**Ozarks Environmental and Water Resources Institute (OEWRI)**
**Missouri State University**

# Geomorphic Assessment of Upper Wards Branch, Springfield, Missouri

## Final report to Olsson Associates for the City of Springfield, Missouri

**Prepared By:**
Robert T. Pavlowsky, PhD, Fluvial Geomorphologist and Professor
OEWRI, Missouri State University
**bobpavlowsky@missouristate.edu**

Marc R. Owen, MS, Research Specialist II
OEWRI, Missouri State University
**mowen@missouristate.edu**

**August 25, 2010**

**OEWRI EDR-10-006**

## PURPOSE AND OBJECTIVES

Olsson Associates (OA) contracted the Ozarks Environmental and Water Resources Institute (OEWRI) at Missouri State University (MSU) to complete a geomorphic assessment of the Upper Ward Branch in Springfield, Missouri. The project reach is located between Republic Road and the Bradford Lake spillway and flows through a highly urbanized area of the city. The City of Springfield wants to address bed/bank instability problems along this reach. The purpose of this project is for MSU-OEWRI to provide OA with information upon which to base channel form designs and channel stability evaluations. The objectives of this study are:

1. Collect stream geomorphic information to evaluate the current and a stable geometry of this reach including channel topography (channel profile and cross-section surveys), boundary conditions (bed and bank substrate) and disturbance indicators (bank erosion, bed scour, bar form) at the reach scale;

2. Describe areas of concern and make recommendations based on interpretations of field data regarding channel morphology, bed substrate and bank stability; and

3. Interpret field data to support the planning and design phases for channel improvement and restoration projects.

This report is based on fieldwork completed on May 19 and 20, 2010 conducted during a relatively wet period when base flow was high. Olsson and Associates provided OEWRI with the longitudinal survey and bed profile for the project reach and also the results of water surface elevation modeling using HEC-RAS at the modeled Q1 flood frequency of 600 cfs and 300 cfs flows. OEWRI performed the geomorphic assessment for the Ward Branch Stabilization Project immediately downstream of the present site.

## WATERSHED CHARACTERISICS

Ward Branch is a 2$^{nd}$ order tributary of the James River located in the Ozark Plateaus region of southwest Missouri in southern Greene County (Figure 1). The headwaters begin in the SW quarter of section 6 and NW quarter of section 8, township 28N, range 21E and flows southwest toward the James River draining a total of 11 mi$^2$. The underlying geology is Mississippian age limestone in which is formed a karst landscape with numerous sinkholes, losing streams, and springs. Soils in the watershed are typical of uplands in Greene County consisting of cherty limestone residuum parent material with a thin loess cap formed under prairie vegetation (Hughes, 1982). Soils within the dissected upper valley have formed in colluvium and cherty alluvium along the narrow floodplains.

The study reach includes the portion of Ward Branch between Republic Road and Bradford Lake, a distance of 4,000 ft, located in the upper portion of the watershed (Figure 2). The stream through the study reach has several gaining and losing sections depending on water levels. The upstream drainage area is approximately 2.4 $mi^2$ and today contains a combination of high intensity development from commercial land use and lower intensity housing developments for a total urban land use of 83% with approximately 47% impervious area (i.e. buildings, roads, and sidewalks) (OEWRI, 2007). Approximately half of the watershed area (1.2 $mi^2$) drains to Bradford Lake, a 3 acre impoundment on the upstream end of the project area.

## METHODS

Geomorphic data on "typical" sub-reach characteristics including channel cross-sections, bed substrate pebble counts, and bank conditions were collected at 9 sites. Visual inspections of channel morphology, bed substrate, bank conditions, and valley form were used to evaluate channel stability and dominant geomorphic processes. Channel cross-sections were measured using an auto-level and stadia rod along a tight tape at glide-riffle crest transition zones when present. Pebble counts were collected at each cross-section to describe the variability in grain roughness along the bed and assess sediment mobility. The intermediate diameters of 15-30 bed samples were measured for both riffle/glide areas at each cross-section site where bed sediment was available, from bar areas, and from inside two box culverts. In addition, the diameters of the the 3 largest mobile clasts were also measured. Longitudinal profile data, stationing, and bed form information used in this report are based on surveys collected by OA survey crews.

Channel dimensions, substrate properties, and bedform are used to analyze flow properties, flood conditions, and sediment mobility. Discharge is calculated at both bankfull and the channel-full capacity using the continuity equation:

$$Q = A \times V$$

Q = discharge ($ft^3/s$)
A = channel cross-sectional area ($m^2$), note: A = W x D
V = mean velocity of flow (ft/s) (estimated using Manning's Equation)
W = width of water surface in channel (ft)
D = mean depth (ft)–both W and D are calculated from channel survey data.

Manning's equation is typically used to calculate mean velocity of the flow for use in the continuity equation. Manning's equation requires a roughness coefficient "n" value that is estimated in this protocol using a field based method. Mean channel velocity is calculated as follows:

$$V = (1.49 \times R^{0.66} \times S^{0.5}) / n$$

R = A/Pw = hydraulic radius (ft), note: R can be estimated by: (W x D) / (2D + W)
Pw = wetted perimeter (ft)
S = channel slope, calculated as rise-over-run either in ft/ft or m/m
n = manning's roughness coefficient (gets larger as roughness increases)

This study uses a field-based approach to estimate Mannings "n" using sinuosity, median grain size, and mean residual pool depth to account for channel irregularities due to planform pattern, bed sediment size, and bed form topography (French, 1985, Pizzuto et al, 2000, Martin, 2001). Manning's roughness coefficient (n) is calculated using the following equation (note metric units):

$$n = F_p (n_g + n_b) + n_g + n_b$$

$F_p = 0.6\ (K-1)$
$n_g = 0.0395\ (D_{50})^{1/6}$
$n_b = 0.02\ (d_{rp}/ d_{bf})$ , note: $n_b = 0.02$ for values > 0.02)
K = sinuosity (reach length/valley length (m/m))
$D_{50}$ = median grain size of the bed (m)
$d_{bf}$ = mean bankfull depth (m)
$d_{rp}$ = mean residual pool depth of the entire active channel area (m)

Channel form roughness is included in the calculation by $F_p$ , the sinuosity factor with sinuosity (K) determined by dividing reach length along the thalweg by the "straight line" valley length measured from aerial photography or topographic map. Grain or particle roughness is accounted for in the equation by $n_g$ using the median ($D_{50}$) grain size diameter from pebble count surveys (Chang, 1988). The bed form roughness resistance factor ($n_b$)is the ratio between the mean residual pool depth ($d_{rp}$) of the reach and the mean bankfull depth ($d_{bf}$).

The follow equation was used to calculate critical bed mobility relating to Shields Criterion (Kaufmann et al., 2009).

$$Dcbf = 0.604\ Rbf\ S / Os$$

$$Rep = [\ (g\ Rbf\ S\ )^{0.5}\ Dgm] / v$$

For Rep < or = 26: $Os = 0.04\ Rep^{-0.24}$
For Rep >26: $Os = 0.5\ \{0.22\ Rep^{-0.6} + 0.06\ (10^{-7.7\ Rep^{-0.6}})\}$

Dcbf = "average" critical bed diameter of particles on the bed surface at bankfull (m)
Rbf = bankfull hydraulic radius (m)

S = energy slope, approximated by water surface or riffle crest slope (m/m)
Os = Shields Parameter, dimensionless critical shear stress for incipient motion
Rep = Bankfull particle Reynolds number
g = acceleration due to gravity, 9.81 $m/s^2$
Dm = geometric mean of bed material from pebble counting (m)
v = kinematic viscosity of water = 1.02 x $10^{-6}$ $m^2/s$

Bankfull shear stress values (Tc ($lbs/ft^2$)) were also used to determine the critical bed material diameter (Dc (mm)) using the empirical equations of Leopold et al. (1964) as:

$$Dc = (77.966)\ Tc^{1.042}$$

and Rosgen (2006) as:

$$Dc = (152.02)\ Tc^{0.7355}$$

## STREAM CHANNEL DATA

### Historical Changes to Channel Planform

The channel at this location has a long history of human disturbance and it is possible there is no segment that is in its original position. Aerial photos from the 1930s show the stream was probably channelized when this area was under cultivation for row crops in the late 1800s and early 1900s. The most significant disturbance in the last 70 years for the study reach is the relocation of the channel during the construction of the James River Expressway (Figure 3). The channel between stations 976-2,800 ft was moved to the north between 50-200 feet on top of a bedrock slab that was left over from the road cut to construct the west bound off-ramp from National. The existing channel was approximately 2,260 ft long with areas of meandering at present stations 1,390-1,600 ft near the approach to the upstream face of the James River Expressway culvert. Channel relocation shortened the reach to 1,820 ft and the meanders were channelized to align to the face of the culvert. A remnant of the old channel position still exists downstream of the James River Expressway that has become part of the road ditch along the south side of the highway. Additionally, it appears the stream was also relocated at some point above National to align with the culvert or during development around that intersection.

### Longitudinal Profile

Slope throughout the study reach has been manipulated by both the presence of in-channel infrastructure and by the re-location of the channel between James River Expressway and Bradford Lake. Artificial hard-points in the channel create significant breaks in slope through the culverts at Republic Road, James River Expressway, and, to a lesser extent, at Independence Avenue. The sewer crossing at station 876 ft and the concrete channel liner at station 120 ft create locally high slopes downstream of their location. Additionally, these hard-points create a damming effect, causing ponding that inundates bedforms and keeps the lower banks saturated upstream. There are few alluvial riffle crests within the study reach, with many riffle-pool features being forced by rip-rap or bedrock outcrops. Water surface slopes from the HEC-RAS model at 300 cfs range from about 0.2%-1.8% and were used to estimate the bankfull Q.

**Channel Morphology**

Bankfull indicators typical of alluvial rivers such as active floodplains and height of gravel bars typical of alluvial rivers are often lacking in urban stream systems. Urban streams must adjust to higher runoff frequency, volume, rate causing channel scour, incision, and widening releasing sediment downstream. The study reach has been heavily disturbed in the past from relocation of the channel, installation of in-channel infrastructure, and the encroachment of development along the floodplain. Due to this long history of disturbance and the natural resistance of Ozarks streams to adjust, morphology indicators were either absent or poorly developed in the project area. Since the channel appears to still be adjusting to disturbance by incising and widening, there is no equilibrium channel reference within the project reach to develop a stable channel cross-section.

Upstream sediment supply has been cut off by the Bradford Lake dam, therefore few gravel bars were observed in the channel along the study reach, indicating a condition of sediment depletion and negative sediment budget where stream power is exerting on the bed and banks instead of sediment transport. One exception is the disturbance reach at station 300-420 ft, where a series of relatively large bars have formed in an area of channel widening due to a LWD jam. The elevation of the high bar is used as an indicator of the maximum height of bed load transport in the channel. This height is expressed inside the culverts at Republic Road and James River Expressway. Both culverts are wider than the stream flowing into them that causes velocity to drop and gravel to deposit inside one or both cells. Additionally, gravel deposition occurs on top of the bank (gravel splays) downstream of the James River Expressway culvert indicating the channel here has high bed load transport capacity at higher flood stages probably due to bedrock limiting channel depth.

The top of the <u>active floodplain</u> or bench formed by recent processes is typically composed of a fine-grained (silty) deposit overlying the high bar deposit and marks the average <u>bankfull</u> stage of the channel. In the reach below James River Expressway, this elevation was expressed in a few locations, however, upstream where the channel was relocated, no active floodplain indicators were observed. The <u>total channel</u> depth is the highest elevation the channel can flood before the water overtops banks and spreads out across the valley floor. This stage represents the first indication of an overbank flood and reflects the maximum width possible of channelized flow in the channel. The total channel is often referred to as the "active meander belt" where lower active floodplains formed by meandering are inset at a lower elevation between higher banks, the top of which is the total channel stage. While this stream would not be considered meandering, local lateral migration creates a cutbank on the outside bend of the channel and deposition on the inside bend of the channel above Republic Road (station 0-115 ft) and at the disturbance reach (300-420 ft).

**Channel Geometry and Discharge**

Bankfull channel dimensions and discharge were determined at 10 cross-sections using the best active floodplain indicators available representing reach-scale variability of this site (Table 1A). Overall, the maximum depth of the bankfull channel varies from about 1.8 ft to 3.8 ft and width from 14.1 ft to 30.5 ft. For the downstream section between Republic Road (station 0 ft) and James River Expressway (stations 976-1,246 ft), the bankfull width is 26 ft and the mean depth is 1.9 ft (Table 2). The bankfull dimensions through the relocated channel sections between stations 1,246-3,750 ft are much smaller than the bankfull channel downstream. Mean bankfull depth for the stations 1,246-2,000 ft is 1.8 ft and the width is 16 ft. From stations 2,000-3,750 ft, the mean bankfull depth is 1 ft and the width is 21 ft.

Total channel dimensions and discharge were also calculated for each site to determine the total capacity of the channel before spilling onto the floodplain (Table 1B). Maximum total channel depth ranges from 2.1-7.2 ft and width ranges from 21.2-63.9 ft through the entire study reach. For the downstream section between Republic Road (station 0 ft) and James River Expressway (stations 976-1,246 ft), the mean total channel width is 38.6 ft and the mean depth is 5.5 ft (Table 2). Similar to the bankfull geometry, total channel geometry upstream of James River Expressway is significantly smaller than downstream. The mean total channel through the relocated channel sections between stations 1,246-2,000 ft is 1.9 ft deep and 25 ft wide. From stations 2,000-3,750 ft, the mean total channel depth is 1 ft and the width is 28 ft, which is probably small for the size of the watershed. These total channel data are similar to the total channel dimensions downstream. Constructed designed channels ranged from a mean depth of 1.5 ft and a width of 30 ft in bedrock-controlled reaches to a mean depth of 2.8 ft and width of 48 ft in the incised reaches for the Ward Branch stabilization project located downstream of Republic Road (OEWRI, 2008). Channels in the urban S. Dry Sac Watershed in northern Springfield have mean depths ranging from 1.7-2.1 ft and widths from 32.4-37.9 ft at the total channel stage for similar drainage areas and geology (Horton, 2003)

The estimated bankfull Q ranging from 73 cfs to 419 cfs is significantly lower than the modeled Q1 flow of 600 cfs for this watershed. The total channel capacity of the downstream section between station 0-976 ft, ranges from 570-1,540 cfs, is able to convey the Q1 event. However, the total channel capacity of the relocated section between stations 1,246-3,750 ft is not able to convey 600 cfs Q1 flood. Typically, the active channel should be able to pass the Q1 flood event. These data suggest the relocated constructed channel is presently too small for the current hydrologic regime, suggesting high frequency discharges are exerting excess force on the bed and banks. However, the total channel capacity of the relocated reach is similar to the bankfull dimensions in the downstream sections where bankfull indicators were observed. This suggests channel morphology may be controlled by a two-stage regime, possibly due to the influence of Bradford Lake dam on hydraulics. During low flood stages the stream receives runoff from areas draining below the dam, but as the lake fills, the upper watershed becomes connected doubling the watershed area and rapidly increases channel flow, depth and energy.

**Bank Stability and Riparian Corridor**

Steep, un-vegetated banks are prevalent throughout most of the downstream section between Republic Road (station 0 ft) and James River Expressway (stations 976-1,246 ft). Soils making up the bank material though this section consist of very-cherty silt-loam material that is typical of alluvial and colluvial soils in headwater tributaries in the Ozarks, (Hughes, 1982). Additionally, it appears the channel is cutting into residuum at several along this section indicating channel incision has occurred in the past. The result is relatively tall, steep banks that are susceptible to erosion when the friction angle exceeds cohesive strength of the bank material and mass wasting occurs (Simon and Rinaldi, 2000). However, the bank material here appears to be cohesive which provides resistance to mass wasting complemented by a narrow, but established riparian corridor. Riparian tree roots frequently protect the bank by reducing near channel shear-stress that helps maintain the steep, scoured bank in this reach. However, trees in the buffer are aging and appear to be weakened in some areas.

Four areas of concern are where local lateral channel erosion threatens existing infrastructure below James River Expressway:

1.) Upstream of Republic Road (station 0-115 ft) where the channel turns sharply to the left and bank erosion threatens the culvert wing-wall and road embankment.

2.) Between stations 300-550 ft where erosion has undercut the detention basin spillway and could eventually destabilize the north embankment of the basin. The highest risk of failure is between stations 300-450 where bank erosion on the left bank has undercut the detention basin outfall spillway and appears to be eroding into the north embankment. The highest risk areas are between stations 350 and 420 ft where the top of the embankment is 12 ft above the stream and 20 ft from the edge of the stream bank.

3.) Right bank erosion between stations 750-850 is exposing and undermining the sanitary sewer casing that crosses the channel at station 850 ft. In some places the channel is 2.5 ft lower than the bottom of the exposed sewer casing. Broken concrete from the casing, unconsolidated supporting rock, and limestone aggregate from the trench are eroding out from underneath the sewer line. Additionally, the angle of flow at the sewer crossing appears to be eroding along the back of the sewer line at higher flows that will continue to expose more of the sewer through this reach.

4.) Block wall supporting commercial parking lot is only 10 ft from the stream near station 825 ft. The stream bank is about 3.5 ft high on top of exposed bedrock. The depth of the block wall footings is unknown, but it is likely supported by bedrock and should be investigated if possible. Some protection of the footing may be appropriate at this location.

The banks above James River Expressway in the section of stream that was relocated from stations 1,246-2,000 ft are lower than the downstream section, but are un-vegetated and steep. Banks through this reach appear to be a mixture of multiple materials including alluvium, colluvium, residuum, fill material, and rip-rap placed along the bank to stop erosion. While this material provides a good deal of resistance, the small channel size and poor riparian corridor create a situation that has caused accelerated bank erosion in this reach. Banks appear to be actively eroding up to the bedrock knick-point at stations 2,000-2,050 ft probably providing a high supply of gravel to downstream areas. Continued bank erosion could eventually destabilize the integrity of the National off-ramp near stations 1,760-2,000 ft. Here the left bank is about 22 ft from the edge of the pavement that is about 7.5-8 ft above the bed of the stream.

The banks between stations 2,050-2,800 ft are more stable than the reach immediately below. Bank height is relatively low as the bed here is either bedrock or stable gravel/cobble that has resisted incision. Bank material here is mainly bedrock, large boulders, and rip-rap used to form the channel on top of the bedrock cut to create the off-ramp from National Ave. While the channel capacity is small compared to the expected bankfull Q at this location, the resistance provided by the rip-rap and boulder banks, that are also vegetated, appear to be stable during higher flood events. However, there is evidence of some floodplain scour suggesting overbank events are exerting high shear during flood flows and may be winnowing and transporting smaller material downstream leaving only the larger material in place.

Upstream of the construction reach (stations 3,750-4,000) both banks are high and steep, suggesting a period of stream bed incision in the past. The right bank appears to be the most susceptible to failure due to its height (≈9.5 ft) and angle (up to 90°). The right bank supports Bradford Parkway and utilities installed behind the curb that is between 20-30 ft from the top of bank. Bank material appears to be chert-clay fill and construction debris including large boulders. Additionally, bed incision cause ponding from the floor of the Independence Road culvert that maintains saturated lower bank conditions in this reach that could compromise the bank strength here.

**Bed Substrate and Sediment Mobility**

Pebble count and large substrate measurements show that median (D50) bed material diameters in Ward Branch range from 15 mm to 66 mm and maximum mobile clast size ranges from 150 mm to 680 mm (Table 3). The bed material size class for the D84 ranges from coarse gravel (35 mm) to large cobble (213 mm). Sediment transported on bars and deposited in culverts is uniform, with the D50 ranging from 18-25 mm, which is similar to the bed material size distribution. The maximum mobile clast on the bars ranges from 93-197 mm. The D50 size for the post-construction channel downstream of Republic road ranged from 30-53 mm in the golf course sub-reaches (OEWRI, 2008).

The calculated critical diameter at each cross-section ranges from 25-260 mm at the bankfull stage (Table 4A). Two of the 9 cross-sections were bedrock beds and were not included in the analysis. When using empirical formulas to calculate critical diameter for the bedrock reaches, size ranges from the Wolman equations fall within the range of the D84 for the other sections. The calculated critical diameter falls between the D50 and D84 for 3 of the remaining 7 cross-sections, indicting the bed material size is in equilibrium with flow energy under present conditions. The critical diameter for the other 4 cross-sections is between the D84 and the max mobile clast of the bed at the bankfull stage, suggesting these cross-sections are receiving excess energy and/or low sediment supply.

At the total channel stage, the calculated critical bed diameter ranges from 20-368 mm (Table 4B). Two of the 7 sections where bed substrate was measured had calculated critical bed diameters near the D50. One is cross-section #1 located upstream of the culvert at Republic Road subjected to backwater effects. The other is cross-section #7 located in the relocated channel section near National where the channel may be too small and the channel forming flows might be overbank. Four of the remaining 5 cross-sections have total channel calculated critical diameters between the D84 and Dmax mobile for the cross-section. Cross-section #9 has a calculated critical diameter greater than the Dmax, suggesting excess energy is being applied to channel here. This is possibly the reason the channel has few depositional features.

Due to the relatively wide culverts at both James River Expressway and Republic Road, gravel deposition has occurred in the east box of both culverts. The height of the gravel in the Republic Road culvert is 3.5 ft thick. The height of the gravel in the James River Expressway culvert is about 1 ft thick at the face, but the elevation of the gravel is consistent through the culvert which is getting thicker as the elevation of the floor of the culvert drops downstream. Additionally, the floor of the James River Expressway culvert is about 1.5 ft above the elevation of the upstream thalweg.

## REACH CLASSIFICATION

The following section describes key disturbance indicators and areas of concern at the sub-reach scale including photographs. Sub-reaches were classified based on changes in the bank (material, erosion, vegetation), bed (slope, grain-size), presence of infrastructure as observed in the field.

### Reach #1 - Historical Channel Reach (-150 - 570 feet)

The following sub-reaches are located in the historical channel location according to aerial photographs:

Sub-Reach 0 – (-150 – 0 ft) **Republic road culvert** is wider than the upstream channel that decreases sediment transport causing gravel deposition within the east box. The top of the gravel in east cell is approximately 3.6 ft above the floor of the culvert.

Sub-Reach 1 – (0 – 115 ft) Bedrock reach below concrete channel liner (Photo 1) at station 115 ft indicating gravel is transported during floods. Grouted rip-rap on right bank in bridge embankment (Photo 2 and 3). **Eroding high right bank** upstream of the culvert threatens west wing-wall and embankment. Cross-section #1 at located station 35 feet.

Sub-Reach 2 – (115 – 300 ft) Located upstream of concrete liner. Water pools behind sewer line which may contribute to bank instability due to saturation (Photo 5 and 6). Sub-reach has a bedrock bed with gravel/cobble veneer suggesting this reach transports gravel during floods and there is also evidence of incision along both banks (Photos 7 and 8). **There is a spring up-welling at station 200 feet.** Cross-section #2 located at station 225 feet.

Sub-Reach 3 – (300 – 420 ft) This is a **disturbance reach** located below the detention basin outfall from the south. Trees and LWD located within the channel cause the channel to split and widen (Photo 9). Bank erosion released gravel/cobble that helped form a mega-bar complex located here (Photo 10). Bank erosion on the left bank has undercut the detention basin outfall spillway and appears to be eroding into the north embankment. The highest risk areas are between stations 350 and 420 ft where the top of the embankment is 12 ft above the stream and 20 ft from the edge of the stream bank.

Sub-Reach 4 – (420 – 570 ft)  This area is pooled upstream of mega-bar complex (Photos 11 and 12).  This reach has bank erosion along the left bank with a floodplain beginning to form along the right bank (Photos 13 and 14).  Cross-section #3 located at station 460 feet.  Between stations 420 ft and 520 ft the risk to the detention basin embankment is more moderate as the distance from the top of the embankment is 50 ft from the edge of the vertical stream bank.

**Reach #2 – Bedrock Reach (570 - 976 feet)**

The following sub-reaches are close to the historical channel location:

Sub-Reach 5a – (570 – 790 ft)  This reach is located below a **bedrock knick-point zone** releasing large blocks and forming large gravel and cobble bars downstream.  Cross-section #4a located at station 700 feet (Photos 15-18).

Sub-Reach 5b – (790 – 850 ft)
This reach is a **bedrock knick-point zone** with a high slope and large blocks of bedrock are breaking loose (Photo 19).  High slope through this reach is also maintained by sewer crossing at station 850 feet that increases the height of the bed at this point.  The concrete sewer line casing is exposed along the right bank and bed of the stream and is undercut nearly 2.5 ft in some places releasing unconsolidated rock and limestone aggregate supporting the pipe (Photos 20-22).  The stream appears to be trying to cut a channel to the north side of the sewer line that will expose more of the line that will continue to deteriorate under these conditions over time.  Block wall supporting commercial parking lot is 10 ft from the top of left bank 3.5 ft to bedrock.   Cross-section #4b is located at station 825 ft (Photos 23-26).

Sub-Reach 6 – (850 – 976 ft)  This reach extends from the downstream face of the James River Expressway culvert to the **sewer line crossing** (Photo 27).  This reach includes a confluence with the tributary running along the southside of the west bound lane of James River Expressway. The bed consists of gravel and cobble and gravel splays and flood channels are found on the floodplain (Photo 28).

**Reach #3 - Relocated Reach (976 – 2,800 feet)**

The following sub-reaches have been moved due to highway construction since the 1970s and are not in their historical channel location:

Sub-Reach 7 – (976 – 1,246 ft)  **James River Expressway Culvert** is a two cell culvert that is wider than the upstream channel that decreases sediment transport causing significant gravel deposition in the east cell.  The top of the gravel is approximately 1 ft thick at the upstream face of the east cell and the elevation of the gravel is maintained all the way through the culvert, even though the floor slopes downstream. The concrete floor of the culvert is about 1.4 ft above the upstream thalweg.

Sub-Reach 8 – (1,246 – 1,390 ft) This reach consists of a gravel and cobble bed with failing grouted rip-rap along the right bank located below the outfall located at 1,390 feet (Photos 29 and 30). Cross-section #5 located at station 1,340 feet (Photos 31 and 32).
Sub-Reach 9a – (1,390 – 1,600 ft) There is evidence of **relatively severe bank and bed scour through this reach supplying gravel and fine-grain material to downstream areas** (Photos 33 and 34). This reach is located below the forced riffle at station 1,600 feet.

Sub-Reach 9b – (1,600 – 1,760 ft) There is **bank and bed scour within this reach, but not as severe as in 9a** (Photo 35). Could be held up by forced riffle created from large boulders located within the channel (Photo 36). Cross-section #6 located at station 1,620 feet (Photos 37 and 38).

Sub-Reach 10a – (1,760 – 1,840 ft) **Loose rip-rap** located along the left bank is falling into the stream (Photo 39). Smaller softball-size material can be found downstream below the James River Expressway. The bed consists of fresh gravel located below the outfall of storm pipe at station 1,840 feet around which local erosion has occurred (Photo 40). Continued bank erosion threatens National Ave off-ramp embankment. The toe of the stream bank is 7.5 ft lower in elevation and 22 ft horizontal distance from the edge of pavement.

Sub-Reach 10b – (1,840 – 2,000 ft) **Rip-rap along the left bank is falling into the channel** and the reach slope appears to be slightly higher than 10a. Located upstream of storm pipe outfall (Photo 41). Continued bank erosion threatens National Ave off-ramp embankment.

Sub-Reach 11 – (2,000 – 2,050 ft) This is a **bedrock knickpoint/outcrop** within the channel where willows are growing in the channel (Photo 42).

Sub-Reach 12 – (2,050 – 2,550 ft) This reach has stable bed and banks (Photos 43 and 44). Moss covered gravel/cobble bed suggests there is not a lot of bed erosion or excessive bedload transport. Banks are artificial with large rip-rap boulders that are now mostly vegetated (Photos 45 and 46). Cross-section #7 located at station 2,210 feet.

Sub-Reach 13 – (2,550 – 2,800 ft) **Bedrock channel with stable rip-rap bank material** (Photos 47 and 48). There is evidence of floodplain scour at high flows due to narrow “valley” between the bedrock cut wall and the off ramp from National, but bedrock appears to stop further cutting (Photos 49 and 50). Cross-section #8 located at station 2,615 feet.

**Reach #4 – Dam/Construction Reach (2,800 – 4,000 feet)**

<u>Sub-Reach 14 – (2,800 – 3,750 ft)</u> This is the **construction reach** under National Avenue to Independence Road Culvert (Photos 51 and 52).

<u>Sub-Reach 15 – (3,750 – 4,000 ft)</u> This reach is located **below the Bradford Lake Dam** and consists of large boulders and construction debris with some bank collapse (Photos 53 and 54). Sediment supply below dam is low and flood peaks are reduced due to impoundment. Channel bank is largely fill on right side and bed elevation appears to have been lowered to meet downstream culvert. Banks are presently slowly eroding towards a lower bank angle but tree roots and boulders keep bank recession rates moderate. Bank erosion rates are also checked by lower shear stress due to controlled peaks below the dam and slope control caused by downstream culvert. However, the right bank between stations 3,750-3,900 ft could destabilize the embankment under Bradford Parkway. The toe of the right bank is 9.5-10 ft lower is elevation and 20-30 ft in horizontal distance from the edge of the curb. Cross-section #9 is located in the reach at station 3,875 ft (Photos 55-58). Additionally, the spillway apron has been undercut about 3 ft exposing the supporting fill material that will continue to deteriorate over time (Photos 59-62).

In summary, the channel below the Bradford Lake dam (SR-15) appears to have incised and widened in the past that has undercut the spillway apron and the embankment supporting the Bradford Parkway before it enters the construction reach (SR-14). Below the construction reach (SR-13 and SR-12), there is a channel made of large rip-rap banks that is on top of artificially cut bedrock created during highway construction to station 2,000 ft where there is a bedrock knick point (SR-11). Below the knick point (SR-10b to SR-8), the channel is actively incised and widening into less resistant bank material made up of a combination of fill, alluvium, colluvium, and residuum that threatens the stability of the National off-ramp to the James River Expressway. Sediment from this reach is deposited into the James River Expressway culvert (SR-7). Below the James River Expressway (SR-6 to SR-5), the steam flows over a deteriorating concrete sewer crossing down a steep bedrock knick-point and into a riffle-pool reach (SR-4). The channel in this reach has incised, but bank erosion is slowed by the presence of a riparian corridor. Below the knick-point at stations 300-420 ft (SR-3) there is a disturbance reach caused by a LWD jam that splits the channel causing substantial local bank erosion in this sub-reach creating a failure risk to the north embankment of the detention basin located here. Downstream of the disturbance reach (SR-2 and SR-1) the channel crosses a concrete liner and is scoured to bedrock and is eroding the right bank of the stream threatening the road embankment and wing wall at the Republic Road culvert (SR-0).

## CONCERNS

1) SR-1: high outside bank on eroding bend entering Republic Road culvert threatens west wing-wall and road embankment provides a source of fine-sediment and some coarse sediment.

2) SR-2 and SR-4: long pooled areas behind downstream barriers (sewer line and large riffle, respectively). Evidence of high rates of bank scour on one or both banks. Bank erosion releases fine-sediment and some bed material.

3) SR-3: Disturbance reach that has shifted left around 30 ft over the past 50 years. It has cut into higher fill banks and rip-rap spillway structure. Trees and large woody debris have acted as barrier to flow and bed sediment transport thus splitting the thalweg and destabilizing the channel even further. Left bank erosion has undercut detention basin spillway and could eventually destabilize the north embankment of the basin.

4) SR-5: Bedrock knickpoint. It is slowly breaking apart and releasing relatively large material to the downstream disturbance reach. Increased slope, velocity, and boulder supply may be the original cause of the disturbance zone (at SR-3). Sewer line crosses at the top of this reach also causes further increase in slope during floods. Concrete sewer casing exposed in the bed and right bank is undercut as much as 2.5 ft and appears to be losing supporting material and will continue to deteriorate as more is uncovered as the channel cuts north.

5) SR-6 and SR-7: confluence of culvert under JRE and south drainage channel maybe be causing hydraulic jump which helps to increase flow stage and gravel/cobble bar deposition as well as gravel splay deposition on top of right, bending bank.

6) SR-8: instability due to tributary confluence, escaped rip-rap, heavy bed load supply from upstream, and bend to meet culvert.

7) SR-9: Evidence of relatively severe incision and bank erosion. Channel has been moved to this location and is still eroding to reach base-level. Erosion process is releasing much gravel from bed and banks as well of fine-grained alluvium, residuum, colluvium, and/or fill.

8) SR-10: Similar situation to SR-9 but maybe erosion rates are not as high. This reach is affected by rip-rap from JRE ramp. Softball-sized rip-rap (white limestone) originally applied to stabilize ramp slope has been transported downstream to at least SR-6 and probably to SR-0 (Republic Rd culvert). Continued bank erosion threatens the National Ave. off-ramp.

9) SR-14: Construction Reach. Both OA and OEWRI did not evaluate this reach to construction activities and severe disturbance to channel. On the day OEWRI visited, excessive fine-grained sediment was being released to the stream from the construction site.

10) SR-15: Modified channel due to upstream dam, probable channelization, floodplain filling/narrowing, and downstream grade control by culvert. Impoundment probably reduces sediment supply to the reach and reduces peak flow stage too. Bank erosion of fines is occurring but probably at more moderate rates compared to downstream segments because the bed elevation is stable and banks are protected by tree roots and boulders/rip-rap. However, continued bank erosion could eventually threaten the embankment integrity of the Bradford Parkway between stations 3,750-3,900 ft. Nearly 3 ft of incision has caused deterioration of the spillway apron.

## RECOMMENDATIONS

1.) **Stable Channel Geometry**-

   a. <u>Dam to construction reach</u> - The current channel dimensions appear to be appropriate for this reach, but due to bed incision the banks are unstable through this reach.

   b. <u>Construction reach to James River Expressway</u> – The stable low flow channel cross-section in this reach should have a top width of **24 ft** and **2 ft** deep with 2:1 bank angle. An additional **6 ft** wide bankfull bench would create a **30 ft** meander belt. Above the low flow channel, the banks should be held at a 3:1 slope to existing grade.

   c. <u>James River Expressway to Station 700 ft</u> - Due to bedrock and sewer line crossing geomorphic indicators of a stable channel cross-section are not present. If the sewer line was removed the channel capacity would be similar to the areas downstream due to the high slope in this reach.

   d. <u>Station 700 ft to Republic Road</u> – Due to the steep, incised banks in this reach, a stable cross-section requires reducing the existing bank angle. A stable two-stage channel dimension for this section would have a low flow channel **40 ft** wide and **2.5 ft** deep with banks at a 2:1 slope. Above the low flow channel, the total channel dimensions should be **74 ft** wide and **3.5 ft** deep at a 3:1 bank angle.

2.) **Excess Sediment Transport Capacity** - The channel through the study area is steep and sediment starved creating a situation where excess energy is causing bank erosion at different degrees along the entire reach. The area above Bradford Lake is about 50% of watershed area for the project and the dam traps sediment and controls flow. Historical channelization and relocation straightened the channel and increased slope. Channel modifications aimed at controlling flow velocity by lowering bed slope and add toe protection to the bank would decrease bank erosion and sediment supply. A two stage culvert design at Republic Road and James River Expressway would help keep the culverts open to maintain flood capacity. The depth of the gravel in the Republic Road culvert is **3.5 ft**. Gravel is **1 ft** thick at the upstream face of the James River Expressway culvert but thickens downstream due to the slope of the culvert.

3.) **Disturbance Reach -** The LWD jam located below the knick-point and the detention basin outfall from station 300-420 ft created a split channel that is causing bank erosion and channel widening. The LWD jam should be removed and the channel allowed to go back to a single thalweg. Bank erosion is threatening the north embankment of the detention basin located here and should be addressed.

4.) **Sewer Line Casing and Block Wall -** Directly below James River Expressway a concrete cased sewer line crosses the stream and is exposed along the north bank of the stream. The stream has undercut the sewer line as much as 2.5 ft downstream of the crossing and unconsolidated rock and limestone aggregate supporting the sewer is being washed away. The concrete is starting to deteriorate in some places as the stream is trying to cut north of the pipe which will continue to be exposed on both sides. Additionally, the left stream bank is 10 ft from a block wall that is probably supported by bedrock that is close to the surface here. Checking the depth of the footing and adding protection may be necessary.

5.) **Relocated Reach Channel Instability and Sediment Supply** - Presently the reach between James River Expressway (station 1,246 ft) upstream to station 2,000 ft is a major contributor of fine-grain sediment and bed sediment via bed incision and bank erosion. This is an area where the channel was relocated during construction of the James River Expressway and the constructed channel was too small for the watershed area creating a situation where excess force was being placed on the bed and banks causing accelerated erosion. With the Bradford Lake dam cutting off sediment supply upstream, this section appears to be the major contributor of gravel supply downstream. Continued bank erosion could destabilize the National off-ramp embankment. Channel modifications here should focus on create a stable channel form appropriate for the slope and drainage area at this location.

6.) **Incision and Bank Erosion below Dam** – Bed incision below the Bradford Lake dam created tall, steep banks susceptible to erosion. While bank erosion rates appear to be moderate here, continued bank erosion along Bradford Parkway embankment threatens the stability of the road and utilities present behind the curb. Additionally, incision has undercut the spillway nearly 3 ft causing destabilization of the structure causing large concrete slabs to be moved downstream. The condition of the spillway appears to be getting worse as the cherty-clay fill that appears to be supporting the structure is actively eroding.

7.) **Aquatic Habitat -** The karst nature of the study reach causes sections of the stream to be gaining and losing at some locations. Base flow and spring seepage may be sufficient to support aquatic life in the lower sections of the study reach. Presently, fish and crawfish were observed below station 700 ft.

## LITERATURE CITED

French, R.H., 1985. Open-Channel Hydraulics. McGraw-Hill, New York.

Horton, J.M., 2003. Channel Geomorphology and Restoration Guidelines for Springfield Plateau Streams, South Dry Sac Watershed, Southwest Missouri. Unpublished Master's Thesis, Southwest Missouri State University.

Hughes, H.E., 1982. *Soil survey of Greene and Lawrence Counties, Missouri*. Soil Conservation Service, United States Department of Agriculture.

Kaufman, P.R., J.M. Faustini, D.P. Larsen, and M.A. Shirazi, 2009a. A roughness corrected index of relative bed stability for regional bed surveys. Geomorphology 99(1-4):150-170.

Kaufman, P.R., D.P. Larsen, and J.M. Faustini, 2009b. Bed stability and sedimentation associated with human disturbance in Pacific Northwest streams. Journal of American Water Resources Association 45(2):434-459.

Leopold, L.B., G.M. Wolman, and J.P. Miller, 1964. Fluvial Processes in Geomorphology. W.H. Freeman, San Francisco, California.

Martin, L.L., 2001. Geomorphic Adjustments of Ozarks Stream Channels to Urbanization, Southwest Missouri. Unpublished Master's Thesis, Southwest Missouri State University.

OEWRI, 2007. Pre-Construction Report for the Ward Branch Stream Restoration Project. Ozarks Environmental and Water Resources Institute, Missouri State University. EDR-07-004.

OEWRI, 2008. The Ward Branch Stream Restoration Project Post-Construction Assessment and Final Report. Ozarks Environmental and Water Resources Institute, Missouri State University. EDR-08-004.

Pizzuto, J.E., W.C. Hession, and M. McBride, 2000. Comparing Gravel-Bed Rivers in Paired Urban and Rural Catchments of Southeastern Pennsylvania. Geology 28-1:79-82.

Rosgen, D., 2006. Watershed Assessment of River Stability and Sediment Supply (WARSSS). Wildland Hydrology, Fort Collins, Colorado.

Simon, A and M. Rinaldi, 2000. Channel Instability in the Loess Area of the Midwestern United States. Journal of the American Water Resources Association 36(1):133-150.

## Table 1. Bankfull (A) and Total Channel (B) Dimensions and Discharge

### A. Bankfull

| Section<br># | Station<br>feet | Width<br>feet | D (BF)<br>feet | D (mean)<br>feet | R<br>feet | A<br>$feet^2$ | Wp<br>feet | Slope<br>ft/ft | Mannings<br>"n" | Mean V<br>ft/s | Q<br>$ft^3/s$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 35 | 29.2 | 3.8 | 1.9 | 1.8 | 56.8 | 32.3 | 0.0020 | 0.019 | 5.1 | 292 |
| 2 | 225 | 19.3 | 3.0 | 2.7 | 2.2 | 52.9 | 24.0 | 0.0067 | 0.026 | 7.9 | 419 |
| 3 | 460 | 22.5 | 2.7 | 2.2 | 2.0 | 49.7 | 25.2 | 0.0067 | 0.039 | 4.9 | 242 |
| 4a | 700 | 28.0 | 3.8 | 1.9 | 1.8 | 52.7 | 29.8 | 0.0100 | 0.036 | 6.0 | 319 |
| 4b | 825 | 30.5 | 2.3 | 0.9 | 0.8 | 26.8 | 33.7 | 0.0160 | 0.020 | 8.1 | 217 |
| 5 | 1,340 | 14.1 | 3.1 | 2.3 | 1.9 | 32.0 | 16.8 | 0.0090 | 0.034 | 6.3 | 202 |
| 6 | 1,620 | 18.0 | 2.2 | 1.3 | 1.2 | 23.4 | 20.1 | 0.0120 | 0.041 | 4.4 | 104 |
| 7 | 2,210 | 19.3 | 1.8 | 0.9 | 0.8 | 17.0 | 20.8 | 0.0100 | 0.030 | 4.3 | 73 |
| 8 | 2,615 | 22.7 | 1.9 | 0.9 | 0.8 | 19.5 | 24.1 | 0.0100 | 0.023 | 5.7 | 111 |
| 9 | 3,875 | 19.2 | 3.8 | 2.9 | 2.2 | 55.2 | 25.1 | 0.0180 | 0.045 | 7.5 | 416 |

### B. Total Channel

| Section<br># | Station<br>feet | Width<br>feet | D (TC)<br>feet | D (mean)<br>feet | R<br>feet | A<br>$feet^2$ | Wp<br>feet | Slope<br>ft/ft | Mannings<br>"n" | Mean V<br>ft/s | Q<br>$ft^3/s$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 35 | 63.9 | 5.3 | 1.9 | 1.8 | 124.4 | 67.8 | 0.0015 | 0.019 | 4.6 | 570 |
| 2 | 225 | 29.3 | 5.2 | 3.5 | 3.5 | 101.5 | 28.7 | 0.0050 | 0.026 | 9.5 | 965 |
| 3 | 460 | 31.5 | 6.0 | 4.4 | 3.4 | 138.8 | 40.9 | 0.0050 | 0.031 | 7.6 | 1,054 |
| 4 | 700 | 26.5 | 6.5 | 4.9 | 3.4 | 130.6 | 38.0 | 0.0110 | 0.030 | 11.8 | 1,540 |
| 4b | 825 | 41.6 | 4.5 | 2.5 | 2.3 | 105.8 | 45.9 | 0.0160 | 0.050 | 6.5 | 692 |
| 5 | 1,340 | 21.2 | 3.7 | 2.0 | 1.7 | 42.6 | 24.4 | 0.0090 | 0.036 | 5.7 | 244 |
| 6 | 1,620 | 29.3 | 3.6 | 1.8 | 1.6 | 53.2 | 32.5 | 0.0120 | 0.036 | 6.2 | 332 |
| 7 | 2,210 | 29.1 | 2.1 | 0.9 | 0.8 | 24.8 | 30.6 | 0.0100 | 0.030 | 4.3 | 106 |
| 8 | 2,615 | 27.3 | 2.1 | 0.9 | 0.9 | 25.8 | 28.8 | 0.0100 | 0.022 | 6.3 | 162 |
| 9 | 3,875 | 31.8 | 7.2 | 4.4 | 3.8 | 141.3 | 37.6 | 0.0150 | 0.037 | 11.9 | 1,686 |

## Table 2. Average Bankfull and Total Channel Width and Mean Depth

Segments in Historical Location (CS# 1-4)
Bankfull: Width= 25 ft Mean Depth= 2.2 ft
Total: Width= 30 ft Mean Depth= 4.3

Segments in New Location below culvert (CS# 5-6)
Bankfull: Width= 16 ft Mean Depth= 1.8 ft
Total: Width= 25 ft Mean Depth= 1.9 ft

Segments in New Location below culvert (CS# 7-8)
Bankfull: Width= 21 ft Mean Depth= 1 ft
Total: Width= 28 ft Mean Depth= 1 ft

Reach Below Dam (CS# 9)
Channelized; no bankfull indicators.

## Table 3. Bed and Bar Sediment Size Distribution

| Subreach | Stations | Section | Bed Pebble Counts (mm) | | | | | | Bar Pebble Counts (mm) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| # | feet | # | D25 | D50 | Dgm | D84 | Dmax (Mobile) | Dmax (Largest) | D25 | D50 | Dgm | D84 | Dmax (Mobile) | Dmax (Largest) |
| 0 | -150 - 0 | - | | | | | | | 10 | 18 | 16 | 43 | 181 | 223 |
| 1 | 0 - 115 | 1 | | Bedrock | | | | | | | | | | |
| 2 | 115 - 300 | 2 | | Bedrock | | | | | | | | | | |
| 3 | 300 - 420 | - | | | | | | | | | | | | |
| 4 | 420 - 570 | 3 | 11 | 20 | 21 | 45 | 150 | 160 | | | | | | |
| 5a | 570 - 790 | 4a | 30 | 50 | 48 | 148 | 317 | 330 | 18 | 19 | 19 | 26 | | |
| 5b | 790 - 850 | 4b | 31 | 66 | 73 | 213 | 680 | 770 | | | | | | |
| 6 | 850 - 976 | - | 8 | 18 | 16 | 43 | 87 | 100 | 15 | 25 | 22 | 43 | 93 | 95 |
| 7 | 976 - 1,246 | - | | | | | | | 10 | 20 | 17 | 30 | 197 | 230 |
| 8 | 1 ,246 - 1,390 | 5 | 7 | 15 | 15 | 59 | 167 | 190 | | | | | | |
| 9a | 1,390 - 1,600 | - | | | | | | | | | | | | |
| 9b | 1,600 - 1,760 | 6 | 19 | 30 | 27 | 54 | 180 | 200 | | | | | | |
| 10a | 1,760 - 1,840 | - | | | | | | | | | | | | |
| 10b | 1,840 - 2,000 | - | | | | | | | | | | | | |
| 11 | 2,000 - 2,050 | - | | | | | | | | | | | | |
| 12 | 2,050 - 2,550 | 7 | 50 | 60 | 57 | 114 | 183 | 220 | | | | | | |
| 13 | 2,550 - 2,800 | 8 | | Bedrock | | | | | | | | | | |
| 14 | 2,800 - 3,750 | - | | Construction | | | | | | | | | | |
| 15 | 3,750 - 4,000 | 9 | 15 | 22 | 21 | 35 | 277 | 280 | | | | | | |

## Table 4. Calculated Critical Diameter for Bed Sediment at Bankfull and Total Channel Stage

### A. Bankfull

| Section | Station | Shear | Critical Dia1 | Critical Dia2 | REP | Geo-Mean Dia | Shields | Dcbf | D25 | D50 | Dgeo-mean | D84 | Mean Dmax (mobile) | Dmax (Largest) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| # | feet | (lbs/ft$^2$) | (mm)[1] | (mm)[2] | # | m | Parameter | mm | mm | mm | mm | mm | mm | mm |
| 1 | 35 | 0.24 | 18 | 54 | 1,609 | 0.016 | 0.0256 | 25 | 10 | 18 | 16 | 43 | 181 | 223 |
| 2 | 225 | 1.15 | 90 | 168 | | | | | Bedrock | | | | | |
| 3 | 460 | 0.93 | 72 | 144 | 4,092 | 0.021 | 0.0273 | 89 | 11 | 20 | 21 | 45 | 150 | 160 |
| 4a | 700 | 1.17 | 92 | 171 | 10,810 | 0.048 | 0.0285 | 114 | 30 | 50 | 48 | 148 | 317 | 330 |
| 4b | 825 | 0.88 | 68 | 138 | 13,973 | 0.073 | 0.0287 | 82 | 31 | 66 | 73 | 212 | 680 | 770 |
| 5 | 1,340 | 1.27 | 100 | 182 | 3,324 | 0.015 | 0.0270 | 116 | 7 | 15 | 15 | 59 | 167 | 190 |
| 6 | 1,620 | 0.97 | 76 | 149 | 5,413 | 0.027 | 0.0277 | 93 | 19 | 30 | 27 | 54 | 180 | 200 |
| 7 | 2,210 | 0.55 | 42 | 98 | 8,732 | 0.057 | 0.0283 | 53 | 50 | 60 | 57 | 114 | 183 | 220 |
| 8 | 2,615 | 0.54 | 41 | 96 | | | | | Bedrock | | | | | |
| 9 | 3,875 | 3.23 | 265 | 360 | 7,080 | 0.021 | 0.0280 | 260 | 15 | 22 | 21 | 35 | 277 | 280 |

### B. Total Channel

| Section | Station | Shear | Critical Dia1 | Critical Dia2 | REP | Geo-Mean Dia | Shields | Dcbf | D25 | D50 | Dgeo-mean | D84 | Mean Dmax (mobile) | Dmax (Largest) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| # | feet | (lbs/ft$^2$) | (mm)[1] | (mm)[2] | # | m | Parameter | mm | mm | mm | mm | mm | mm | mm |
| 1 | 35 | 0.18 | 13 | 43 | 1,423 | 0.016 | 0.0253 | 20 | 10 | 18 | 16 | 43 | 181 | 223 |
| 2 | 225 | 1.08 | 85 | 161 | | | | | Bedrock | | | | | |
| 3 | 460 | 1.37 | 109 | 192 | 4,636 | 0.021 | 0.0275 | 113 | 11 | 20 | 21 | 45 | 150 | 160 |
| 4a | 700 | 3.38 | 278 | 373 | 15,820 | 0.048 | 0.0288 | 242 | 30 | 50 | 48 | 148 | 317 | 330 |
| 4b | 825 | 2.54 | 206 | 302 | 23,756 | 0.073 | 0.0290 | 234 | 31 | 66 | 73 | 212 | 680 | 770 |
| 5 | 1,340 | 1.13 | 89 | 167 | 3,186 | 0.015 | 0.0269 | 107 | 7 | 15 | 15 | 59 | 167 | 190 |
| 6 | 1,620 | 1.36 | 107 | 191 | 6,409 | 0.027 | 0.0279 | 129 | 19 | 30 | 27 | 54 | 180 | 200 |
| 7 | 2,210 | 0.53 | 40 | 96 | 8,695 | 0.057 | 0.0283 | 53 | 50 | 60 | 57 | 114 | 183 | 220 |
| 8 | 2,615 | 0.59 | 45 | 103 | | | | | Bedrock | | | | | |
| 9 | 3,875 | 4.16 | 344 | 434 | 8,458 | 0.021 | 0.0282 | 368 | 15 | 22 | 21 | 35 | 277 | 280 |

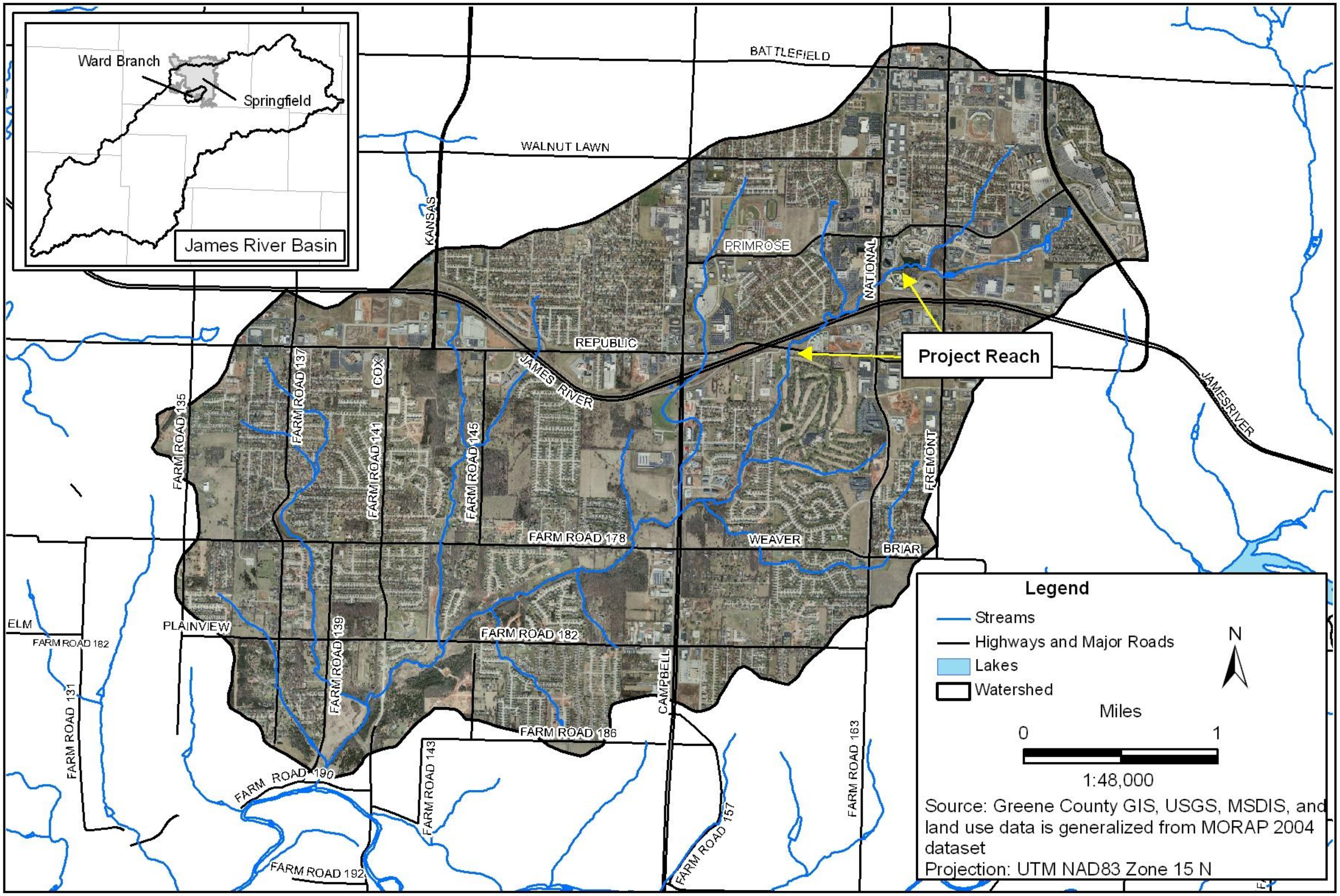



**Figure 1. Upper Ward Branch Study Area**

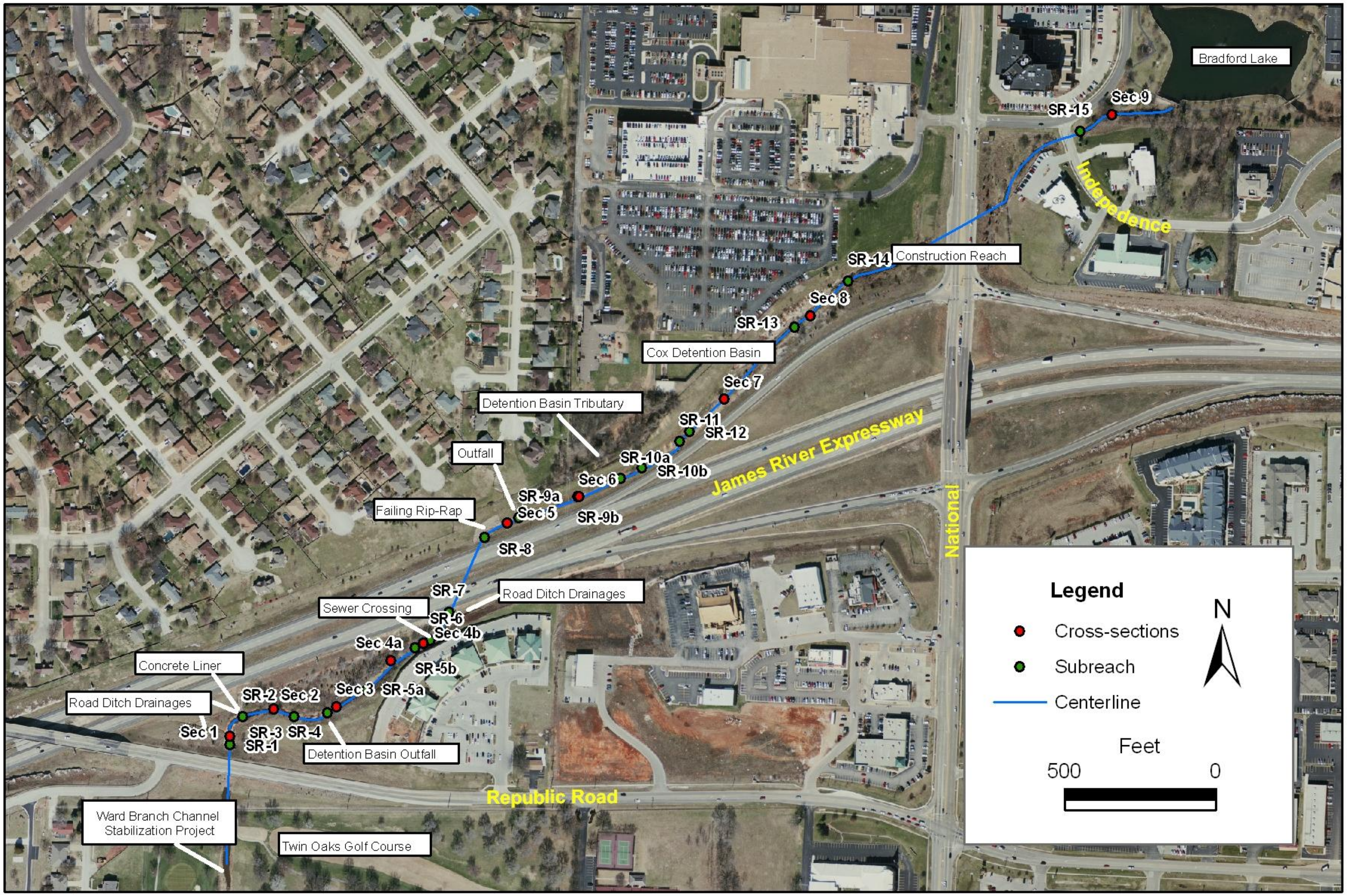



**Figure 2. Study Reach**

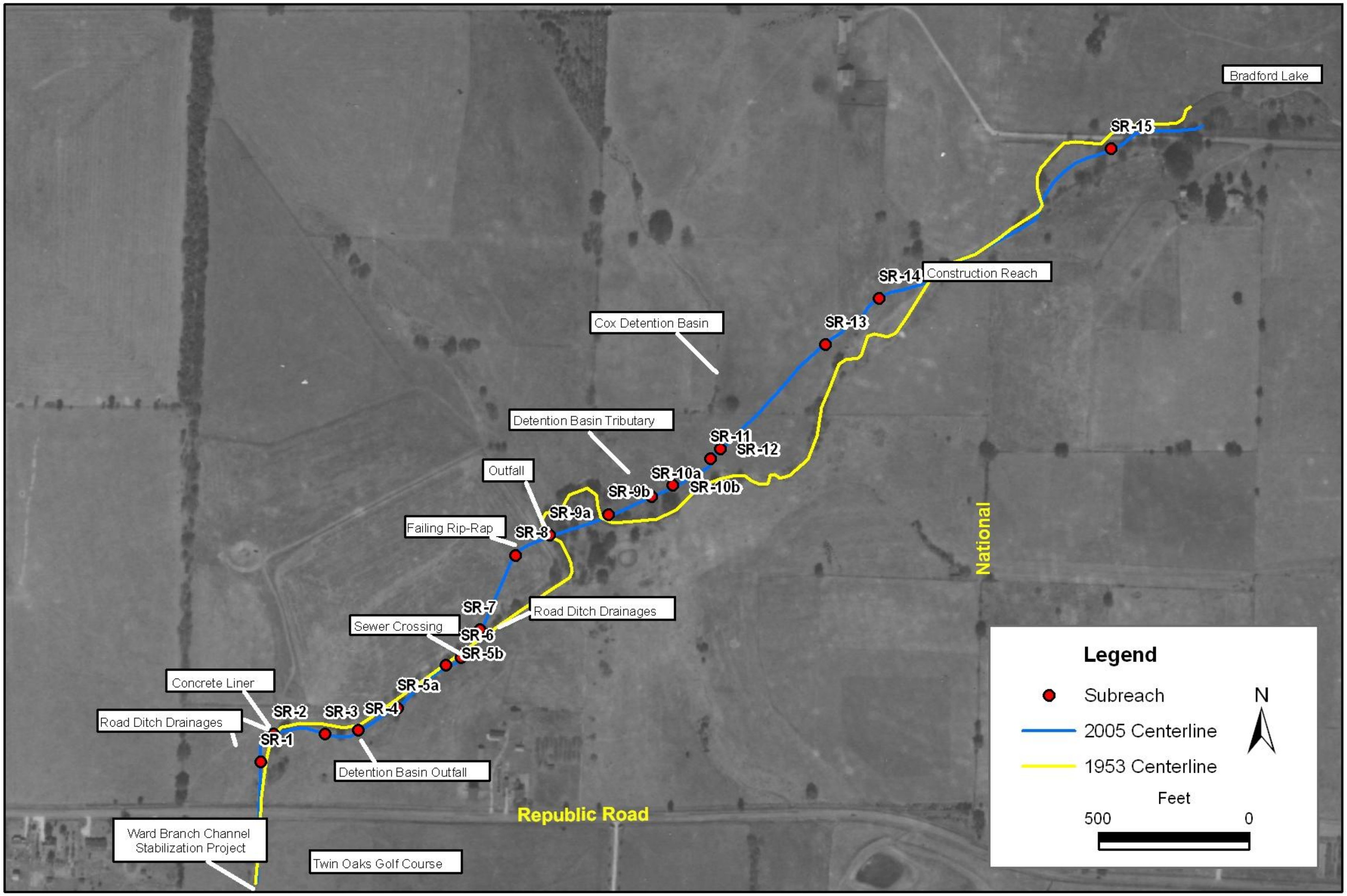



**Figure 3. 1953 Aerial with Centerline and 2005 Centerline**

**Photo 1.  SR-1 cross-section #1 (station 35 ft) looking upstream at concrete liner.**

**Photo 2. SR-1 cross-section #1 (station 35 ft) looking downstream at Republic Road culvert.**


**Photo 3. SR-1 cross-section #1 (station 35 ft) right bank.**


**Photo 4. SR-1 cross-section #1 (station 35 ft) left bank.**

**Photo 5. SR-2 cross-section #2 (station 225 ft) looking upstream.**

**Photo 6. SR-2 pooled area upstream of concrete liner at cross-section #2 (station 225 ft) looking downstream.**

**Photo 7. SR-2 cross-section #2 (station 225 ft) right bank.**

**Photo 8. SR-2 cross-section #2 (station 225 ft) left bank.**

**Photo 9. SR-3 large woody debris jam and mega bar formation (station 350 ft).**

**Photo 10. SR-3 bank erosion and gravel/cobble deposition in disturbance reach (station 350 ft).**

**Photo 11. SR-4 cross-section #3 (station 460 ft) looking upstream.**

**Photo 12. SR-4 cross-section #3 (station 460 ft) looking downstream.**

**Photo 13. SR-4 cross-section #3 (station 460 ft) right bank.**

**Photo 14. SR-4 cross-section #3 (station 460 ft) left bank.**

**Photo 15. SR-5 cross-section #4a (station 700 ft) looking upstream.**

**Photo 16. SR-5 cross-section #4a (station 700 ft) looking downstream.**

**Photo 17.  SR-5 cross-section #4a (station 700 ft) right bank.**

**Photo 18.  SR-5 cross-section #4a (station 700 ft) left bank.**


**Photo 19.  SR-5 undercut concrete sewer casing starting to fail (station 750 ft)**


**Photo 20.  Unconsolidated material supporting sewer casing is washing away (station 750 ft)**

**Photo 21. SR-5 bedrock knick point assemblage, boulders (>700 mm) appear to be transported in this reach (station 800 ft).**

**Photo 22. SR-5 sewer line casing exposed along right bank through bedrock knick point assemblage. Stream is cutting north (right bank) that will continue to expose more of the sewer line (station 830 ft).**

**Photo 23.  SR-5 cross-section #4b (station 825 ft) looking upstream.**

**Photo 24.  SR-5 cross-section #4b (station 825 ft) looking downstream.**

**Photo 25.  SR-5 cross-section #4b (station 825 ft) right bank.**

**Photo 26. SR-5 cross-section #4b (station 825 ft) right bank.**

**Photo 27. SR-6 above sewer crossing at station 850 ft to downstream face of James River Expressway culvert.**

**Photo 28. SR-6 gravel splay on the right bank near station 900 ft.**

**Photo 29. SR-8 cross-section #5 (station 1,340 ft) looking upstream.**

**Photo 30. SR-8 cross-ection #5 (station 1,340 ft) looking downstream.**

**Photo 31. SR-8 cross-section #5 (station 1,340 ft) right bank.**

**Photo 32. SR-8 cross-section #5 (station 1,340 ft) left bank.**

**Photo 33.  SR-9a looking upstream at station 1,500 ft.**

**Photo 34.  SR-9a bank erosion at station 1,500 ft.**

**Photo 35. SR-9b cross-section #6 (station 1,620 ft) looking upstream.**

**Photo 36. SR-9b cross-section #6 (station 1,620 ft) looking downstream.**

**Photo 37. SR9b cross-section #6 (station 1,620 ft) right bank.**

**Photo 38. SR-9b cross-section #6 (station 1,620 ft) left bank.**

**Photo 39.  SR-10a located below storm pipe at station 1,840 ft.**

**Photo 40.  SR-10a local scour around storm pipe outfall at station 1,840 ft.**

**Photo 41. SR-10b looking upstream from station 1,840 ft with rip-rap along left bank falling into channel.**

**Photo 42. SR-11 bedrock knick point at stations 2,000-2,050 ft.**

**Photo 43. SR-12 cross-section #7 (station 2,210 ft) looking upstream.**

**Photo 44. SR-12 cross-section #7 (station 2,210 ft) looking downstream.**

**Photo 45. SR-12 cross-section #7 (station 2,210 ft) right bank.**

**Photo 46. SR-12 cross-section #7 (station 2,210 ft) left bank.**

**Photo 47. SR-13 cross-section #8 (station 2,615 ft) looking upstream.**

**Photo 48. SR-13 cross-section #8 (station 2,615 ft) looking downstream.**

**Photo 49. SR-13 cross-section #8 (station 2,615 ft) right bank.**

**Photo 50. SR-13 cross-section #8 (station 2,615 ft) left bank.**


**Photo 51. SR-14 downstream of National in the construction reach (station 3,050 ft).**

**Photo 52. SR-14 upstream of National in the construction reach (station 3,700 ft).**

**Photo 53. SR-15 right bank erosion and slump along Bradford Parkway (station 3,825 ft)**

**Photo 54. SR-15 "surf" trees with barked roots are evidence of mass wasting of bank material in the past. Suspended root crowns suggest wedge failure is slowly eroding and these trees could fall into the stream causing future instability (station 3,850 ft).**

**Photo 55.  SR-15 section #9 (station 3,875 ft) looking upstream.**

**Photo 56.  SR-15 section #9 (station 3,875 ft) looking downstream.**

**Photo 57. SR-15 section #9 (station 3,875 ft) right bank.**

**Photo 58. SR-15 section #9 (station 3,875 ft) left bank.**

**Photo 59. SR-15 looking upstream toward the Bradford Lake spillway with busted pieces of concrete in the channel downstream of the scour hole below the apron (station 3,940 ft).**

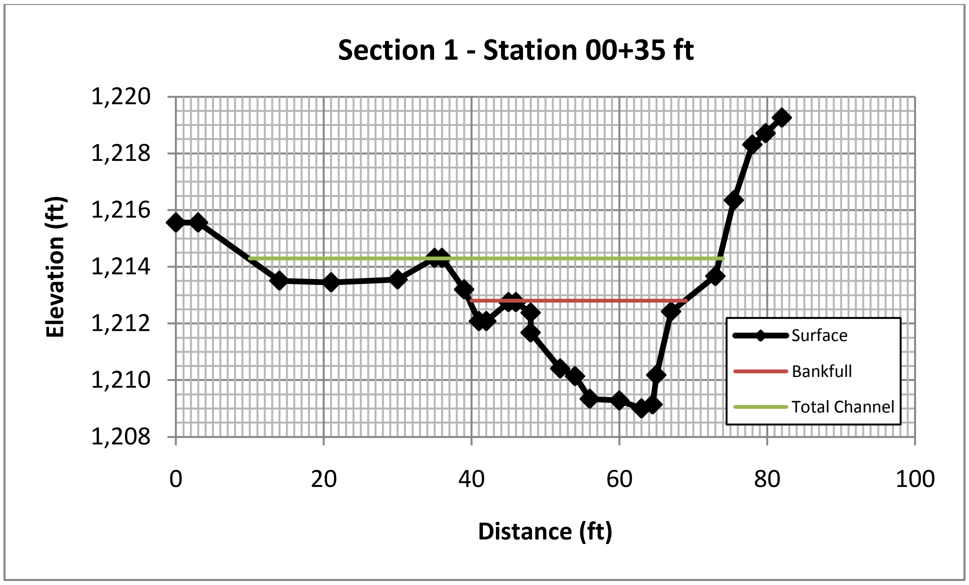
**Photo 60. SR-15 scour hole below concrete apron appears to be supported by compacted cherty-clay fill material that is being undercut (station 4,025 ft).**

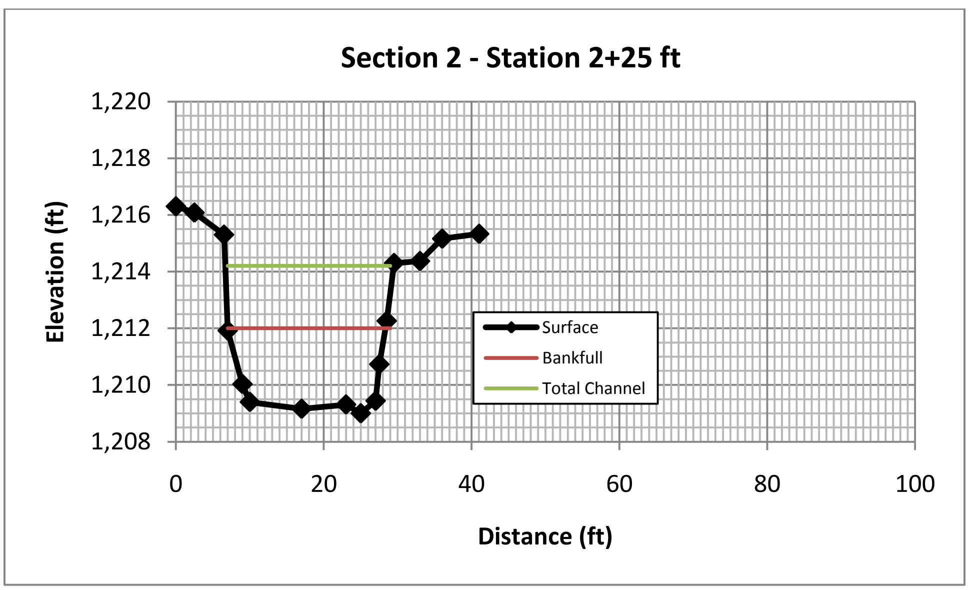
**Photo 61.  SR-15 concrete apron of spillway is undercut around 3 ft (station 4,025 ft).**

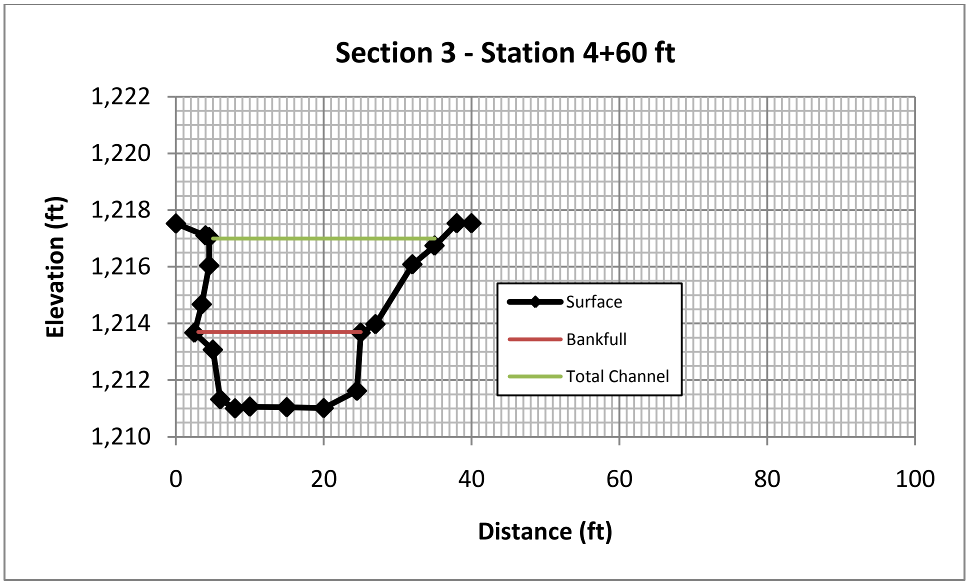
**Photo 62.  SR-15 downstream of Bradford Lake outlet structure concrete slabs are being pulled off the floor of the spillway.**

## APPENDIX

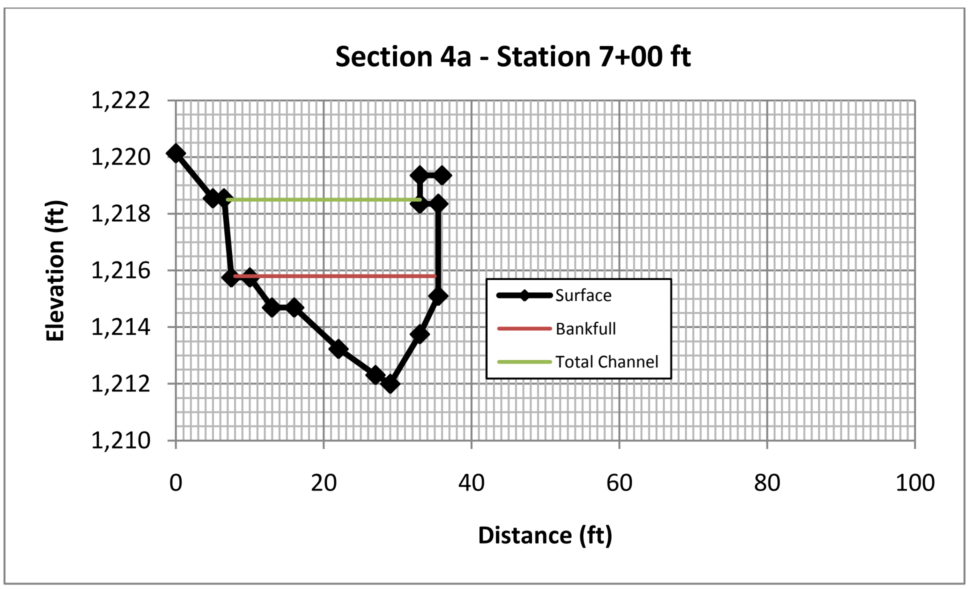
### Channel Cross-sections



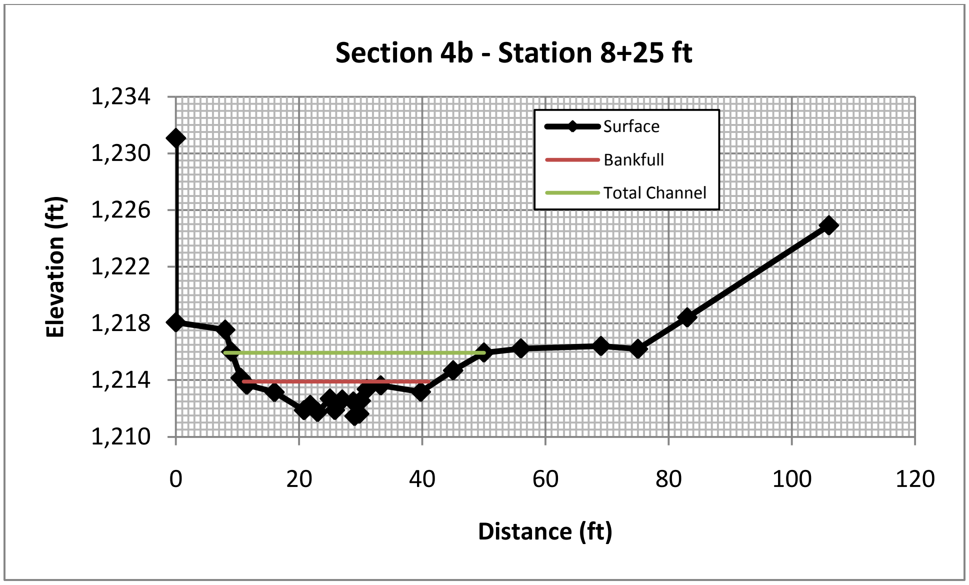



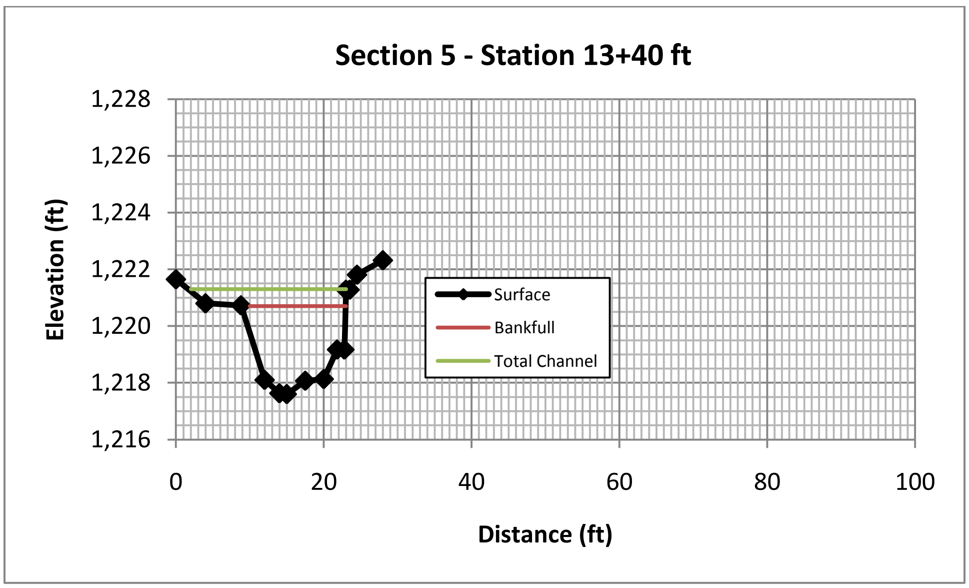


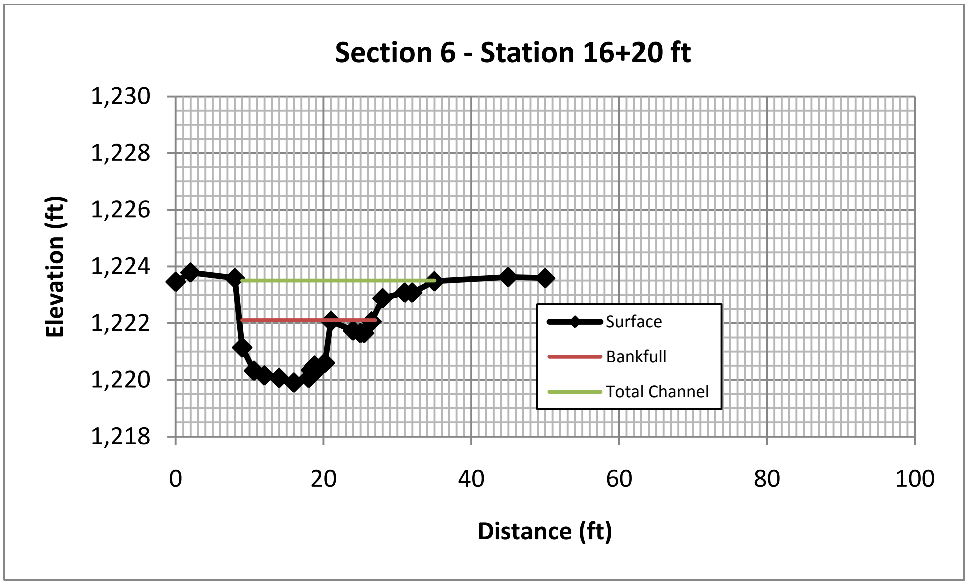
Section 3 - Station 4+60 ft
Elevation (ft)
1,222
1,220
1,218
1,216
1,214
1,212
1,210
0
20
40
60
80
100
Distance (ft)
Surface
Bankfull
Total Channel

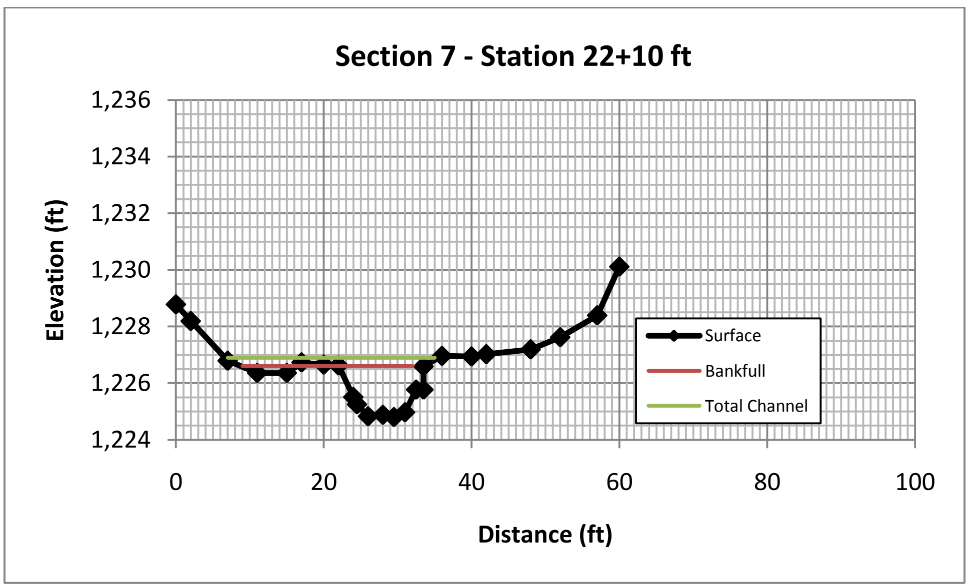



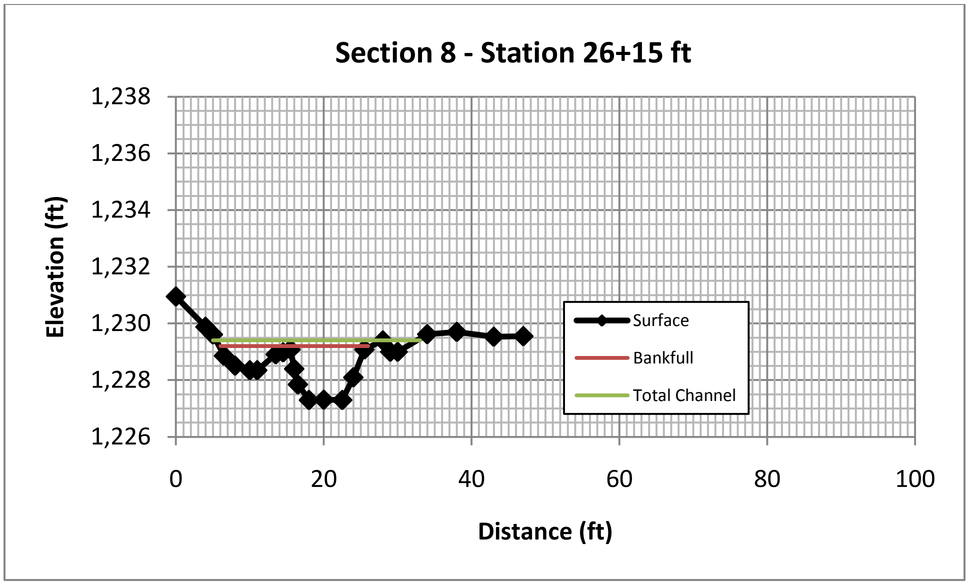
Section 4a - Station 7+00 ft
Elevation (ft)
1,222
1,220
1,218
1,216
1,214
1,212
1,210
0
20
40
60
80
100
Distance (ft)
Surface
Bankfull
Total Channel

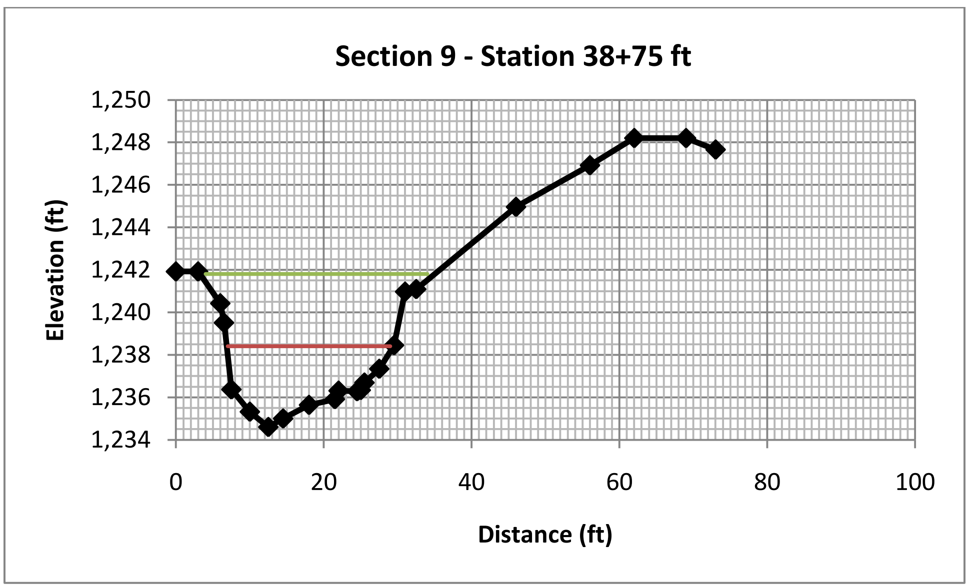

Section 4b - Station 8+25 ft
1,234
1,230
1,226
1,222
1,218
1,214
1,210
Elevation (ft)
0
20
40
60
80
100
120
Distance (ft)
Surface
Bankfull
Total Channel


Section 5 - Station 13+40 ft
1,228
1,226
1,224
1,222
1,220
1,218
1,216
Elevation (ft)
0
20
40
60
80
100
Distance (ft)
Surface
Bankfull
Total Channel


Section 6 - Station 16+20 ft
Elevation (ft)
1,230
1,228
1,226
1,224
1,222
1,220
1,218
0
20
40
60
80
100
Distance (ft)
Surface
Bankfull
Total Channel


Section 7 - Station 22+10 ft
Elevation (ft)
1,236
1,234
1,232
1,230
1,228
1,226
1,224
0
20
40
60
80
100
Distance (ft)
Surface
Bankfull
Total Channel


Section 8 - Station 26+15 ft
Elevation (ft)
1,238
1,236
1,234
1,232
1,230
1,228
1,226
0
20
40
60
80
100
Distance (ft)
Surface
Bankfull
Total Channel


Section 9 - Station 38+75 ft
Elevation (ft)
1,250
1,248
1,246
1,244
1,242
1,240
1,238
1,236
1,234
0
20
40
60
80
100
Distance (ft)