## Ozarks Environmental and Water Resources Institute (OEWRI)

# Geomorphic Assessment of City Center Athletic Club Development Impacts on Existing Stream Channel Stability, Lenexa, KS.

### Final report to Olsson Associates for the City of Lenexa, Kansas

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## Executive Summary of Findings

Recommendation: This report supports the opinion of the preliminary memo submitted by Eric Dove, P.E., Olsson Associates, to Tom Jacobs, City of Lenexa, on September 13, 2007 that "the proposed City Athletic Club will degrade the stream and should utilize full spectrum detention."

The main findings of this study upon which this conclusion is based are as follows:

1. Increased runoff will destabilize existing stream. City Center development will reduce existing detention volume due to removal of the on-site farm pond, increase runoff volume and peaks due to increased impervious cover, and increase drainage area by the extension of the storm water drainage system. The net hydrologic effect of these improvements will be to increase both the magnitude and frequency of runoff rates and geomorphic effective flow in the on-site stream. This increased energy delivered to the stream will increase channel erosion, bank failure, and sediment delivery to off-site areas.

2. Present stream conditions are sensitive to proposed hydrologic changes. The existing stream channel from the farm pond to its confluence with Mill Creek appears to be in a state of quasi-equilibrium and in balance with current hydrologic conditions and sediment transport. Quasi-equilibrium refers to the stream's ability over time to adjust and form a relatively stable condition in relation to imposed physical disturbances (rubble dam, farm pond, etc.). A channel in quasi-equilibrium can still erode its banks, meander, and change bed elevation, but usually at a reduced rate that allows for improved function of the stream for ecological benefits and more natural geomorphic behavior. The removal of the farm pond and proposed development without adequate storm detention facilities will cause this stream to become unstable and adjust to a new hydrologic regime. Moreover, relatively steep reaches (3 to 4%) along the tributary will increase stress to a critical level much more rapidly than before development and thus further increase the chances for channel instability.

3. Headwater location and geology of the site may limit the natural ability of the stream to dissipate excess hydraulic stress. Close proximity of the stream bed to bedrock will limit vertical adjustments of the channel and excess storm water energy will be expended or focused on bank erosion or an increase in the caliber of bed sediment erosion and transport. Lateral adjustments in channel location will likely be in the form of channel widening or meandering with bank erosion

liberating fine-grain sediment causing increased sediment and related nutrient yields from this watershed and potential degradation of habitat in downstream areas. Increased mobility of larger diameter bed load will result in bar formation that will fill in the channel further increase the frequency of lateral flows directed against banks.

4. Influence of historical disturbance on the channel system is still evident and can lead to present-day channel instability. Over the past century or more, the contributing watershed area of the study stream has been affected disturbances due to early settlement, land clearing, grazing, and row-cropping. These conditions caused increased soil erosion and runoff from uplands and slopes that increased the volume of fine-grained sediment storage in the form of higher bank deposits on floodplains. In addition, increased flooding caused head cuts to form along the channel bed and evidence of stalled head cuts are observed in the stream today. The addition of more runoff may cause renewed head cutting and accelerated erosion of higher banks. Presently, there is evidence of a period of recovery along the stream due to improved soil conservation practices and the development of a quasi-equilibrium channel.

5. Increased runoff may destabilize the downstream ruble dam and the sediment storage above it. A large and poorly constructed ruble dam is located just downstream of the site. The entire stream and floodplain is blocked by debris and all stream flow is forced through a 30" concrete pipe outlet. The conveyance of this pipe is not sufficient to pass most floods and water is retained for a short (unknown) period behind the ruble dam. During this period, fine-grained sediment also settles out and the existing channel bed and floodplain has aggraded to a depth of about 3 feet. Channel slope decreases in the aggraded area upstream of the dam and the channel takes on a meandering form. Additional flows may weaken the ruble dam with unknown effects on flow and sediment transport. In addition, increases of flow energy within the ruble dam sedimentation area may increase bank and bed erosion rates and release excessive quantities of stored silt downstream.

6. Detention plans should consider the geomorphic controls and processes and their impacts on the property as described above.

## Study Scope

This is the final report for the geomorphic channel assessment of the Lenexa-City Center Athletic Club site located on an un-named tributary to Mill Creek (Figure 1). The purpose is to evaluate whether storm water detention is required to limit the effects of runoff, sediment production, and channel instability to the downstream tributary. It describes the dominant geomorphic processes, disturbance factors, and stability conditions present in the system. Two geomorphologists from Missouri State University (Dr. Robert Pavlowsky and Marc Owen) representing Olsson Associates visited the site and completed field work on September 11-12, 2007 and February 28, 2008.

## Site Description

The tract under consideration is located in the eastern half of section 31, township 12-S, range 24-E (Figure 1). The area is underlain by Pennsylvanian age limestones and shales (O'Conner, 2000). Upland soils are derived from loess while hillslope soils are weathered from residuum and colluvial parent material (Evans, 2005). The majority of the evaluated stream flows through a hillslope landscape position with a shallow residual soil where outcrops of limestone and shale are common.

The stream in question is a headwater stream originating as a first order channel from a farm pond outlet (Figure 2). About 1,200 feet of stream was evaluated on-site from the earth dam of the farm pond to the southern boundary of the property (drainage area approx. 87 acres). Just above the property line, the stream meets another tributary from the northwest draining a golf course (drainage area approx. 30 acres of the 87 acres) and becomes a second order stream. In addition, another 1,200 feet of channel was evaluated offsite from the property border to the confluence with a larger stream. The total drainage area of the un-named tributary or entire study stream is approximately 114 acres at its confluence with Mill Creek.

Where not disturbed, the on-site and downstream portions of the channel represent a typical headwater stream system in the area which has undergone a history of agricultural and more recent suburban influence. The uppermost portions of the stream are controlled by colluvial processes and soil stability and the rest of the channel is alluvial in nature, but largely confined in a narrow valley with varying degrees of bedrock control. Streams tend to be straight to slightly sinuous where a riparian buffer is present. Often the channel runs along the left valley margin and is thus affected by hillslope conditions. Cobble beds with varying degrees of exposed bedrock are found throughout.

Besides the long history of land use change affecting the site which is typical for streams in this area, there are three additional sources of major physical disturbances to the stream. Physical disturbance is common and represents the most significant considerations for development of the site. These disturbances include:

1. Farm pond;
2. Off-site rubble dam across valley; and
3. Location of a sewer line along the valley floor.

The general lay out of the study area is presented in Figure 2 and going downstream as follows:

- (1) Pond dam at the beginning of the study area (st. 2,573 ft)
- (2) 1,098 feet of first order channel from pond dam to the golf course tributary (st. 2,573-1,475 ft)
- (3) 317 ft of second order channel flowing off the property to the valley fill inlet (st. 1,475-1,158 ft)
- (4) 406 ft of underground flow through rubble dam (st. 1,158-752 ft).
- (5) 752 ft of second order channel to confluence with larger stream (st. 752-0 ft) Municipal sewer line runs along this stream segment.

**Methods**

All site locations described in the report were determined using a hand-held GPS receiver (Figure 1, Tables 1 and 2). Field data were collected to describe the channel morphology and slope for one on-site reach and one downstream reach. At each reach, two channel cross-sections were measured at glide-riffle crest transition zones and longitudinal profiles included at least four riffle crests. Topographic data were collected with auto-level and stadia rod along a tape. Erosion pin arrays were deployed at 8 sites (6 on-site and 2 downstream). These arrays consisted of 3 to 7 rebar pins driven horizontally into the bank until flush with the bank line. Monitoring of depth of exposure of the pins over time is used to measure bank erosion rates. The stream channel was classified into sub-reaches based on the visual assessment of channel morphology and substrate, bank conditions, and valley form to evaluate channel stability and dominant geomorphic processes along the length of the study area.

**Sub-Reach Channel Classification**

The 2,590 ft long stream system can be divided into the following sub-reaches based on both broad and specific characteristics as follows:

<u>On-site drainage above rubble dam influence</u> (1,098 ft in total length)

Farm pond affected reach (194 ft in total length)
Sub-reach (SR) 1: length= 194 ft

Upland colluvial reach (112 ft)
SR-2: length= 112 ft

Bedrock-controlled reach (375 ft)
SR-3a: straight, length= 213 ft
SR-3b: slightly meandering, length= 162 ft

Transitional bedrock-alluvial reach (254 ft)
SR-4a: straight, length= 73 ft
SR-4b: steep, length= 103 ft
SR-4c: slightly meandering= 78 ft

Alluvial reach (163 ft)
SR-5: length= 163 ft

<u>Rubble dam-affected reach (776 ft)</u>

SR-6: upstream impounded area, length= 317 ft
SR-7: Underground culvert, length= 406 ft
SR-8: Downstream rubble-affected, length= 53 ft

Off-site drainage below rubble dam (716 ft)

Bedrock-influenced reach (415 ft)
SR-9: Straight, length= 303 ft.
SR-10: Meandering, length= 112 ft

Low-water bridge affected reach (170 ft including bridge)
SR-11a: Upstream culvert backwater, length= 68 ft
SR-11b: Downstream outlet, length= 85 ft

Confluence with Mill Creek (131 ft)
SR-12: Confluence backwater, length= 131 ft

Each of the sub-reaches identified in this study is described in detail below along with supporting field data. There are fifteen sub-reaches (SR-#) within the study area as follows:

*SR-1 Pond Outlet Influence (length= 194 ft)*
The farm pond above this sub-reach has limited flood storage capacity with outlet controlled through a 24" pipe. A small scour pool has formed at the outlet to dissipate energy. The channel below the outlet is straight with exposed bedrock or boulders common. In some areas a step-pool bedform is obvious. The bankfull channel averages about 5.3 ft wide, ranging from 3.7 ft to 7.8 ft. A young treed buffer is present. The steep stream and low sediment supply due to deposition in the upstream pond results in incision to bedrock. Without the pond, this reach would probably look more like a grassed-waterway or colluvial channel like described for sub-reach 2 below (Photos 1 and 2).

*SR- 2 Colluvial Channel (length = 112 ft)*
The channel is straight and narrow with heavy influence of soil creep in controlling the colluvial nature of the channel. The stream crosses an open area and grass is the common buffer vegetation. The channel is 2.3 ft wide and 0.8 ft deep. Flat coarse gravel and cobble are the dominant substrate. This sub-reach represents the lowest extent of the colluvial (soil creep-dominated) channel conditions along the study reach. Presently, this area is in transition with a narrow threadlike channel incising into the soil surface of the grassed, waterway channel (Photo 3).

*SR- 3a Bedrock control (straight)(length = 213 ft)*
Downstream from this point, upland colluvial influence ends the stream channel is controlled by shallow bedrock, with relatively large cobble common on the bed with small boulder-sized material occurring in some places. There is evidence of a minor head cut at the top of this sub-reach, but no cut banks are present. The head cut probably stalled in the past on shallow bedrock. The upstream channel survey was collected in this sub-reach (Photo 4). The channel is relatively stable in this area due to high bedrock resistance and confinement by bedrock bluffs outcropping along the left valley margin and relatively resistance colluvial deposits along the right side of the channel.

*SR- 3b Bedrock control (slightly meandering)(length = 162 ft)*
This sub-reach is similar to 3a but with some meandering. Pin array 1 (PA-1) is located in this sub-reach consisting of 4 pins, 3 on the outside of the meander, and 1 pin on the outside. The three outside pins are positioned evenly in a vertical orientation (Photo 5). While no slope measurements were collected in this reach, there appears to be a slight break in slope between SR-3a and SR-3b.

*SR- 4a Alluvial Transition (straight)(length = 73 ft)*
The channel is straight and with a riffle-pool form that is about 6.8 ft wide and 0.75 ft deep. The bed is composed of large flat cobbles and coarse gravel and sometimes takes on a step-pool form where boulders or bedrock influence the channel bed. Sub-reaches 4a, 4b, and 4c contain historical alluvial deposits with higher bank development than upstream areas. In effect this is the transition between steeper, upland areas and gentler, valley areas where alluvial floodplain deposition begins to occur (in contrast to occurrence of colluvial valley floors above this point). A small ephemeral spring marked by an old cattle watering tub is located at the top of this sub-reach. A minor head cut appears to be stalled at the upstream end of sub-reach 4a where bedrock comes to the surface and increases channel resistance to erosion (Photo 6).

*SR- 4b Alluvial Transition (steep)(length = 103 ft)*
The channel is straight and slightly steeper with a riffle-pool form that is about 8.3 ft wide and 0.75 ft deep. The bed is composed of large flat cobble and sometimes takes on a step-pool form where boulders or bedrock influence the channel bed. PA-2 is located in this sub-reach where 3 sets of evenly spaced vertical pin arrays are located on a cutbank. The upstream set consists of three pins and the two downstream sets have two pins each (Photo 7).

*SR- 4c Alluvial Transition (meandering)(length = 78 ft)*
The channel is meandering (sinuosity of about 1.3) with a riffle-pool form that is about 4 ft wide and 0.75 ft deep. Bed slope is decreasing due to the downstream control of flow by the damming of the channel by rubble dam and a 30" diameter concrete pipe. Bed material becomes finer with silt and mud covering the bed in most places. PA-3 is located in this sub-reach with three sets of vertical pin arrays with two pins in each array (Photo 7).

*SR- 5 Alluvial (meandering)(length = 163 ft)*
The channel is meandering (sinuosity of about 1.2) with a riffle-pool form that is about 4.5 ft wide and 0.75 ft deep. Locally, bed slope increases a bit and the bed substrate becomes more gravelly with some cobbles. This is probably due to locally shallow bedrock conditions as observed in the bed and along the valley margin. PA-4 is located in this sub-reach with one set of four pins. Three pins are vertically spaced on the cutbank and 1 in the eroding active floodplain on the inside of the meander (Photo 8).

*SR- 6 Impounded Valley (length = 317 ft)*
The channel becomes more meandering as fine-grained sedimentation is enhanced due to rubble dam and influence of the golf course tributary (Photos 9 and 10). The channel bed is silty and has aggraded more than 3 feet over its pre-dam bed level (Photos 11 and 12). The width of the channel here is 3.3 ft with a depth of 0.8 ft. Both PA-5 and PA-6 are located in this sub-reach. PA-5 is an array of 4 locations of 1 pin each in the middle of the cutbank, which is relatively

lower due to channel aggradation at this location. In addition, 2 pins were driven horizontally into the top of the active floodplain to measure overbank sedimentation. PA-6 consists of 1 set of 3 vertically spaced pins on a cutbank location 30 feet upstream of the property line (Photos 13, 14 and 15).

*SR- 7 Underground Pipe (length = 406 ft)*
This reach takes water under the rubble dam fill material through a 30” concrete pipe with slope of about 0.04. This limits the flow of water to the downstream reach to 45 cfs at 6 ft of head elevation. The rubble dam appears to be constructed of non-engineered fill not suitable for a water retaining structure. A suitable auxiliary spillway does not exist and the fill is covered with woody plants. In addition, the 30” concrete pipe does not appear to be reinforced and the joints of the short (< 5ft) sections are not soil tight.

*SR- 8 below Fill Outlet (length = 53 ft)*
The channel is straight with a bed rock and riffle-pool form that is about 3.7 ft wide and 1 ft deep. The bed is silty with local areas of gravel and cobble. Rubble debris forms the left bank in many places and large blocks and debris provide obstacles to the flow in some places (Photo 16).

*SR- 9 Bedrock-influenced, Straight (length = 303 ft)*
The channel is straight and with a bed rock and riffle-pool form that is about 3.8 wide and 0.8 ft deep. The bed is composed of flat cobble. Quarry debris forms the left bank in many place and large blocks and debris provide obstacles to the flow in some places. The channel flows along the right valley margin here and appears to be locked in place in this location (Photo 17).

*SR- 10 Bedrock-influenced, slightly meandering (length = 112 ft)*
The channel is sinuous with one or two meander bends and with a bed rock and riffle-pool form that is about 3.8 ft wide and 0.8 ft deep. The bed is composed of gravel and cobble that are 70% embedded with fines. PA-7 is located in this sub-reach with 1 set of 3 vertically spaced pins on the cutbank and one in the opposite side in the eroding active floodplain (Photo 18).

*SR- 11a and 11b Low Water Crossing (11a length = 68 ft)(11b = length = 85 ft)*
Sub-reach 11 is relatively straight and affected by a low water culvert stream crossing. This reach represents the relatively localized effect of channel and floodplain constriction by a small bridge. Sub-reach 11a is upstream of the bridge where sedimentation and minor aggradation has occurred. The channel is 3 ft wide and 1 ft deep with over 70% of cobble and gravel bed embedded with silt. Sub-reach 11b is below the bridge. The channel is 3.7 ft wide and 0.75 ft deep with less embeddedness. There are more large cobble and boulders in the bed compared to the SR-11a (Photos 19 and 20).

*SR- 12 Confluence (length = 131 ft)*
The channel meanders as it is affected by the floodplain control of the larger stream valley. The channel is 2.4 ft wide and 1.1 ft deep with coarse gravel and large cobble on the bed. PA-8 is located in this sub-reach consisting of 2 sets of pins; two vertically spaced pins in the upstream set and three in the downstream set. One pin was positioned in the eroding active floodplain on the inside of the meander at both locations (Photos 21 and 22).

## Channel Morphology and Sediment Mobility

The "typical" on-site channel morphology and sediment mobility was evalauted in subreach 3a above the influence of the rubble dam. The mean slope of the reach is approximately 3.5% with riffle slope ranging from 3.4% and 5.3% at the cross-sections (Figure 3). The mean bankfull dimensions at these sections are 9.1 ft wide by 0.7 ft deep at the thalweg (Figures 4 and 5). Mean boundary shear stress estimates in the reach range from 1.07-1.17 lbs/$ft^2$ which can transport between the 84 mm to the 171 mm size fraction based on empirical relationships. This sediment distribution is in the small to large cobble range that matches the measured bed sediment in the reach containing a range of substrate from cobble to flat boulders (Table 3).

The analysis of "typical" off-site channel morphology and sediment mobility was conducted in subreach 9 below the rubble dam. The mean slope of this reach is 4.2% with riffle slopes at cross-section locations ranging from 4.2% to 4.4% (Figure 6). The mean bankfull dimensions at these sections are 6.6 ft wide by 0.7 ft deep at the thalweg of the channel (Figure 7 and 8). Mean boundary shear stress estimates in the reach range from 1.22-1.39 lbs/$ft^2$ which can transport between the 96 mm to the 193 mm size fraction based on empirical relationships. This sediment distribution is in the small to large cobble range matching the measured bed sediment in this reach (Table 3).

## Erosion Pin Results

Pin arrays that were installed in actively eroding banks on September 11th and 12th, 2007 were checked on February 28th, 2008. Table 2 summarizes results of the erosion pin monitoring discussed here:

*PA-1* is located in SR-3b where the channel starts to meander. Pins here showed no change over the monitoring period, but the channel did have some fresh fine gravel deposition on the bed (Photos 23 and 24).

*PA-2* is located in SR-4a which is an alluvial transition reach from a colluvial dominated landscape position. There was less than 0.1 ft of pin exposed in the upper bank and the lower pins were buried by upper bank slump. In addition a large woody debris jam has moved into this reach, but no significant disturbance was observed as of February 2008 (Photos 25 and 26).

*PA-3* is located in SR-4c where the alluvial transition zone begins to meander. Pins remain unchanged with some upper bank slumping lowering the bank angle (Photos 27 and 28).

*PA-4* is located in SR-5 above the confluence with the golf course tributary. Approximately 0.1 ft of the pin located in the upper bank has been exposed with the lower bank pin being covered indicating some mass wasting of this bank at this location Photos 29 and 30).

*PA-5* is located in SR-6 where valley fill has caused channel/valley aggradation. The upstream pin had 0.25 ft exposed, the next pin going downstream had < 0.1 ft exposed with the remaining pins having no change (Photos 31 and 32).

*PA-6* is also located in SR-6. Pins at this location showed upper bank slump covering the lower pin decreasing the bank angle at this location (Photos 33 and 34).

*PA-7* is located in SR-10 which is a sinuous stable reach below the valley fill. Pins here had <1 ft of upper bank slump deposition at the toe of the bank (Photos 35 and 36).

*PA-8* is located in SR-12 above the confluence of the main tributary where slope decreases as the channel meets a larger alluvial floodplain. Here, pins showed between 0.1 and 0.25 ft of erosion during the monitoring period (Photos 37 and 38).

**Conclusions**

The geological setting of the stream system forms a transition zone of geomorphic influence from hillslope or "colluvial" processes in the upper reaches to valley floor or "alluvial" processes in the lower reaches. In addition, bedrock is relatively close to the surface and exposed along the valley margin and bed at several places along the stream. Thus, the natural and quasi-equilibrium form of the channel reflects the influence of shallow bedrock and valley confinement throughout. Geomorphic measurements reported for "typical" reaches in both upstream and downstream locations describe examples of these bedrock-influenced channels that best represent the present condition of the least disturbed portions of the stream channel.

Four disturbance factors influence the present behavior of the stream. First, the historical land use practices of the region involving early settlement, land clearing, and row-cropping increased runoff and soil erosion rates in the watershed. Evidence of storage of fine-grained sediment in floodplain deposits and head-cutting in the past is found along the study stream, but in many places the stream appears to be in a recovery phase due to construction of the farm pond and improved conservation practices. The second disturbance involved the construction of the farm pond which would have reduced runoff peaks to some extent, fine-grained sediment loads to a lesser extent, and all of the bed load transport into it. However, the bed load supply rates from the upper portions of the watershed may have been limited since soil depth, soil creep, and colluvial deposits may have limited scour to bedrock and the source of coarser materials.

The third disturbance factor was the filling of the valley with the rubble dam on the downstream property. The backwater influence of this dam on runoff and sediment transport has clearly caused excessive fine-grained deposition, channel meandering, bank erosion, and bed aggradation to a distance of at least 300 ft upstream and possibly to a lesser extent to almost 500 ft upstream of the dam. The fourth disturbance factor was the construction of a small low-water bridge along the off-site portion of the stream. This bridge only has a local effect on the geomorphology of the stream.

The existing stream channel is generally in quasi-equilibrium throughout with one exception. The channel on the southern end of the property is influenced by the affects of the rubble dam across the valley. Beginning in Sub-reach 4c, channel slope decreases and fine-grained sedimentation rate increases. Due to flow constriction and impoundment by the undersized culvert, flow to the downstream reach is controlled and energy is checked. Stream energy probably decreases downstream since bankfull discharge is probably less than the pre-dam condition. The present channel form indicates that the lower reaches are somewhat more stable than the upper reaches due to the controlling influence on flood peaks by rubble dam detention. If the rubble dam is removed and the valley reconnected to the channel, the downstream reach will become more exposed to the hydrologic changes in the upper watershed.

It is expected that sedimentation will continue to occur in Sub-reach 6 and the wedge of influence will slowly shift upstream over time. Development upstream should focus on reducing sediment load to the stream to prevent excessive sedimentation and destabilization of the channel. Bank conditions are relatively stable except where recent alluviation (vertical bank deposition) and aggradation (vertical or upward bed elevation change) has occurred in the impounded areas affected by the rubble dam. Relatively stable beds have formed along most of the study stream, both on and off the property, due to bedrock control and coarse substrate. In the aggraded reach, similar bed substrates are found buried under much finer material to a depth of 3 ft or more.

Additional study conclusions are found at the beginning of this report in the executive summary.

## References

Evans, B.C., 2005. Soil Survey of Johnson County, Kansas. United States Department of Agriculture, Natural Resources Conservation Service in cooperation with the Kansas Agriculture Experiment Station.

O'Conner, H.G., 2000, Geologic Map of Johnson County, Kansas. Kansas Geological Society, M-92, 1 sheet, 1:50,000

**Table 1. Sub-reach locations and lengths (State Plane Kansas North (ft))**

| Sub-Reach | Reach Length (ft) | Reach Stations (ft) | X | Y |
|---|---|---|---|---|
| 1 | 194 | 2,379-2,573 | 2,226,953.44623 | 246,415.19458 |
| 2 | 112 | 2,267-2,379 | 2,226,829.41857 | 246,286.25175 |
| 3a | 213 | 2,054-2,267 | 2,226,776.97287 | 246,200.12998 |
| 3b | 162 | 1,892-2,054 | 2,226,603.10101 | 246,123.98262 |
| 4a | 73 | 1,819-1,892 | 2,226,509.43124 | 246,035.23908 |
| 4b | 103 | 1,716-1,819 | 2,226,442.32423 | 246,010.12884 |
| 4c | 78 | 1,638-1,716 | 2,226,369.88141 | 245,937.92910 |
| 5 | 163 | 1,475-1,638 | 2,226,315.95296 | 245,912.12630 |
| 6 | 317 | 1,158-1,475 | 2,226,172.04986 | 245,885.24059 |
| 7 | 406 | 752-1,158 | 2,226,096.03254 | 245,730.70584 |
| 8 | 53 | 699-752 | 2,226,005.50473 | 245,335.33326 |
| 9 | 303 | 396-699 | 2,226,011.39890 | 245,277.65987 |
| 10 | 112 | 284-396 | 2,225,958.98696 | 245,008.09553 |
| 11a | 68 | 216-284 | 2,225,968.63379 | 244,898.29746 |
| 11b | 85 | 131-216 | 2,225,964.62366 | 244,821.28372 |
| 12 | 131 | 0-131 | 2,225,948.75196 | 244,760.26709 |

**Table 2. Pin array locations in sub-reach (State Plane Kansas North (ft))**

| Pin Array | Sub-Reach | X | Y |
|---|---|---|---|
| 1 | 3b | 2,226,603.10101 | 246,123.98262 |
| 2 | 4a | 2,226,442.32423 | 246,010.12884 |
| 3 | 4c | 2,226,356.09933 | 245,945.02071 |
| 4 | 5 | 2,226,267.55418 | 245,919.27123 |
| 5 | 6 | 2,226,167.52217 | 245,890.60889 |
| 6 | 6 | 2,226,139.40978 | 245,827.72031 |
| 7 | 10 | 2,225,958.98696 | 245,008.09553 |
| 8 | 12 | 2,225,920.29542 | 244,711.35881 |

**Table 3. Typical cross-section data at bankfull stage**

| Sec ID | DA | BFW | BFD (max) | BFD (mean) | R | CSA | Wp | Slope | "n" | Mean v | BFQ | SS | Crit. 1 | Crit. 2 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Station | (acres) | ft | ft | ft | ft | $ft^2$ | ft | ft/ft | | ft/s | cfs | (lbs/$ft^2$) | mm | mm |
| U-69 | 42 | 7.62 | 0.79 | 0.52 | 0.51 | 3.98 | 7.87 | 0.034 | 0.04 | 4.35 | 17.28 | 1.07 | 84 | 160 |
| U-109 | 42 | 10.48 | 0.64 | 0.29 | 0.36 | 3.05 | 8.58 | 0.053 | 0.04 | 4.29 | 13.07 | 1.17 | 92 | 171 |
| D-25 | 104 | 7.08 | 0.75 | 0.33 | 0.51 | 2.37 | 4.69 | 0.044 | 0.04 | 4.95 | 11.72 | 1.39 | 110 | 193 |
| D-88 | 104 | 6.12 | 0.58 | 0.50 | 0.47 | 3.06 | 6.56 | 0.042 | 0.04 | 4.58 | 14.02 | 1.22 | 96 | 176 |

DA = drainage area (acres)
BFW = bankfull width (ft)
BFD = bankfull depth (ft)
R = hydraulic radius (ft)
CSA = cross-sectional area ($ft^2$)
Wp = wetted perimeter (ft)
V = velocity (ft/s)
BFQ = bankfull discharge (cfs)
Ss = shear stress (lbs/ft2)
Crit 1 = critical diameter (mm) using empirical relationships (Leopold, Wolman, and Miller, 1964)
Crit 2 = critical diameter (mm) using empirical relationships (Rosgen, 1986)

**Table 4. Erosion Pin Array Data**

| Array # | Pin #s | $W_{bf}$ # (ft) | $Dmax_{bf}$ # (ft) | Top Bank Ht# (ft) | Erosion/Deposition (4 month period) |
|---|---|---|---|---|---|
| 1 | 4 | 5.4 | 1.3 | 2.7 | 0- no change |
| 2 | 7 | 5.4-5.6 | 0.8-1.2 | 3.5-4.2 | <0.1 ft upper bank<br>Slope deposition at toe |
| 3 | 6 | 4-8.3 | 0.5-1 | 4.8-5.3 | <0.1 ft upper bank<br>Slope deposition at toe<br>(i.e. Bank angle recession) |
| 4 | 4 | 4.4 | 0.8 | 4.8 | 0.1ft upper bank<br>Slope deposition at toe |
| 5 | 6 | 4.3-5.8 | 0.7 | 2.5-4.3 | 0-0.25 ft |
| 6 | 3 | 3.5 | 0.4 | 2.9 | 0.1 ft upper bank<br>Slope deposition at toe |
| 7 | 3 | 2.9 | 1.1 | 3.8 | 0.1 ft upper bank<br>Slope deposition at toe |
| 8 | 3 | 2.9 | 1.3 | 3.3 | 0.1-0.25 ft |

# Abbreviations defined as follows:

$W_{bf}$ = width of bankfull channel at top of active floodplain elevation

$Dmax_{bf}$ = maxium height of bankfull channel above the thalweg

Top Bank Height= Height of top of bank where pin array was deployed. This surface typically represents the historical floodplain of the system and is sometimes referred to as the low terrace.

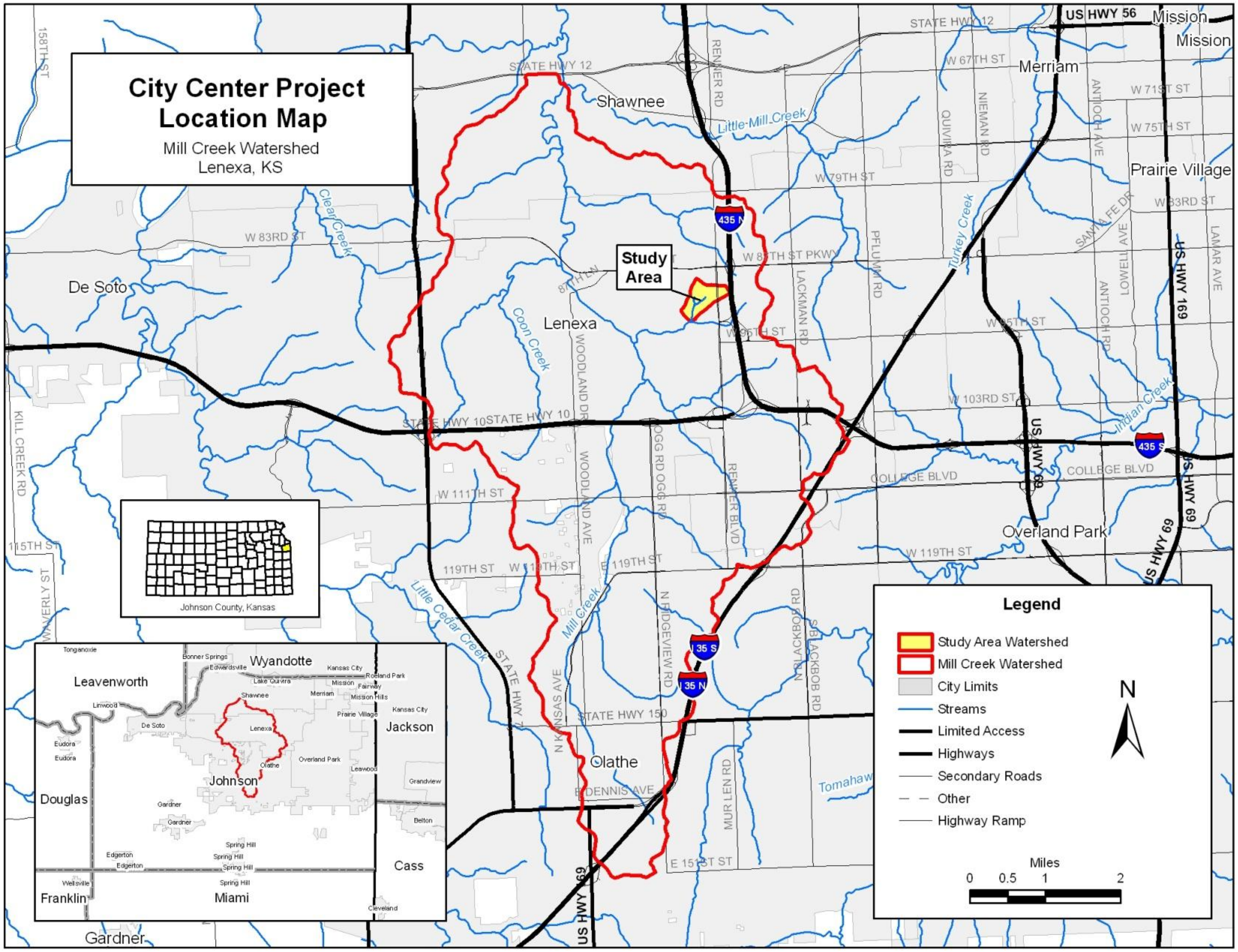


**Figure 1. Mill Creek Watershed Study Area**

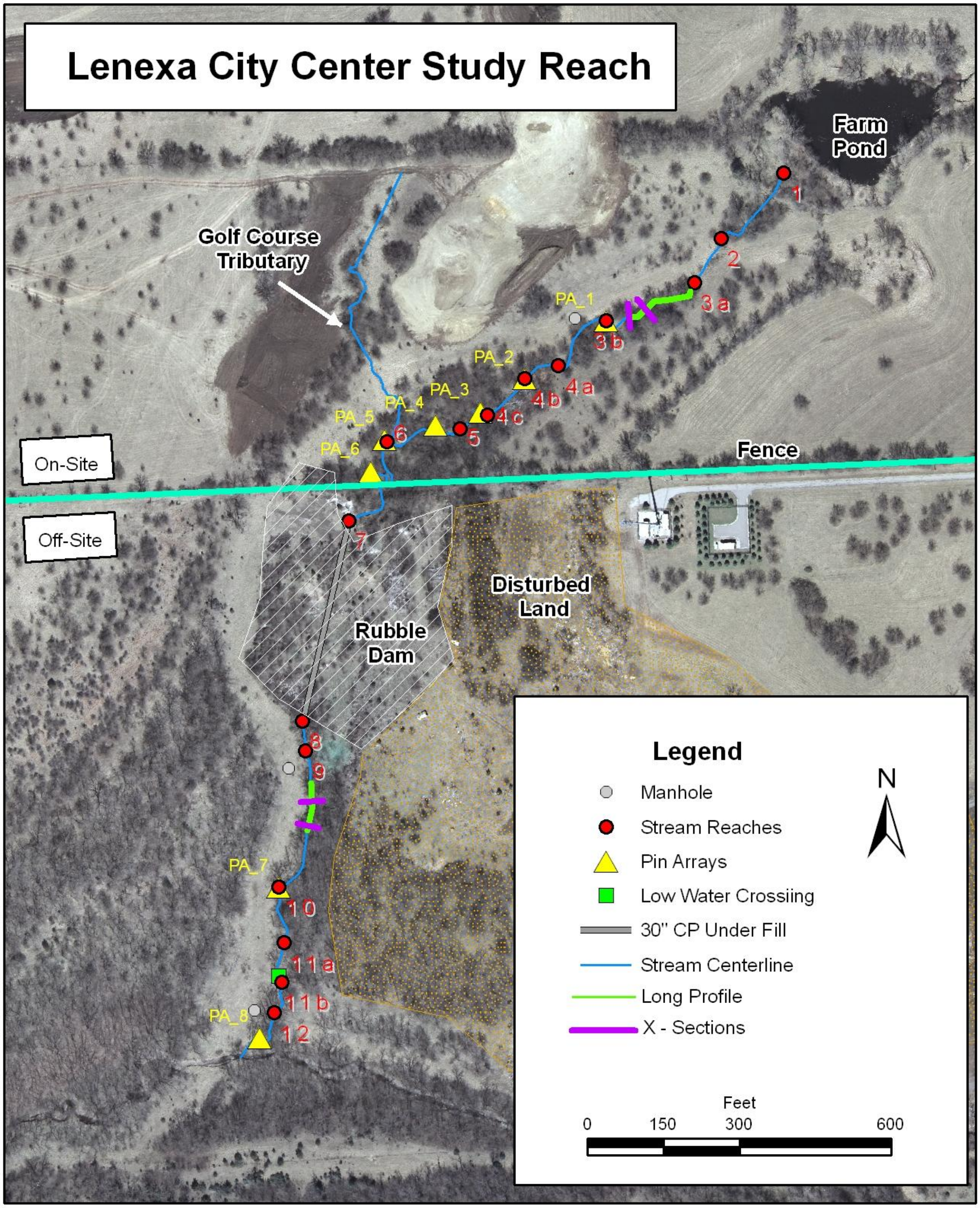


**Figure 2. Study Reach Map**

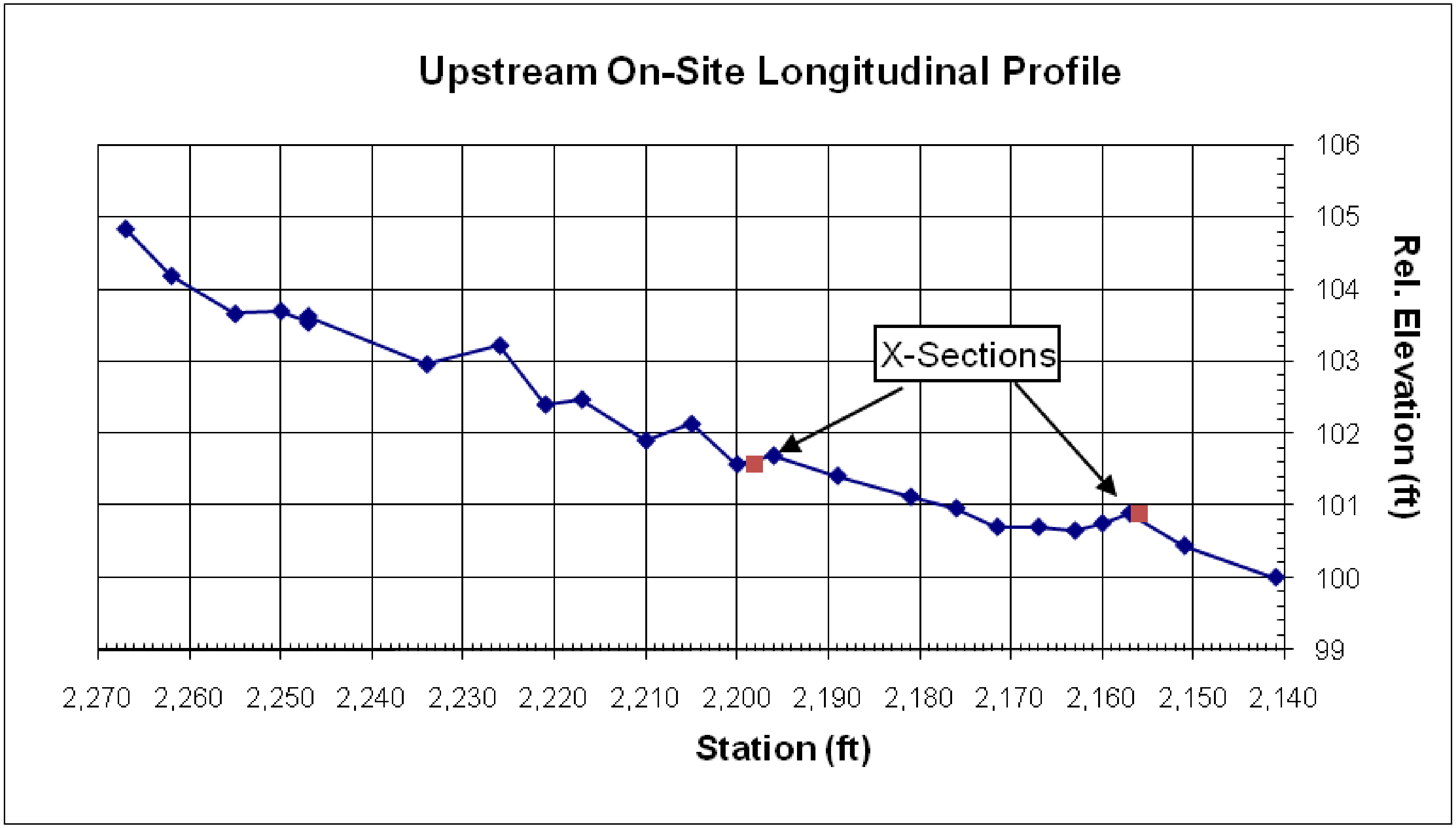


**Figure 3. On-site Longitudinal Profile for Typical Reach**

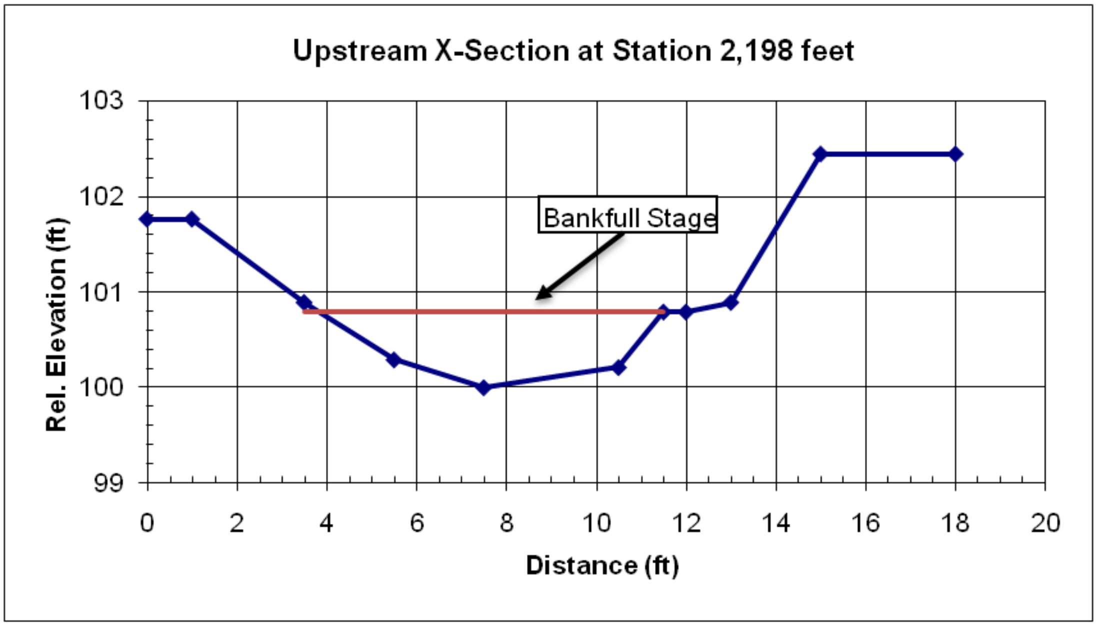


**Figure 4. On-site cross-section at 69 ft on long. profile**

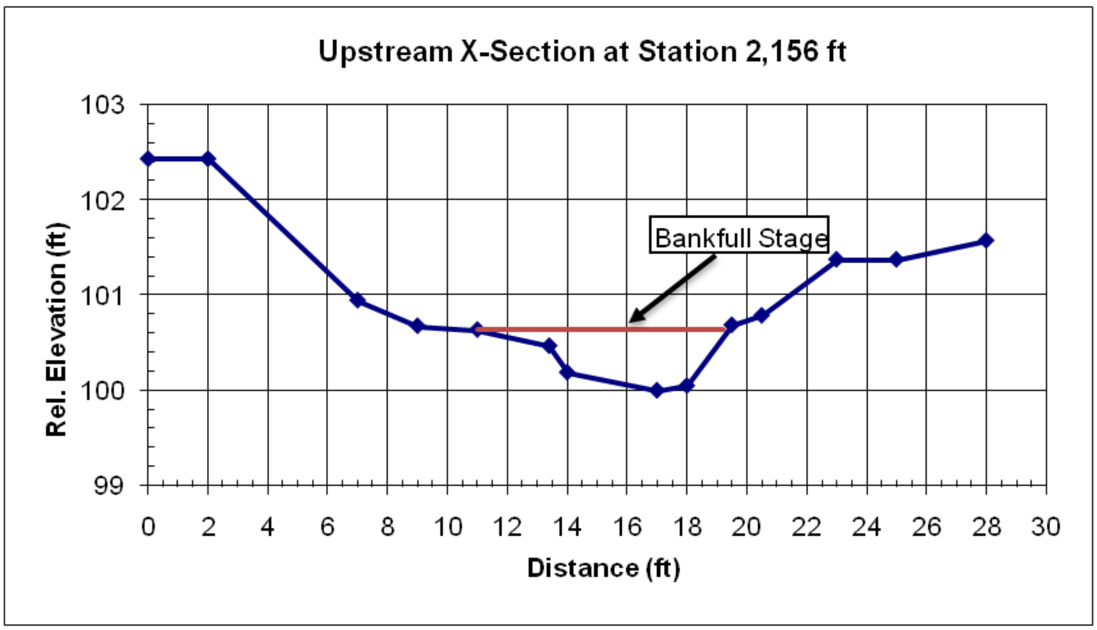


**Figure 5. On-site cross-section at 109 ft on long. profile.**

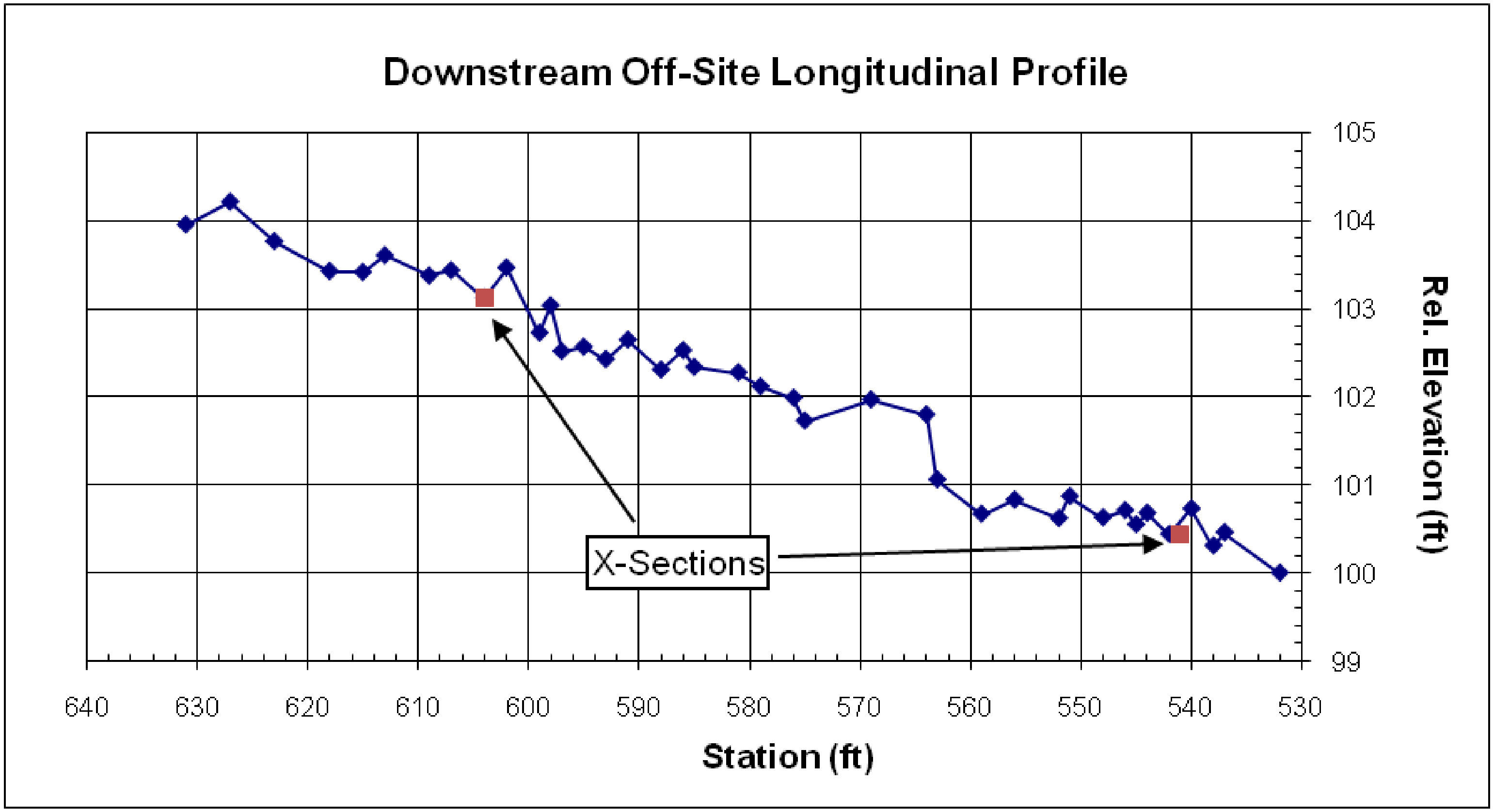

**Figure 6. Off-site longitudinal profile downstream of rubble dam.**

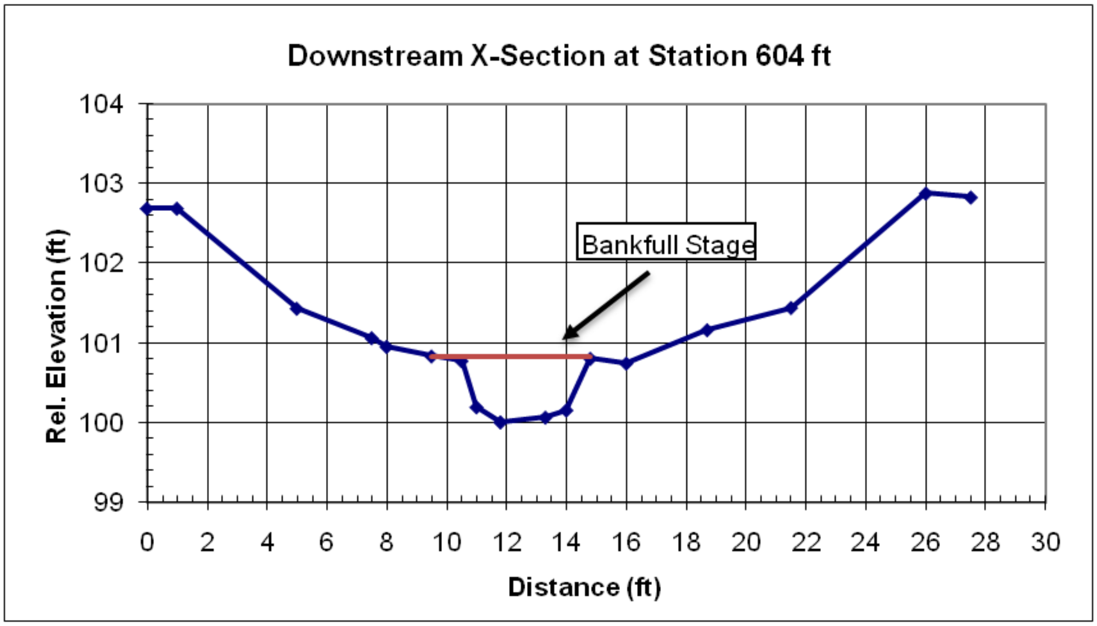


**Figure 7. Off-site cross-section at 25 ft on long. profile.**

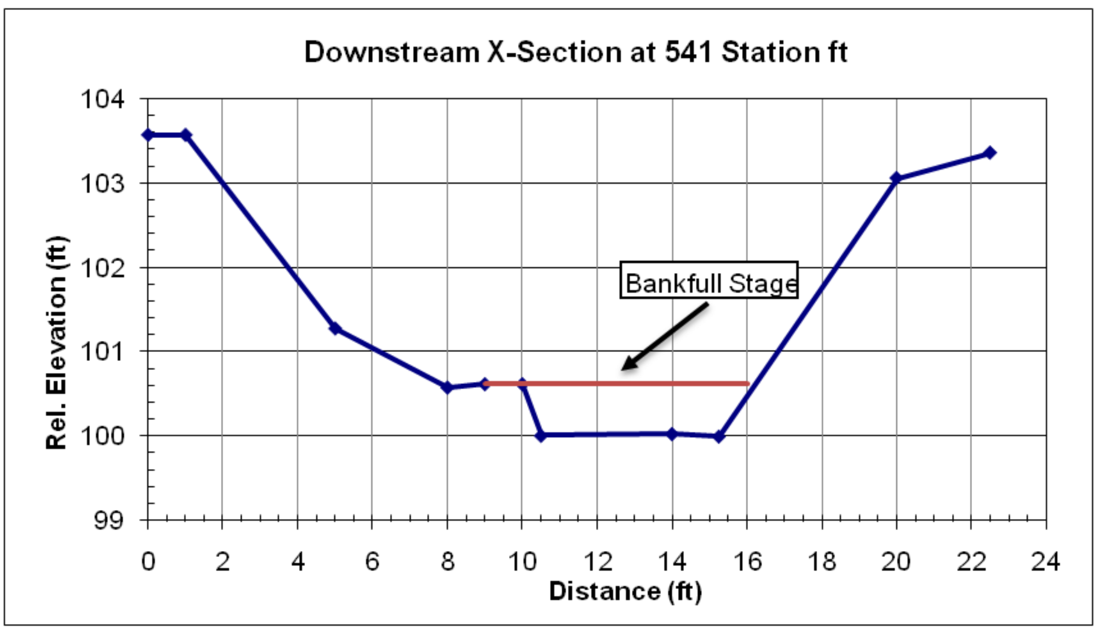


**Figure 8. Off-site cross-section at 88 ft on long. profile.**

**Photo 1. Pond dam outlet begins SR-1 (Feb. 2008)**

**Photo 2. SR-1 looking downstream (Feb. 2008)**


**Photo 3.  SR-2 looking downstream (Feb. 2008)**


**Photo 4.  SR-3a looking downstream (Feb. 2008)**

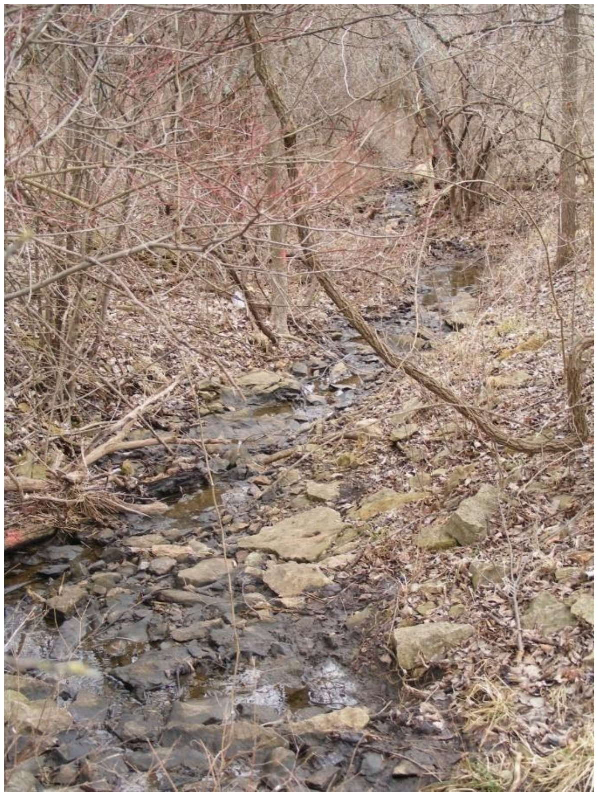

**Photo 5. SR-3b looking downstream (Feb. 2008)**

**Photo 6. SR-4a looking downstream at headcut near concrete stock tank (Feb. 2008)**

**Photo 7. SR-4b looking downstream to SR-4c (Feb. 2008)**

**Photo 8. SR-5 looking downstream (Feb. 2008)**

**Photo 9. SR-6 looking downstream (Feb. 2008)**

**Photo 10. SR-6 confluence with the golf course tributary (Feb. 2008)**

**Photo 11. SR-6 tile probe below confluence (Sept. 2007)**

**Photo 12. SR-6 >3ft of fine grain material in channel (Sept. 2007)**


**Photo 13. SR-6 looking downstream (Feb. 2008)**


**Photo 14. SR-6 forced riffle (Feb. 2008)**


**Photo 15. End of SR-6 at property line looking downstream (Feb. 2008)**


**Photo 16. SR-8 begins below rubble dam outlet (Feb. 2008)**

**Photo 17. SR-9 looking downstream (Feb. 2008)**

**Photo 18. SR-10 looking downstream (Feb. 2008)**

**Photo 19.  SR-11a looking upstream from culvert (Feb. 2008)**

**Photo 20.  SR-11b looking downstream from culvert (Feb. 2008)**

**Photo 21. SR-12 looking downstream to confluence (Feb. 2008)**

**Photo 22. End of SR-12 at confluence with main tributary (Feb. 2008)**

**Photo 23. PA-1 installation September 12, 2008**

**Photo 24. PA-1 in Feb. 2008.**


**Photo 25. PA-2 installation Sept. 2007.**


**Photo 26. PA-2 as of Feb. 2008 showing upper bank slump.**

**Photo 27. PA-3 installation Sept. 2007**

**Photo 28. PA-3 in Feb. 2008**

**Photo 29. PA-4 installation Sept. 2007**

**Photo 30. PA-4 as of Feb. 2008.**

**Photo 31.  PA-5 installation Sept. 2008**

**Photo 32.  PA-5 Feb. 2008**


**Photo 33. PA-6 installtion Sept. 2007**


**Photo 34. PA-6 Feb. 2008**

**Photo 35. PA-7 installation Sept. 2007**

**Photo 36. PA-7 Feb. 2008**

**Photo 37. PA-8 installation Sept. 2007**

**Photo 38. PA-8 Feb. 2008**