Memorandum

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DATE: November 7, 2012 NHC PROJECT: 200051
TO: Erik Peters, P.E.
COMPANY/AGENCY: King County WLRD
FROM: Vaughn Collins, P.E.
SUBJECT: Reddington Levee Setback Project 60% Design Submittal: Scour Evaluation

Introduction

Northwest Hydraulic Consultants (NHC) is providing engineering design services for the Reddington Levee Setback Project between River Miles (RM) 28.25 and 29.5 near Auburn, Washington. This memorandum presents a scour depth analysis required for design of the integrated erosion protection for the setback project. The main objectives are to estimate scour depths and extents needed in order to design the proposed rock revetments, rock barbs, and engineered log jams (ELJs).

Scour Component Evaluation

Long Term Scour (Degradation)

The accompanying geomorphology memorandum prepared by NHC evaluated long-term bed elevation changes in the project reach. NHC used cross-sectional comparisons by NHC and those presented in the Feasibility Study (Tetra Tech, 2010); a gage height analysis at the Green River near Auburn USGS gage; and consideration of the factors driving geomorphologic evolution of the river. Comparing design cross sections for the circa 1962 River Mobile Estates (RME) levee segment with current bathymetry indicated little change in this area. The gage height analysis indicates around 2 feet of degradation occurring between 1962 until the 1980s, and the channel has been a vertically stable channel since then. Comparison of 1985, 2006, and 2010 river cross sections, documented in the Feasibility Study (Tetra Tech, 2010), also show a stable channel profile in the reach. The conclusion is that the reach has degraded, likely beginning with the White River diversion in 1906, but has reached a state of equilibrium in the last few decades. Future conditions, with the setback levee in place and the consequent increase in flow area are more likely to cause aggradation as in-channel velocities are expected to decrease. As a result, long-term bed scour is not expected in the project reach.

General Scour

Standard practice is to calculate both general and bend scour and take the greater of the two for design use. Bend scour equations include the effects of general scour and so the two types of scour are not additive. A check of the bends using updated hydraulic model results shows that bend scour, discussed below, was consistently greater than general scour. For instance, at Bend G, Lacey and Blench general scour depths are predicted to be 5.7 and 3.7 feet, respectively, while the Soar & Thorne and Maynord bend scour depths are 11.5 and 10.1 feet, respectively. General scour was therefore not considered in calculating design scour depth.

Contraction Scour

The active channel width of the Green River through the project reach is fairly uniform and does not have any bridge abutments that constrain the flow. The most significant channel contraction occurs at Bend F (Figure 1), where the channel toe width reduces from 140 to 85 feet at the bend apex. Applying the highest exponent in the Laursen contraction scour equation (FHWA, 2001) predicts 5.7 feet of contraction scour occurring under 100-year flood conditions. The three bends that show deeper scour holes (A, F, and H in Figure 1) all have noticeable contractions in width, suggesting that contraction scour is one part of the processes forming the deeper pools at these locations.

Bend Scour

Bend scour is the dominant scour mechanism for the two revetments on this project and was calculated using a number of scour equations recommended in various design manuals. Four empirical best fit and four Safe Design Curve (SDC) equations were used in the bend scour analysis. Table 1 lists the methods used.

Table 1: Bend Scour Estimation Methods

Method	Referenced In	Notes	Key Variables
Galay (1987)	(Maynord, 1996)	For gravel bed rivers, used 60 degree curve equation.	R_c/W
Maynord (1996)	(Maynord, 1996)	Developed for sand bed rivers. Project W/D ratios below minimum recommended limit of 20.	R_c/W, W/D
Soar & Thorne (2001)	(Soar & Thorne, 2001)	Used equation for W/D ratio < 60.	R_c/W
Zeller (1981)	(Simons Li & Associates, 1985)	Developed for sand bed rivers.	R_c/W, D,D_{max}, Vel,E.G.
SDC – Maynord (1996)	(Maynord, 1996)	Used safety factor of 1.08 which results in 10% of the observed data exceeding the prediction.	R_c/W, W/D
SDC – Soar & Thorne (2001)	(Soar & Thorne, 2001)	Very conservative envelope curve at low R_c/W.	R_c/W
SDC – USACE (1994)	(USACE, 1994)	Used gravel bed river curve.	R_c/W
SDC II – USACE (1994)	(USACE, 1994)	10% reduction for smooth bends per reference.	R_c/W

R_c = Radius of Curvature. W = upstream cross section width. D = Average upstream cross section depth. D_{max} = Maximum depth at upstream cross section. Vel = Average velocity at upstream cross section. E.G. = Energy gradeline.

Predicted scour depths for the 100-year and 500-year floods were calculated using each equation. The calculated scour depths for a 100-year flood were compared with the existing river channel bathymetry in order to check the applicability of the equations. Due to flow regulation provided by the Howard

Hanson Dam, flows have approached the 100-year value (12,500 cfs) many times in the past decades since dam construction.Thus the 100-year flood hydraulic conditions were judged to be reasonably close to typical scouring flows in the project reach. The Reddington Levee setback project is using a 500-year design flow of 14,900 cfs. Please refer to the end of the memorandum for a discussion on the implications of recently issued revised flood frequency estimates by the Corps of Engineers.

Seven existing bends within the project reach were used in the analysis (Figure 1). In addition, one historic bend (Bend D in Figure 1) was measured, as it is likely the river will occupy this bend in the future. Radius of curvature for each bend was developed by fitting a circle to the channel centerline of each bend in GIS. The existing river planform is characterized by tighter bends in the upper portion of the reach and gentler bends downstream.

Data for scour calculations at each current bend was taken from HEC-RAS modeling results. The HEC-RAS model is described in the accompanying Hydraulic Memorandum being simultaneously delivered for the 60% design submittal. Conservative (reach average) values of hydraulic depth, velocity, and top width were taken from the hydraulic model in areas where the river was fully confined on both banks. These values are assumed to be representative of areas where the river is not fully confined due to the consistent channel form and generally high floodplain surfaces that convey little flow. Water surface elevations, energy grade, and thalweg elevations were taken from individual cross sections representative of the approach and bend geometry. The HEC-RAS model was set up to ensure that cross sections were located at the point of maximum scour on each bend and the most representative upstream crossing or approach cross location. Table 2 lists the input data used.

Table 2: Bend Scour Input Data

Bend	Approach XS	Top Width	Avg Depth	Max Depth	Avg Vel	Energy Slope	Bend Radius	WSEL at Bend	Thalweg Elev. at Bend
100-Year Flood									
A	27.903	200	13.7	20.51	4.6	0.000136	755	54.16	26.2
B	28.054	200	13.6	20.55	5.1	0.000253	825	55.38	32.5
C	28.620	200	13.2	19.1	7.0	0.000624	988	56.68	35.9
E	28.928	200	12.9	17.86	6.0	0.000568	933	57.46	36.9
F	29.077	200	12.8	14.91	6.0	0.000333	506	58.59	31.8
G	29.383	200	12.5	15.82	6.0	0.000439	629	58.94	39.0
H	29.798	200	12.2	11.39	8.2	0.000939	450	60.88	36.9
500-Year Flood									
A	27.903	215	13.7	22.18	4.6	0.000126	755	55.78	26.2
B	28.054	215	13.6	22.23	5.1	0.000204	825	57.06	32.5
C	28.620	215	13.2	21.01	7.0	0.00022	988	58.26	35.9
E	28.928	215	12.9	19.23	6.0	0.000551	933	58.75	36.9
F	29.077	215	12.8	16.43	6.0	0.000216	506	60.2	31.8
G	29.383	215	12.5	17.11	6.0	0.000329	629	60.42	39.0
H	29.798	215	12.2	12.53	8.2	0.000858	450	62.02	36.9

Results for bend scour are presented in **Error! Reference source not found.**, Figure 2 and Figure 3 for the 100-year and 500-year floods, respectively. Scour depths for the 500-year flood were less than 100-year depths in many cases; this is due to the increase in water surface elevation (from which depth is measured) being more than the increase in scour depth, a function of the low W/D ratio of the river.

Table 3: Predicted Maximum Bend Scour Elevations (ft)

	Best Fit				Safe Design Curve			
Bend	Soar & Thorne	Maynord	Zeller	Galay	SDC USACE	SDC Soar & Thorne	SDC Maynord	SDC USACE II
100-yr Flood								
A	28.2	29.8	28.4	34.0	20.7	17.2	27.8	24.0
B	29.9	31.4	30.5	35.7	23.0	20.1	29.5	26.3
C	32.5	34.1	34.4	38.2	27.1	25.0	32.3	30.1
E	33.6	35.2	36.7	39.2	28.0	25.7	33.4	30.9
F	33.5	35.1	38.2	38.2	23.9	16.7	33.2	27.3
G	34.9	36.3	38.7	39.9	26.8	22.3	34.5	30.0
H	36.7	38.3	45.1	40.9	26.8	18.3	36.5	30.2
Avg Error	-1.4	0.1	1.8	3.9				
RMSE	2.74	2.40	4.12	4.48				
500-yr Flood								
A	29.6	31.2	29.4	35.4	21.6	17.5	29.2	24.9
B	31.4	32.9	31.5	37.2	24.0	20.7	31.0	27.3
C	33.9	35.5	34.4	39.6	28.0	25.7	33.6	31.0
E	34.8	36.2	37.6	40.3	28.6	26.0	34.4	31.6
F	35.0	36.6	38.7	39.5	24.8	16.6	34.7	28.3
G	36.2	37.7	39.4	41.1	27.7	22.4	35.8	30.9
H	37.7	39.4	45.8	41.6	27.3	17.6	37.6	30.8

When compared with existing scour depths Maynord has the lowest mean error and root mean square error (RMSE), followed by Soar & Thorne. Galay parallels these methods but consistently under predicts scour depths. The Zeller method does well in some locations but has a high variance RMSE. All methods under predict existing scour in Bends A, F, and H. As described previously, this may be due to contraction scour effects also being exerted in these bends.

The Maynord SDC results in very little additional scour depths, and in fact is higher than the existing bed at Bend F. The other four SDCs result in elevations from 5 to 18 feet below the existing bed. The Tetra Tech SDC predicts values only two feet lower than existing in Bends F and H.

Barb Scour

A literature review was conducted on the subject of scour induced by barbs or similar flow deflecting structures such as abutments, bendway weirs and spur dikes. Virtually all the sources with quantitative scour prediction equations use results from physical model studies in flumes. Much of the literature addresses scour at non-overtopping abutments, and the equations developed commonly predict extremely deep scour depths. There are a limited numbers of articles on scour at low angle, overtopping structures. Results are consistent between the studies that lower profile and gentler sloped structures induce significantly less scour than non-overtopping steep sided structures. Four barb scour equations from three sources were selected for use based on their similarity to the proposed design.

Table 4: Barb Scour Estimation Methods

Method	Referenced In	Notes
Papanicolaou et. al. (2004)	Papanicolaou et. al. (2004)	Washington State University flume study, only study with sediment scaled to gravel bed rivers, very similar geometry to proposed design
Nagy (2005)	Nagy (2005)	Flume Study
Rahman & Haque (2004)	Rahman & Haque (2004)	Flume Study, limited field validation.
Modified Melville(1992)	Rahman & Haque (2004)	Extension of Melville equation to flatter slope structures, based on same dataset as used above.

The equations used and input values are included in the appendix to this memorandum.

Results from the four methods are presented in the following table. There is approximately a five foot range in the estimates. All depths are considered best-fit, not safe design curve values.

Table 5: Estimated Barb Scour Depths

Method	Papanicolaou	Nagy	Rahman & Haque	Modified Melville
Max Scour Depth (ft)	8.1	12.9	10.9	10.8

Design Scour Elevations

Revetments

Rock revetments are proposed for the Brannan Park pump station and along the wetland meander at River Mobile Estates. Bend scour is the controlling factor for these areas.

For design of riprap armoring the USACE II SDC method, (with one modification as explained below), was selected. This curve accounts for the greater expected scour depths from the tighter upstream curves in the reach (which the Maynord and Tetra Tech SDCs do not), and overall predicts scour depths which are reasonable in our professional opinion and experience.

Geotechnical levee stability analysis also requires estimates of scour depth along the revetments as a parameter. In this case, it is appropriate to use best-fit or average case estimates rather than safe design curves as scour depths are only one of many parameters used in the geotechnical analysis.

The geomorphologic analysis concludes that the overall river planform is stable and will remain so in the future. The area with the largest and most likely opportunity for migration is into the wetland at River Mobile Estates (Bend E). Elsewhere, channel migration will likely be limited, and the current bends will generally remain in their existing position. This will be enforced in the upstream end of the project by a series of barbs designed to keep the channel away from the levee prism. Consequently, only two areas where protection from bend scour of the proposed levee itself is required are at Bend E, as mentioned above, and Bend G, which is located at the Brannan Park pump station.

Brannan Park Design Elevations

At Bend G, the proposed barbs and revetment at the Brannan Park pump station will keep the overall bend radius at current extents. The selected design bend scour elevation for riprap design using the USACE II method is 30 feet, which is about 9 ft below the lowest existing bed level in the bend.

For geotechnical design a scour elevation of 35 feet was selected. This elevation falls between the Maynord and Soar&Thorne methods results, which best predict observed scour elevations.

River Mobile Estates Design Elevations

At River Mobile Estates (Bend E) there is more opportunity for channel migration. Bends D, F, and H indicate that tighter radius bends than currently exist at Bend E are possible in this reach. Bend F has a small radius, a contracted channel formed by natural processes, and the deepest scour depths in the reach. A bend of this geometry is assumed capable of forming in the wetland at RME and impinging upon the proposed erosion protection.

Therefore, for riprap design elevations the SDC value for Bend F is applied to Bend E with an adjustment for bed slope as shown on Figure 2 and Figure 3. The resultant design scour elevation for the RME wetland is 26 feet. This is approximately 20 feet below existing ground in the wetland. Note that this design elevation assumes no engineered logjams are present as proposed in the project plans - the rock bench design accounts for the potential loss of the ELJs in the future through decay or other processes.

For geotechnical design the Bend F observed scour depth is transposed to Bend E and rounded down to an elevation of 31 feet.

Barbs

A design barb scour depth of 8 feet based on the study by Papanicolaou et al (2004) was selected in consultation with King County. As mentioned previously, this study used a model geometry most similar to that proposed for the project, and was the only study reviewed that scaled flume sediments to represent gravel bed rivers. This approach gives the smallest scour depths of the methods evaluated. The design scour depths for barbs are therefore not as conservative as those used for bend scour on the revetments. As the purpose of the barbs is to prevent erosion of the levee, some deformation of the barb tip itself should actual scour depths exceed design levels used is acceptable and will not affect project performance. A thickened rock blanket for the barb tips has been designed (in addition to the scour launch aprons) in order to accommodate uncertainty in deformation without exposure of the soil core.

Bend scour is not expected to develop at barbs 1 through 4, which are located on a straight reach of the river. Therefore the barb tip scour depth is applied to the average bed elevation of 44 feet at barbs 1 and 2. The lower thalweg at Barbs 3 and 4 (Figure 2) is on the far bank and is due to abutment/barb type scouring forces from a projection on the bank, therefore this is considered to not be additive to the scour estimate, just as bend scour calculation depths are not added to the existing bend thalweg. The design elevation is therefore 36 feet.

Barbs 5 and 6, downstream of the Brannan Park P.S. revetment, will have exposure to both bend scour and barb tip scour. Based on review of studies where barb-like structures were modeled in bends it is clear that barb scour should be considered additive to bend scour. In order to avoid overly conservative total scour depths bend scour was taken as the best-fit Maynord equation value for the 100-year flood (as noted above this was the most accurate equation evaluated). The barb tip scour depth is added to the calculated bend scour depth. This results in a design scour elevation of 28 feet.

Barb 7 is considered in a transition zone between the bend at barbs 5 and 6 and the crossing at barbs 8 and 9. Its design elevation of 31 feet is selected at midpoint between the bounding barbs.

Barbs 8 and 9 are located on the crossing. No bend scour is expected, and the barb tip scour is applied from the average bed elevation of 43 feet, resulting in a design scour elevation of 35 feet.

Engineered Log Jams

ELJs are proposed along the wetland meander revetment. The design bend scour elevation for Bend E is 26 feet. Allowing for some additional barb/abutment type scour from the structure, scour elevations could reach 21 feet, around 19 feet below the design installation grade. The structures are designed to flexibly deform and settle into the scour hole as it develops. The riverward end of the ELJ will rotate down into the scour hole while the landward end is held at the bench elevation, supported on a short rock spur. Detailed estimates of ELJ scour depth are not required: variations in scour depth of the ELJs will not affect the integrity of the revetment, and the flexible nature of the structures accommodates a wide range in scour.

Summary of Design Elevations

A summary of the design scour elevations for the various project elements (except ELJs) is shown in the following table and visually in Figure 4.

Table 6: Summary of Design Elevations

Structure	Bend	Design Scour Elevation	Notes
Barbs	G	25	Includes bend and contraction scour
Brannan Park Revetment	G	30	Bend scour with no change to current bend geometry
		35	For geotechnical evaluation
River Mobile Estates Revetment	E	26	Bend scour based on Bend F geometry. Assumes no scour reduction from ELJs.
		31	For geotechnical evaluation
Wetland Meander ELJs	E	21-26	Bend scour based on Bend F geometry

Effects of Revised Hydrology on Scour Estimates

In November 2012, the Corps of Engineers Seattle District released new estimates of regulated flood frequencies for the Green River (USACE, 2012). The median 100-year flow remains 12,000 cfs, but the 500-year median flow is now estimated to be 18,800 cfs compared to the previous estimate of 14,900 cfs. King County has determined that the project design has progressed too far to be changed at this point, but key design parameters were checked using the revised flows to ensure the project will function as intended under extreme flood conditions.

Scour estimates for the Brannan Park and River Mobile Estates revetments using the revised 500-year flow of 18,800 cfs were calculated. It is noted that in the analysis presented above 100-year scour depths were greater than 500-year depths due to the relative changes in key parameters. Scour depths using the new, higher 500-year flow are now greater than 100-year estimates, which have not changed. Using the Soar & Thorne and Maynord methods (the two most accurate methods when compared with observed data), the new 500-year scour predictions range from 0.5 to 0.9 feet deeper compared to the 100-year governing condition used in design. This additional depth results in scour elevations that remain above the safe-design curve used in project design.

References

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Figure 1: Bend Locations

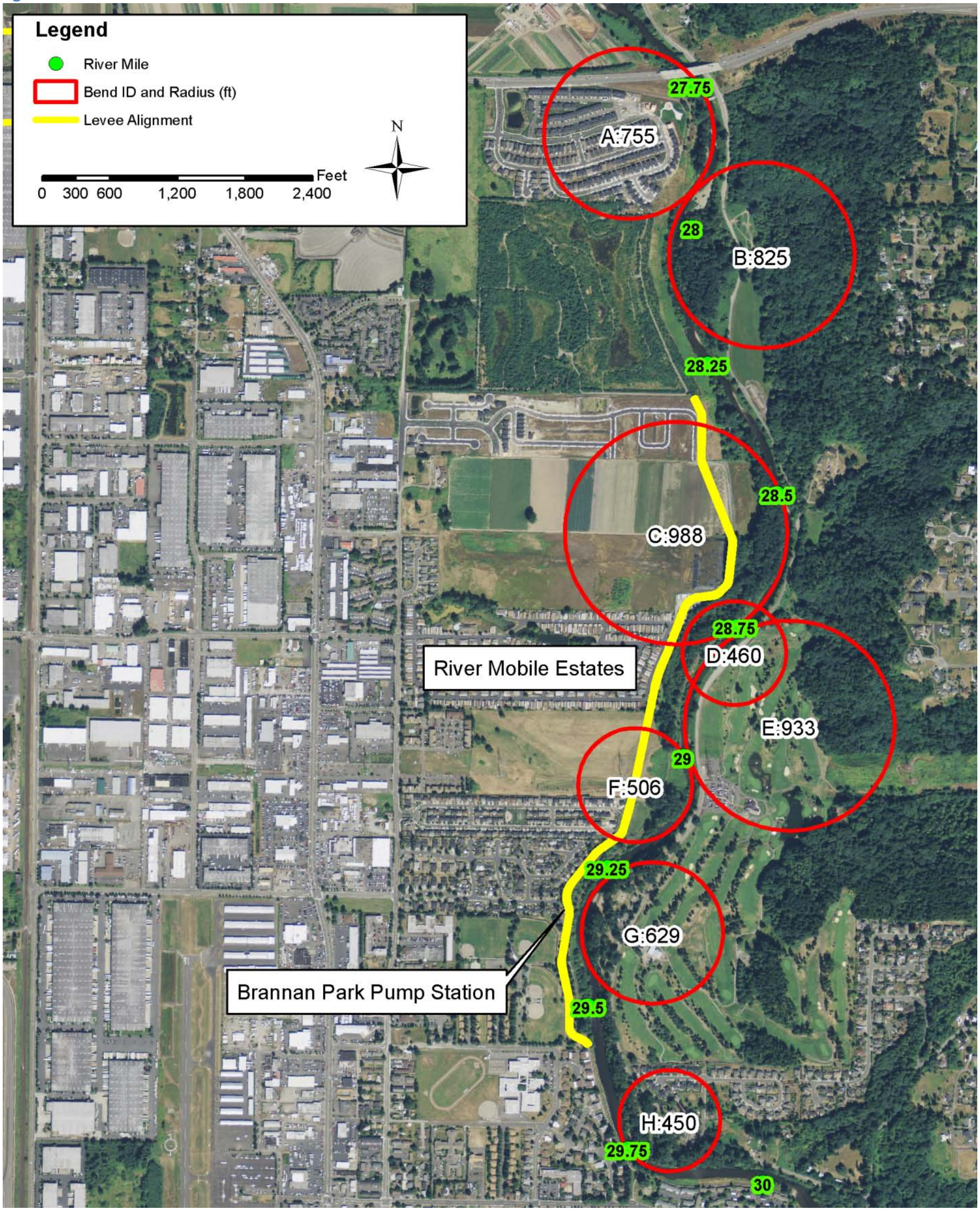


Figure 2: 100-Year Flood Scour Depths

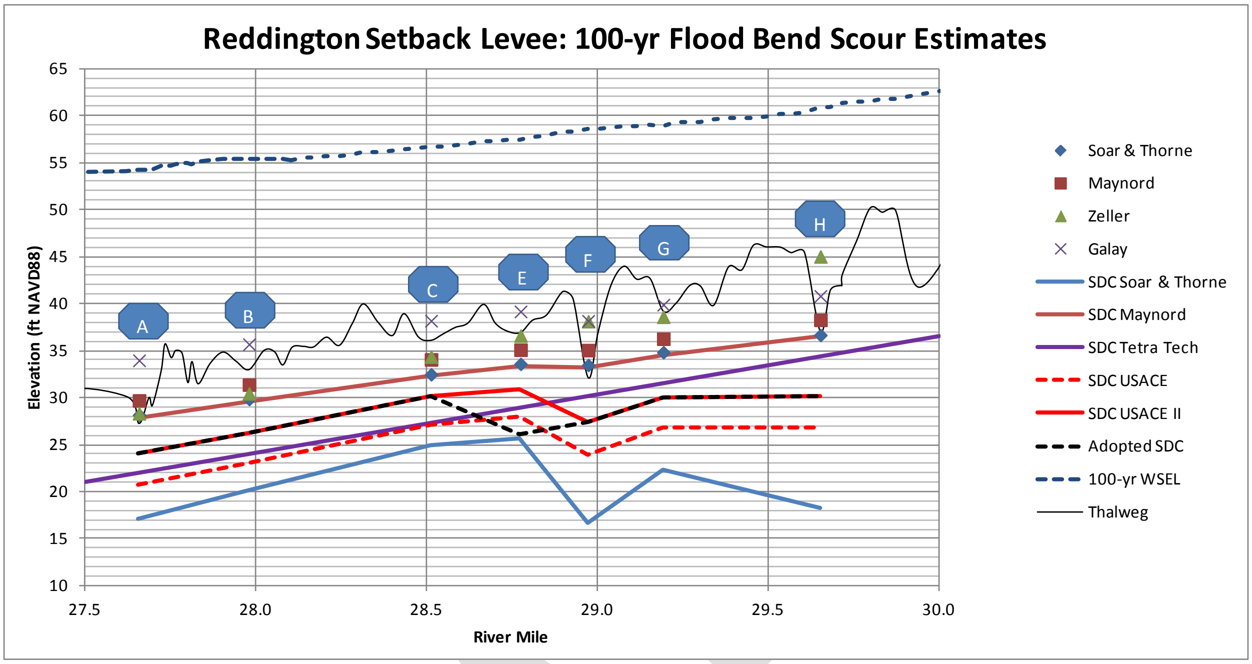
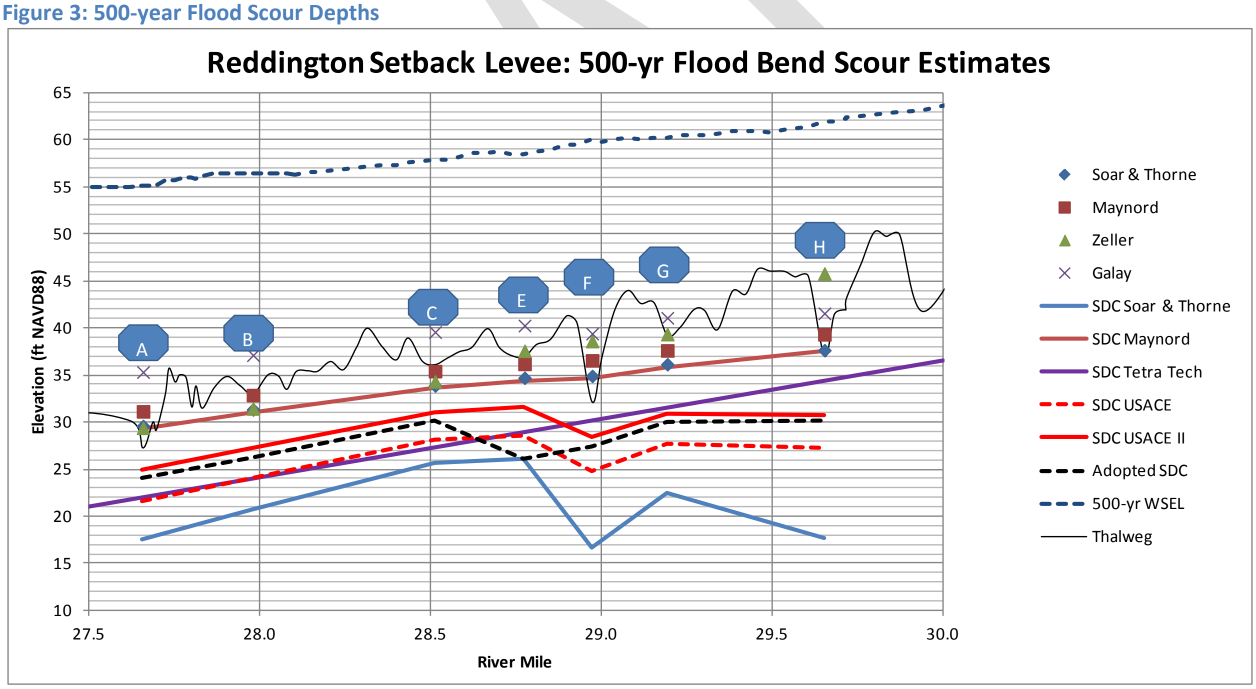


Figure 3: 500-year Flood Scour Depths



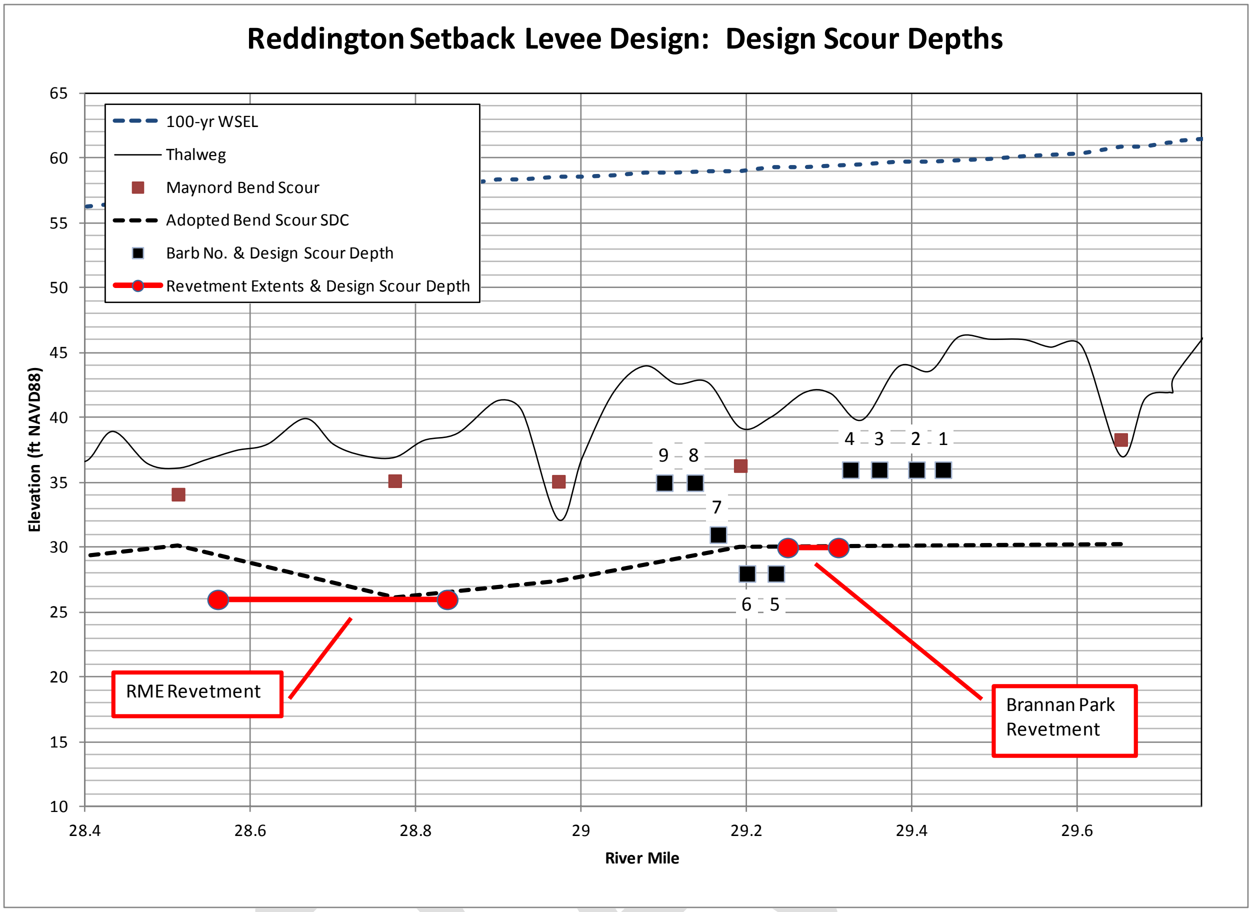


Figure 4: Project Design Scour Depths