred. It is unlikely however that during the tranquil hydrodynamic conditions preceding the 2008 survey the bed was eroded to a larger extent than during the Irene event.

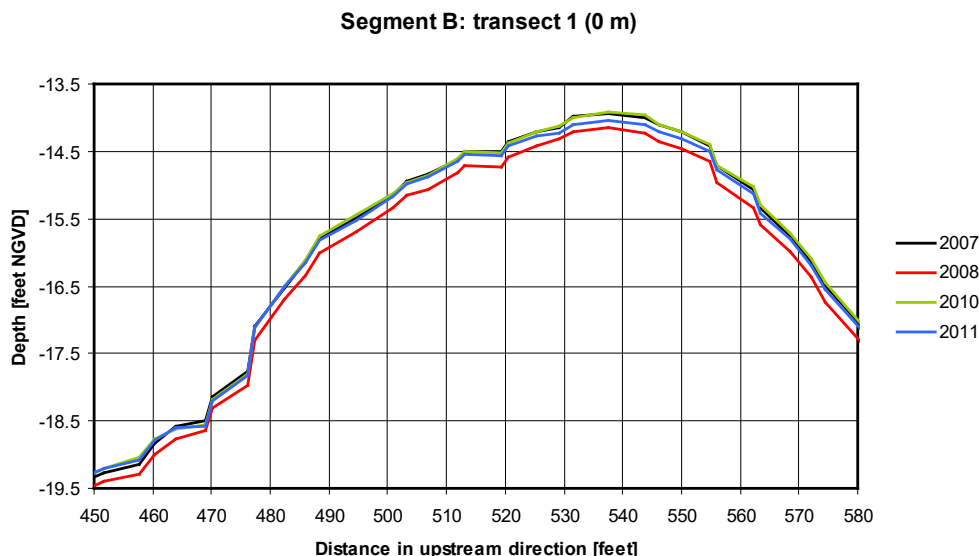


Figure B-8: Segment B: bed levels from 2007, 2008, 2010 and 2011 (post Irene) surveys along the river stretch with assumed immobile bed.

The average differences between the 2008 and the other three surveys for the non-erodible river stretch are given in Table B-1 for transects 1, 2 and 3. It follows that the 2008 bathymetry in segment B is on average 0.25 ft deeper compared to the bathymetries of 2007, 2010 and 2011 (post Irene).

Table B-1: Segment B: average difference between 2008 and 2007, 2010 and 2011-post Irene bed levels for transects 1, 2 and 3.

Transect	2008-2007 [feet]	2008-2010 [feet]	2008-2011 [feet]	Average [feet]
1	-0.21	-0.22	-0.16	-0.20
2	-0.22	-0.32	-0.20	-0.25
3	-0.30	-0.30	-0.27	-0.29
Average	-0.24	-0.28	-0.21	-0.25

Segment C

The center of this river stretch is located at RM 8.50. Figure B-10 shows the Google Earth image and the 2007 bathymetry with a 5x5 ft² resolution, the surficial sediment map (Aqua Survey Inc., 2006) and a detailed bathymetric map with a 1x1 ft² resolution.

Segment C is at the location of the Belleville Turnpike Bridge where the bed consists of sand over a distance of more than one mile. In this region also a mixture of gravel and sand is present along the river banks. Just south of the bridge there is rock and coarse gravel protruding from the western river bank. Figure B-9 presents the analysis on the basis of the 1x1 ft² bathymetry. This transect (indicated in Figure B-10) shows almost congruent

shapes in depth, but the 2008 bathymetry is approximately 0.3 ft lower. It is highly unlikely that the riverbed would be eroded by 0.3 foot, yet maintaining its shape exactly. Hence, Figure B-9 suggests a 0.3 error in either of the bathymetries.

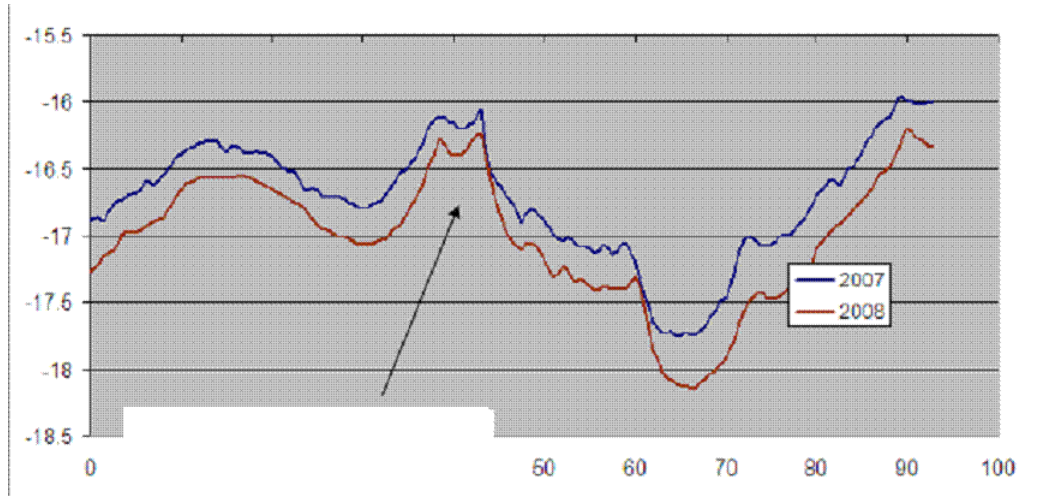


Figure B-9:Segment C: bed levels from 2007 and 2008 from the 1×1 ft survey

Next, five transects parallel to the river axis are defined at distances of 20 ft, see Figure B-11, based on the 5×5 ft² bathymetry. The transect's cross a structure of some kind which is about 150 ft south of Belleville Bridge. Bed levels along transect 4 (20 ft west of the middle transect) for 2007, 2008, 2010 and 2011 (post Irene) are shown in Figure B-12 (upper window). Also shown in Figure B-12 (lower window) are the differences between the 2008 bathymetry and the 2007, 2010 and 2011 bathymetries along this transect. For the river stretch enclosed by the vertical solid orange lines the river bed appears to be more or less stable. Outside this region the 2011 Irene event results in erosion relative to the 2008 bathymetry (here indicated as positive values). Over a length of 20 feet, the 2008 bed level of the non-erodible section appears to be systematically lower compared to the bed levels from the other surveys. Similarly, transect 1 (middle transect, see Figure B-13) shows that over a length of 10 feet the bed appears to be rather stable with the 2008 bed level systematically lower. Some erosion may have occurred during the 2011 river flood. Finally the results for transect 2 (20 ft east of the middle transect, see Figure B-14) show that a non-erodible section is present over a length of 10 feet with the 2008 river bed at larger depth. The results indicate again that during the 2011 Irene river flood erosion occurs at both sides of the stable section but that the river flood has no effect on the bed levels within this section.

Results for the three transects of segment C are summarized in Table B-2 showing that the 2008 bathymetry for the identified stable section is on average 0.2 ft lower than the bathymetries of 2007, 2010 and 2011 (post Irene).

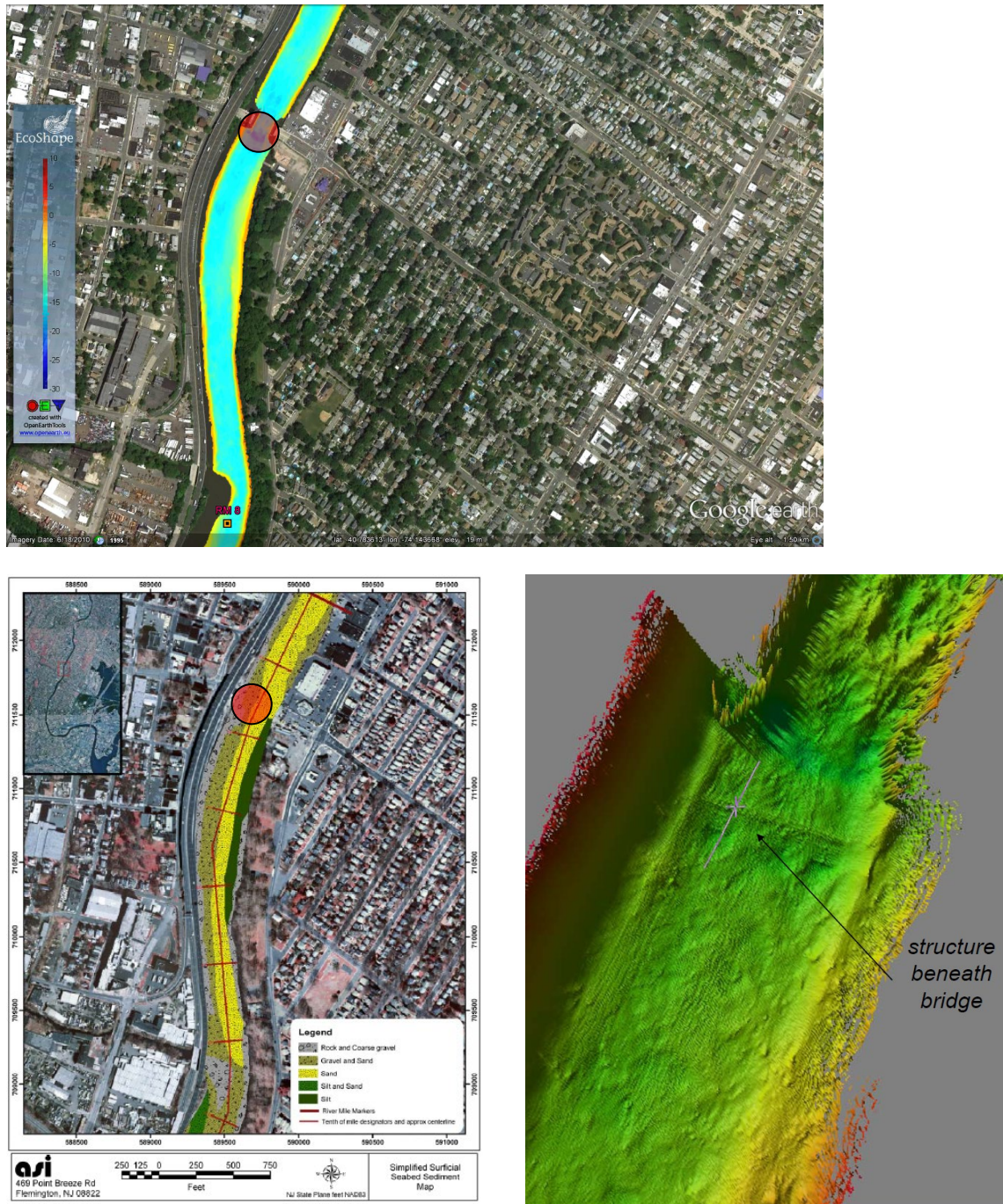


Figure B-10: Segment C: upper window: Google Earth image with 2007 bathymetry; lower left window: surfacial sediment map (Aqua Survey Inc., 2006); lower right window: detailed bathymetry of 2007 with transect at RM 8.50.

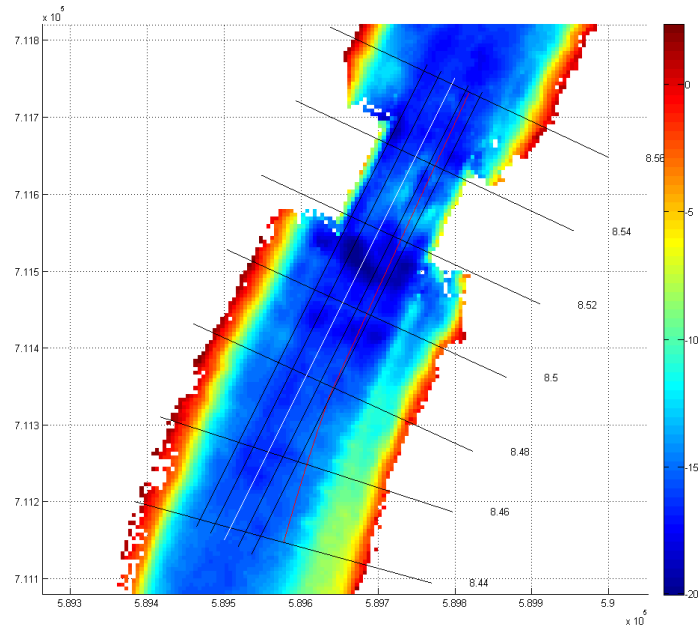


Figure B-11: Segment C: locations of transects. Centre transect is at 0 m, transects to the right at 20 and 40 ft and to the left at -20 and -40 ft.

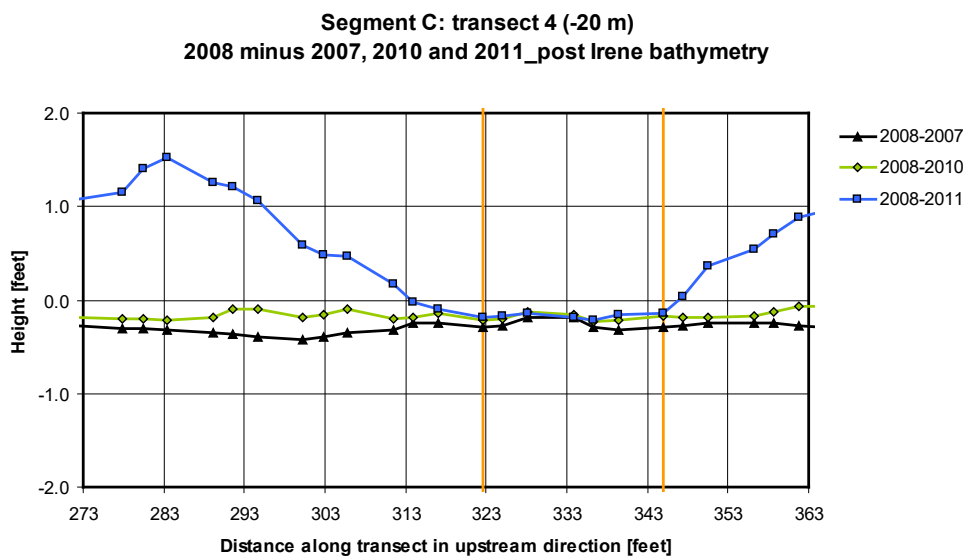
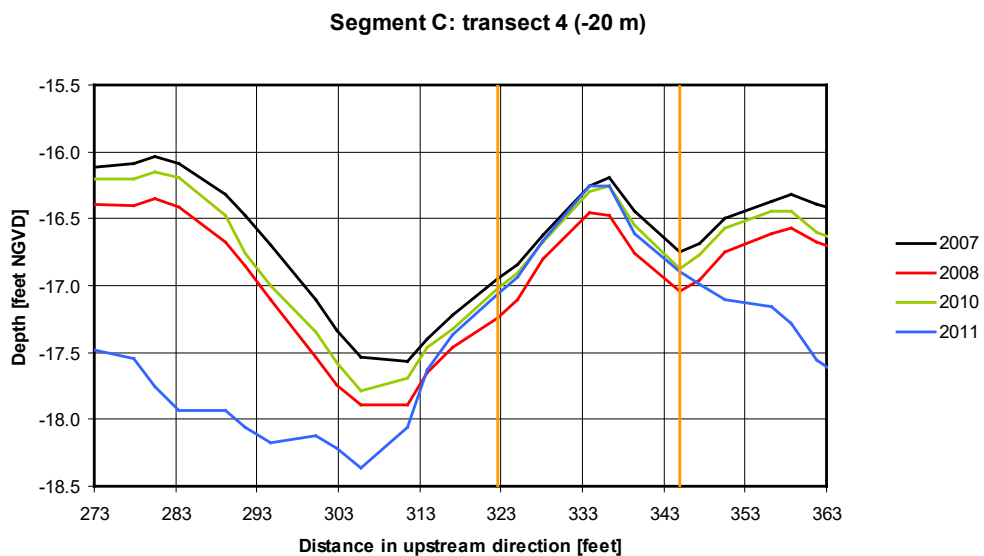


Figure B-12: Segment C: bed levels along transect 4 from 2007, 2008, 2010 and 2011-post Irene surveys (upper window) and differences relative to 2008 bathymetry (lower window).

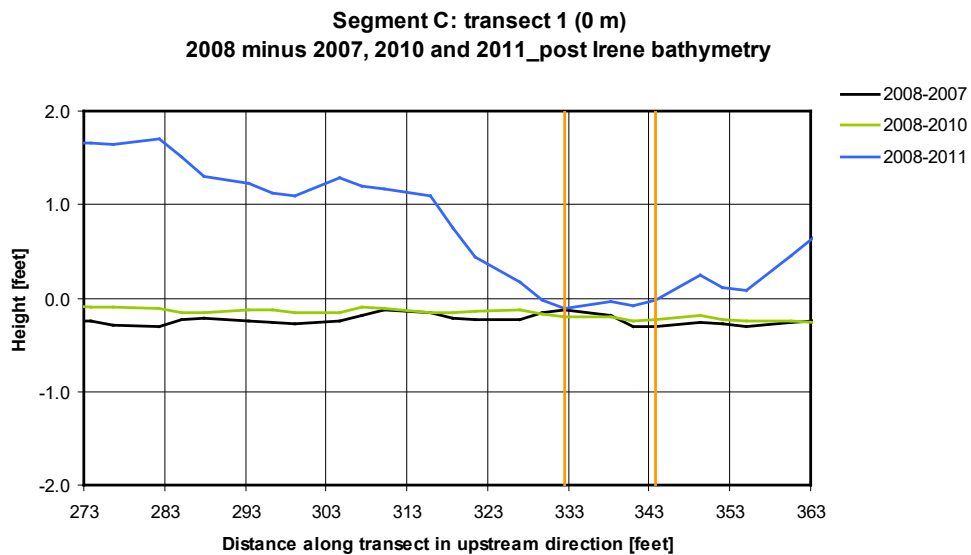
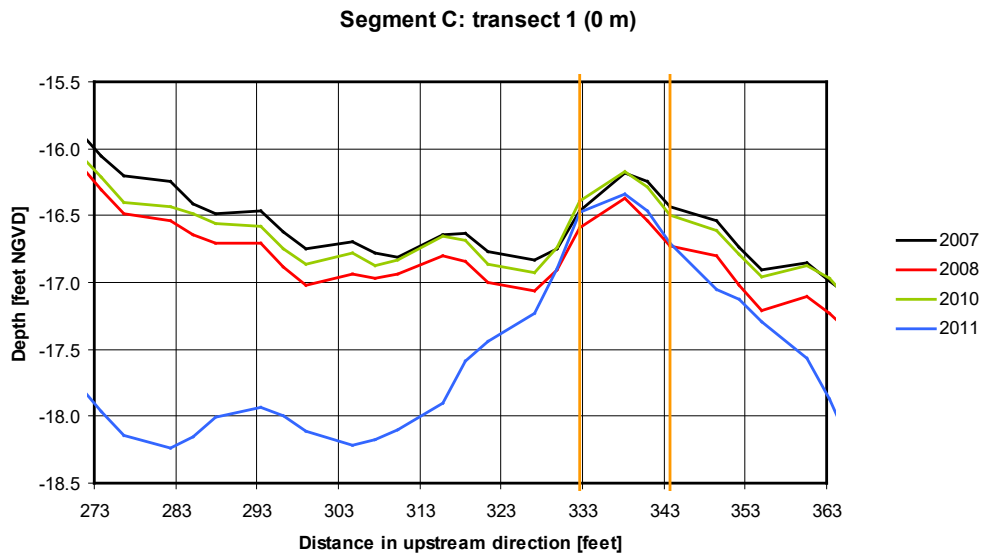


Figure B-13: Segment C: bed level differences along transect 1 between 2008 bathymetry and 2007, 2008, 2010 and 2011-post Irene bathymetries.

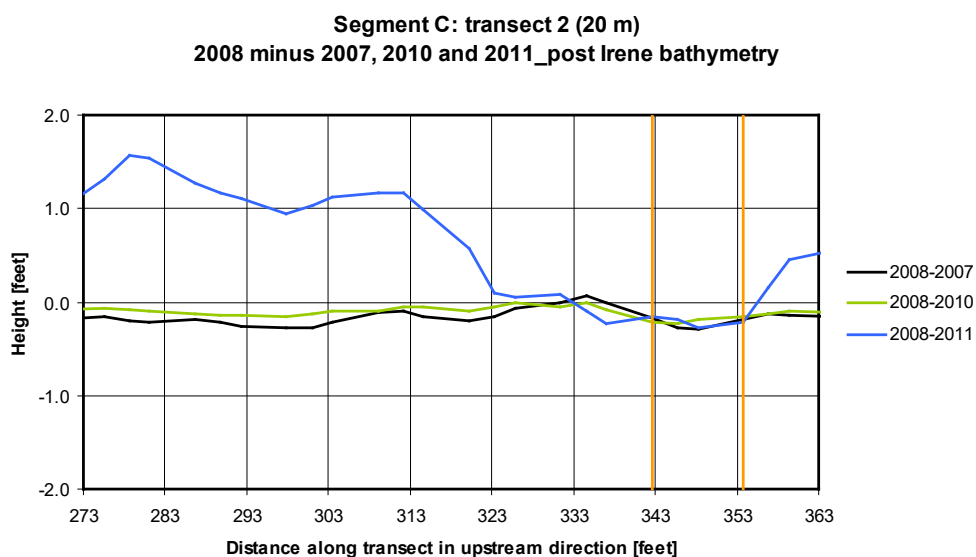
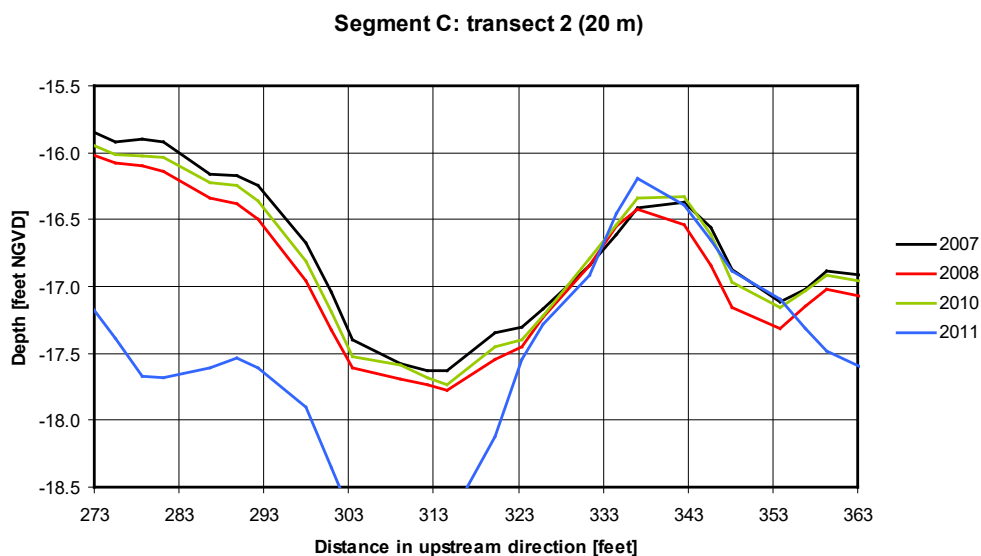


Figure B-14: Segment C: bed level differences along transect 2 between 2008 bathymetry and 2007, 2008, 2010 and 2011-post Irene bathymetries.

Segment D

Segment D is located around RM 4.5, i.e. in a stretch of the river with many bends. Figure B-15 and Figure B-16 show the 2007 and 2008 bathymetries and bed level differences, based on the bathymetries with a $1 \times 1 \text{ ft}^2$ resolution. Though some erosion and deposition take place in this part of the river, some structures in the outer bend (indicated with a white and red circle in Figure B-15) are exactly maintained, indicating no bed level changes.

Figure B-16 suggests a relative off set between the two surveys of 0.2 – 0.4 foot, with an average value of about 0.3 ft.

**Table B-2:Segment C: average difference between 2008 and 2007, 2010 and 2011-
post Irene bed levels for transects 4, 1, and 2.**

Transect	2008-2007 [feet]	2008-2010 [feet]	2008-2011 [feet]	Average [feet]
4	-0.26	-0.19	-0.17	-0.21
1	-0.23	-0.22	-0.06	-0.17
2	-0.23	-0.20	-0.21	-0.21
Average	-0.24	-0.20	-0.15	-0.20

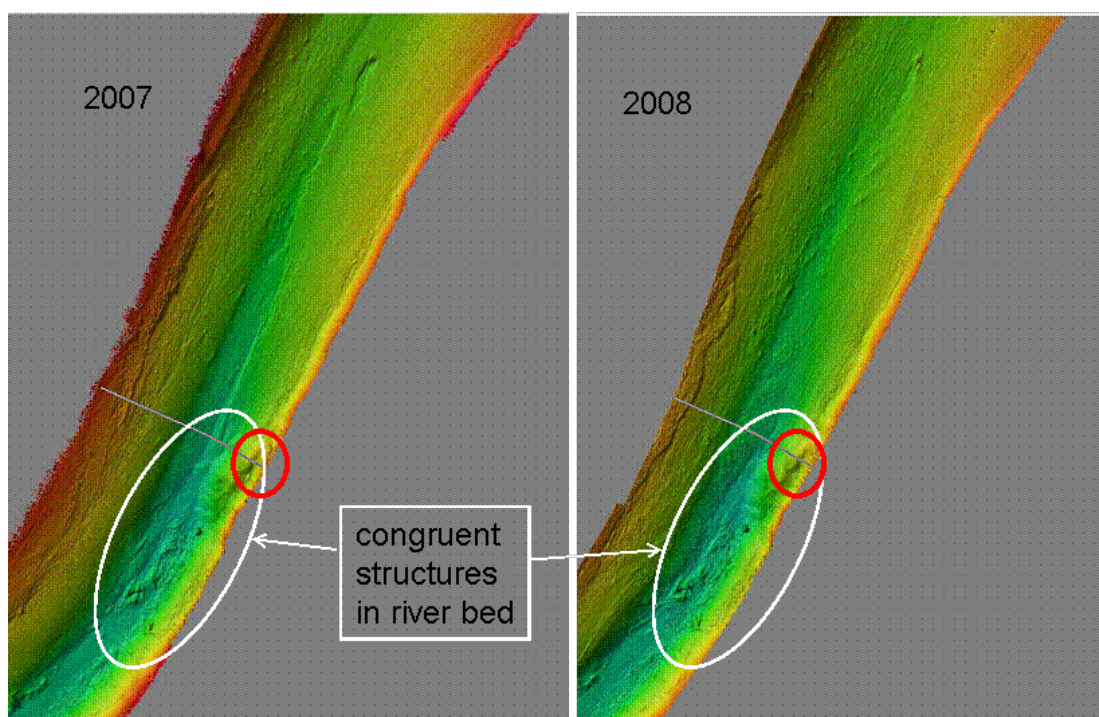


**Figure B-15: Segment D: bed levels from 2007 and 2008 from the 1×1 ft survey.
Note congruent structures in bed level – grey line and red circle refer to Figure B-16**

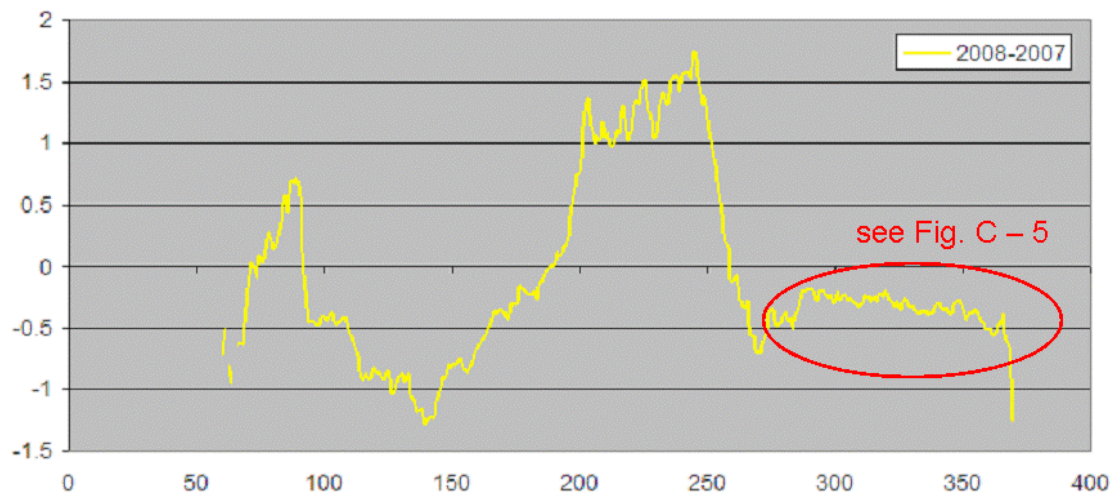


Figure B-16: Segment D: difference in bed levels from 2007 and 2008 from the 1×1 ft² survey.

Car wrecks and sonar targets

On/within the river bed of the Lower Passaic River 16 car wrecks and 24 sonar targets have been identified (Aqua Survey, 2006). Most cars are located between RM 3.7 and RM 6.5 with only one car wreck near RM 11.5. The sonar targets are more uniformly distributed between RM 2 and RM 16. It is hypothesized that these alien objects are immobile and that the bed level at the location of each object should be identical for all surveys. It is noted that not for each object and all bathymetries a vertical position could be determined as some cars and sonar targets are in areas where no multi beam measurements are available.

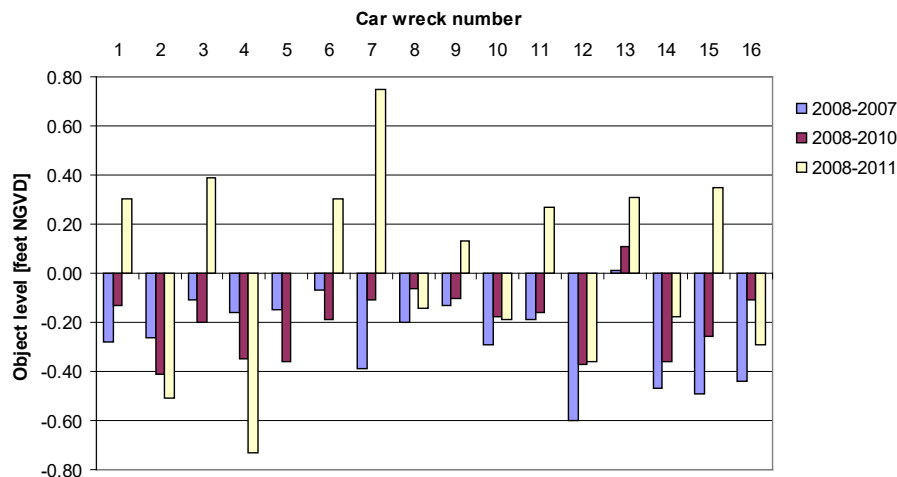


Figure B-17: Differences of bed levels between 2008 survey and 2007, 2010 and 2011 (post Irene) surveys at locations of car wrecks.

Figure B-17 shows the bed level differences between the 2008 survey and the 2007, 2010 and 2011 (post Irene) surveys at the locations of the car wrecks. Comparison of the results of the 2008 survey with those of the 2007 and 2010 surveys shows that the 2008 bed levels at the locations of the car wrecks are on average 0.26 to 0.20 ft lower than those of 2007 and 2010 surveys respectively. Comparison of the 2008 and 2011 results indicates that for both surveys the average bed levels at the location of the cars are almost identical. Possibly the high peak discharge of the Irene flood moved some cars to larger depths resulting in the positive differences shown in Figure B-17.

Bed level differences of the locations of the sonar targets are shown in Figure B-18. Also for these objects the local bed levels for the 2008 bathymetry is on average lower than for the 2007, 2010 and 2011 (post Irene) bathymetries, i.e. 0.27, 0.14 and 0.13 ft respectively.

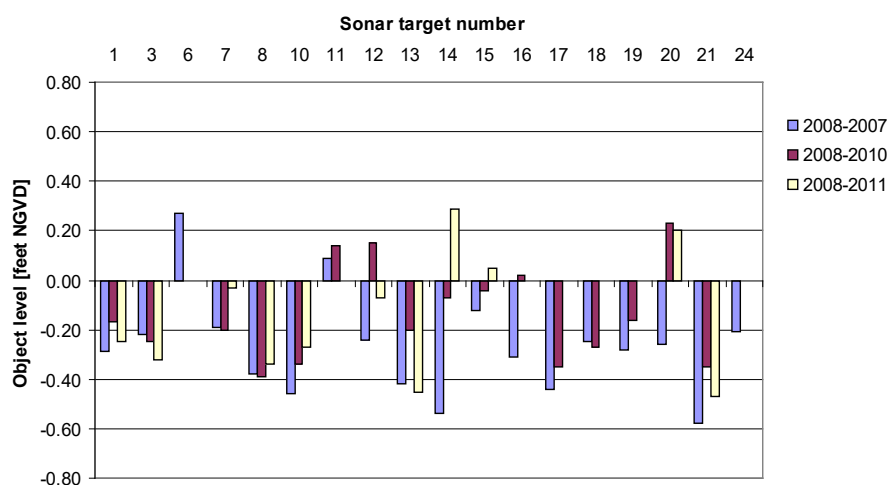


Figure B-18: Differences of bed levels between 2008 survey and 2007, 2010 and 2011 (post Irene) surveys at locations of sonar targets.

Results on bed level differences at the locations of the car wrecks and sonar targets are summarized in Table B-3 showing that the local 2008 bathymetry is 0.17 ft lower than the bathymetries of 2007, 2010 and 2011 (post Irene).

Table B-3: Car wrecks and sonar targets: average difference between 2008 and 2007, 2010 and 2011-post Irene bed levels.

Item	2008-2007 [feet]	2008-2010 [feet]	2008-2011 [feet]	Average [feet]
Cars	-0.26	-0.20	+0.03	-0.15
Sonar	-0.27	-0.14	-0.13	-0.19
Average	-0.27	-0.17	-0.04	-0.17

An overall summary for the results in segments A, B, C and D and for the car wrecks as well as the sonar targets is presented in Table B-4.

Table B-4: Average difference between 2008 and 2007, 2010 and 2011-post Irene bed levels for segments A, B, C and D, car wrecks and sonar targets.

Item	2008-2007 [feet]	2008-2010 [feet]	2008-2011 [feet]	2011-2010 [feet]
Segment A ¹⁾	-0.35			
Segment B	-0.24	-0.28	-0.21	-0.07
Segment C	-0.24	-0.20	-0.15	-0.05
Cars	-0.26	-0.20	+0.03	-0.23
Sonar	-0.27	-0.14	-0.13	-0.01
Segment D ¹⁾	≈ -0.3			
Average	-0.3	-0.2	-0.1	-0.1

¹⁾ Based on 1x1 ft² resolution of bathymetric grid.