Ozarks Environmental and Water Resources Institute (OEWRI)

Geomorphic Analysis of Lackman Tributary, Lenexa, KS.

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

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EXECUTIVE SUMMARY

(1) **System-wide incision**: There is evidence along the entire length of the stream for bed incision (lowering of bed elevation by erosion) and valley floor alluviation (fine-grained deposition on top bank surfaces by increased flooding or construction fill). These processes combine to give the stream an entrenched form in many places. Incision may have begun with past land use changes during settlement of the area and early agricultural practices. Residential construction and build-out occurred about 25 years ago and stream beds show recent effects of incision related to development. However, it seems that compared to the geomorphic assessment completed by Intuition and Logic almost 10 years ago, the stream system today has recovered to a slight degree.

(2) **Bedrock Knick-points**: Bedrock is intermittently exposed on the channel bed and along lower banks below station 6,500 ft to the mouth on Mill Creek. Seven well formed bedrock knick points, some with drops to 7 feet, are found between stations 2,000 to 6,400 ft between elevations of 900-1000 feet. Less resistant shale erodes out from under limestone beds until the slab fails and forms a step. The ages of these knick-points are not known, but most do not appear to be actively migrating upstream at timescales of interest here. However, there are several head-cuts that may be actively migrating upstream at rates of concern between stations 5,800 to 5,900 ft.

(3) **Channel Bed Stability and Bedform**: For the most part, bed elevation and erosion/deposition processes of this stream are controlled by bedrock either at the surface or nearly so. In places where there is sufficient sediment and capacity for vertical adjustment, well developed riffle-pool sequences form. In places where excess sediment supply occurs, plane-beds form. Bedrock slab beds occur locally both upstream and downstream of knick-point zones. However, in the upper portion of the watershed, deep loess soils on uplands create conditions for colluvial channel formation.

(4) **Bank Stability**: Stream banks are generally stable along Lackman Tributary due to the influence of root protection, bedrock bluffs, low sinuosity channels, artificial bank stabilization, and cohesive banks. However, where channel slope decreases abruptly and channels are free to migrate laterally (i.e. wider valley and lack of lateral bedrock control) a meandering planform develops and bank erosion can potentially become a problem. Four meandering reaches have been identified that may need some degree of bank stabilization totaling over 2,000 ft of channel length or about 25% of total stream length.

(5) **Large Woody Debris Management:** An urban forestry program aimed at reducing the amount of large wood supplied to the channel and stabilizing banks should be implemented. In addition, inspections should be made annually or after large storms to locate and remove large wood jams. Large wood jams can destabilize the channel by deflecting flow, increasing flood height, and increasing turbulence or flow velocities resulting in bank erosion.

(6) **Action Reaches**: The following reaches are identified for further action (after Table 7):
R-4: Meandering reach (St. 6,940 – 6,650 ft): Bank stabilization
R-5: Plane-bed reach (Station 6,650-6,400 ft): Monitor recovery
R-6: Bedrock-Controlled Reach (St. 6,400 – 5,150 ft): Head-cut stabilization
R-8: Plane-bed Reach (St. 4,950 – 4,420 ft): Monitor recovery
R-9: Meandering Reach (St. 4,420-4,000 ft): Bank Stabilization
R-11: Step-pool Reach (St. 3,800-3,500 ft): Monitor recovery, low bank protection
R-13: Meandering Reach (St. 2,700-2,300 ft): Inspect reach; evaluate for bank stabilization
R-14-B: Riffle-pool Reach (St. 2,050-1,750 ft): Bridge protection and bank stabilization
R-15: Meandering Confluence Reach (Station 1,100-0 ft): Bank stabilization

PURPOSE AND OBJECTIVES

Olsson Associates (OA) contracted the Ozarks Environmental and Water Resources Institute (OEWRI) at Missouri State University to complete a geomorphic assessment of the Lackman Tributary of Little Mill Creek in Lenexa, Kansas. The project stream flows for over 7,000 feet through a residential urban area. The purpose of this study is to provide OA with information for flood control decisions, channel stability evaluations, and channel form designs. The objectives of this study are:

1. Collect field data in the form of channel topography (channel profile and cross-section surveys), boundary conditions (bed and bank substrate) and disturbance indicators (bank erosion, bed scour, bar form) along Lackman Tributary.
2. Interpret field data to support the planning and design phases for channel improvement and restoration projects.
3. Describe areas of concern and make recommendations based on interpretations of field data.

WATERSHED CHARACTERISTICS

Lackman Tributary drains 380 acres and is a 2nd order stream that flows northeast from the NE1/4 of section 29 to the SE1/4 of section 21, township 12-S, range 24-E to the confluence with Little Mill Creek (Figure 1). After initial settlement in the 1800s this area was transformed from tall-grass prairie to predominately row-crop agriculture that is often associated with increased runoff, soil erosion, and stream sedimentation due to poor tillage practices prior to improved conservation practices in the 1940's. An aerial photograph in 1954 shows the land use of the watershed was primarily agricultural in row-crops, hay, and pasture with <10% forest (Figure 2). Rapid encroachment by residential development starting in the 1980's and today most of the watershed is covered by urban residential and commercial land use (Figure 3). This type of urban development typically increases the impervious surface area of the watershed and causes increased runoff. However, compared to the agricultural period, rates of upland soil erosion and sediment supply have probably been reduced due to the construction of stormwater infrastructure and maintenance of landscaping and lawn vegetation cover. Today

the stream has a relatively continuous riparian corridor of small trees and brush established along the majority of its length that appeared to be only minimally altered during subdivision construction.

The geology and soils of the study area are fully described in the appendix with their spatial distribution described in Table 2 and Figure 3. In general, the bedrock geology of the area is composed of inter-bedded limestones and shales that are frequently exposed along the stream bed, especially along strath terraces in the lower segment of the stream (O'Conner, 2000). Upland and summit soils are derived from loess, while hillslope soils are formed in parent materials formed in the residuum and colluvium of weathered limestone and shale (Evans, 2005).

METHODS

Robert Pavlowsky and Marc Owen completed the field work for this report during the period of September 9 to 11, 2009. The study area included the entire stream system from 83rd Street to the confluence with Little Mill Creek, a distance of 7,870 ft. Geomorphic data on "typical" sub-reach characteristics including channel cross-sections, bed substrate pebble counts, and bank conditions were collected at 17 sites (Table 1; Figure 3). 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. 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 25 bed samples were measured for both riffle and glide areas at each cross-section site. In addition, the diameters of the 5 largest boulders and the 5 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: $A = W \times D$
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}).

Relative Bed Stability (RBS, m/m) generally describes the ability of bankfull flows to transport the dominant substrate size found on the bed (after Kaufmann et al., 1999). Ideally, the ratio should equal "1" where the critical sediment size predicted to be mobile under imposed hydraulic forces is equal to the median particle size on the actual channel bed. A high value (>100) may indicate an extremely stable bedrock reach or conditions below a dam, a low number <0.01 indicates a bed where substrates are easily moved. A negative trending RBS with increasing land use intensity can indicate: (i) more sediment is being delivered to the channel network from slope or gully erosion causing bed " fining" or sedimentation; (ii) reduction in riparian buffer function to trap fine sediment and resist bank erosion; and (iii) increased runoff and flood frequency has increased bed shear stress on the bed and reduced channel roughness (Kaufman et al, 2009a).

This study calculates the relative bed stability (RBS*) using a method that corrects for the influence of additional flow resistance on sediment transport by large woody debris and riffle-pool forms in the reach (Kaufman et al, 2009a,b). RBS* requires input data on channel slope, flow cross-section, bed material size, large woody debris volume, and residual pool length and depth. The procedures and equations for calculating RBS* are below:

$$RBS^* = 1.66\ Os\ Dgm\ /\ [\ Rbf\ (Cp\ /\ Ct\ )^{0.333}\ S\ ]$$

Calculate Os as follows:

(1) Determine particle Reynolds Number: $Rep = [\ (\ g\ Rbf\ \ S\ )^{0.5}\ Dgm]\ /\ v$

(2) Then calculate Os based on the Rep value:

(i) For Rep < or = 26: $Os = 0.04\ Rep^{-0.24}$

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

Cp = reach-scale particle grain resistance at bankfull flow, minimum Cp = 0.002

$= fp/8 = (1/8)\ [\ 2.03\ Log\ (12.2\ d_h\ /\ Dgm)]^{-2}$

Ct = reach-scale total hydraulic resistance at bankfull flow

$= 1.21\ dres^{1.08}\ (\ d_{res} + W_d)^{0.638}\ \ d_{th}^{-3.32}$

RBS*= corrected relative bed stability ratio (m/m)
Os = Shields Parameter, dimensionless critical shear stress for incipient motion
Rep = Bankfull particle Reynolds number
v = kinematic viscosity of water = $1.02 \times 10^{-6}\ m^2/s$
g= acceleration due to gravity, $9.81\ m/s^2$
Dgm= geometric mean of bed material from pebble counting (m)
Rbf = bankfull hydraulic radius = 0.65 dbfm (m)
dbfm = maximum bankfull depth (m)
Cp = reach-scale particle grain resistance at bankfull flow (m/m)
d_h= mean depth (m)
Ct= reach-scale total hydraulic resistance at bankfull flow (m/m)
d_{res}= mean thalweg residual depth (m), length-weighted average of $d_{res\text{-}max}$ / 4
W_d = total wood volume (m^3) / total active channel planform area (m^2)
d_{th}= thalweg mean depth or mean maximum depth (m) (same as d_{bfm})
S = energy slope, approximated by water surface or riffle crest slope (m/m)
LRBS*= Log10 RBS*

Large woody debris was not present in significant amounts at the cross-sections evaluated and so Wd was set equal to 0 at all sites (note: LWD and log jams around found in some other places along the stream). Residual pool depths were estimated using the OA survey data and the percent residual pool in a reach was assumed to be 50%. The RBS* value is typically reported in the log form: LRBS* = Log10 [RBS*]. In the log form, a value of 0 indicates the stable condition (i.e. RBS*=1). For the purposes here, LRBS* ratings are as follows: Excellent = -0.2 to 0.2; Good = -0.5 to 0.5; and Fair = -1 to 1.

RESULTS

Longitudinal Profile

Olsson Associates provided the longitudinal profile data used for this report. All elevations and channel stationing used in this report are also consistent with the OA database. The longitudinal profile for the entire stream shows a gradual decrease in channel slope downstream punctuated with steps associated with bedrock knick-points and head cuts (discussed later) (Figure 4). The segments with relatively high channel slopes >2% by station are: 6,800 to 7,200 ft; 5,500 to 6,000 ft; and 3,300 to 3,800 ft. Locally, channel slopes can increase to >3% below culverts or obstructions, knick-points and riffle crests. Drainage area increases in a gradual manner downstream until station 4,500 ft where a relatively large sub-tributary enters from the north (Figure 5).

Channel Cross-sections

Channel and substrate data were collected at 17 cross-section sites (Table 1; Figure 3, Appendix). Four different geomorphic surfaces were identified in the field. The "High Bar" elevation indicates the highest stage of bed load transport in the channel. It is located at the top of the bar where a relatively flat surface has formed and finer-grained deposition of sand or fine gravel is present. This surface represents the minimum elevation of the bankfull channel. The "Low Floodplain" elevation is represented by the top of the active floodplain or bench formed by recent processes. This surface is typically composed of a fine-grained (silty) deposit overlying the high bar deposit and marks the average bankfull stage of the channel. The "High Floodplain" is the previous floodplain surface or bench that reflects the active floodplain stage in the historical past (within the last 100 years or so). This feature is sometimes called the low terrace or historical floodplain and it is a high bankfull channel indicator. Finally, the "Total Channel" elevation is the highest elevation the channel can flood before the water rises and spreads out across the valley floor. This stage represents the first indication of an "out of channel" flood and reflects the maximum width possible of channelized flow in the channel. The total channel is often referred to as the "meander belt" where lower active floodplain surfaces formed by meandering are inset between higher banks, the top of which is the total channel stage.

Bankfull channel dimensions and discharge were determined for all 17 cross-sections at the low floodplain elevation (Table 3, Appendix B). In the Lackman Tributary, drainage area and channel form variables are strongly correlated among the 16 non-colluvial reaches examined for this study for width, mean depth, and mean velocity (Figure 6) and channel area and bankfull discharge (Figure 7). The rating equations describing these relationships can be used to predict bankfull channel morphology and discharge given drainage area for any site along Lackman Tributary. Total channel dimensions and discharge were also calculated for each site (Table 4). These calculated discharge values are an estimate of the flood capacity of the channel and can be used to assess the minimum flood risk to adjacent properties if associate flood frequencies are determines for each site. In addition, strong correlations such as found here suggest that the geomorphic characteristics of the stream are tending toward an equilibrium condition and are approaching balance with urban disturbances and hydrologic regime initiated 20 years ago.

Downstream relationships of channel and floodplain characteristics can indicate variations in erosion and deposition processes that control reach geomorphology. Overall, the maximum depth of the bankfull channel varies from about 1 ft to 3.5 ft and width from 3 ft to 25 ft (Figures 8 & 9). Total channel maximum depth varies from 3 ft to 7 ft and width from <20 to almost 70 ft. Where found, high bar channels are 1 ft to 2 ft deep and 5 ft to 18 ft wide. Analysis of the downstream trends in width and maximum depth for each geomorphic surface shows some clear spatial trends (Figures 8 & 9). High bar surfaces are well represented only along segments (below 4,800 ft) where channel slope is usually <2%, with the exception of one upstream location at station 6,840 ft where upstream culvert construction locally reduced slope thus allowing a meandering channel to form in this relatively steep segment. The 2% limit is often used to mark the threshold of bar deposition in sand and gravel streams. Low floodplain or bankfull channel dimensions almost double below the tributary confluence at station 4,380 ft. Maximum depth jumps from about 1 ft to 1.5 ft deep above to 2 ft to 4 ft below the tributary and width from about <10 ft to 20 ft.

High floodplain surfaces are poorly represented along Lackman Tributary and are only found at sites located at the bottom of 400 to 800 ft long segments where reach slope decreases in the downstream direction at sites 2-3, 7-10, and 16-17 (Figure 4). If the above explanation is correct, then we would expect to find high floodplain features at site 14, however a 7 ft knick-point is located immediately downstream and this may interfere with the formation or preservation of high floodplain features. Reaches with higher slopes and/or incising or scouring channels may have removed high floodplain remnants by erosion. Conversely, lower-sloped reaches may not have incised enough to strand their previous floodplain and form the low terrace.

Bed Substrate and Sediment Mobility

Pebble count and large substrate measurements show that typical bed material diameters in Lackman Tributary range from 10 mm to 120 mm and maximum mobile clast size ranges from 150 mm to 320 mm (Table 5; Figure 10). The bed material size class for the D50 and D84 ranges from very coarse gravel to small cobble. Sediment size tends to increase in reaches with more

bedrock exposed on the bed and where the channel is pinned against the rocky valley bluff or cutting into toe slope deposits. The largest bed material is found where: (i) bedrock plucking is common near knick-points or fractures; (ii) mass-wasting occurs along bedrock bluff lines, and (iii) bedrock blocks have been dumped for ad hoc bank stability measures or are eroding out of bank and slope fill materials.

The critical diameter calculated for Lackman Tributary ranges from 40 mm to 140 mm (Figure 11). The downstream patterns are controlled by shear stress values calculated for each site (Table 6). Relative bed stability values indicate that all but four of the sites are within normal ranges of a balanced condition between imposed hydraulic force and sediment size on the bed (Figure 12). Typically, LRBS* values between -0.5 and 0.5 are in the stable range and values <-2 are considered unstable and values >2 are considered extremely stable. Three relatively unstable sites are have LRBS* values below -0.5:

(1) Site 3 (-0.70): The channel bed at this site is a plane-bed that expresses some attributes of a riffle-pool channel. This site is receiving finer-grained sediment from erosion of loess soils and from bank erosion upstream. A negative LRBS* value is consistent with excess sediment loading affecting the reach (Kaufman et al. 2009a).

(2) Site 11 (-0.74): The channel at this site is being affected by fast flowing water from the culvert under Lackman Road. Scouring of the channel bed and lower banks has reduced overall channel roughness which is consistent with a negative LRBS* value (Kaufman et al. 2009a).

(3) Site 17 (-0.59): The channel at this site is affected by backwater of Mill Creek and excess fine gravel deposition. Increased delivery and deposition of finer sediment within a reach is consistent with a negative LRBS* value (Kaufman et al. 2009a).

Channel Bars

Bar deposits on Lackman Tributary are typically related to reaches with bed slopes <2% (Figure 8). They are best developed along inside bends where sinuosity is >1.1 and there is some meandering in the channel planform. Poorly organized bar deposits are sometimes associated with riffle crests. Bar deposition in not a cause of instability in the upper and middle segments of the stream system. However, bar development is best expressed and sometimes covers relatively large areas on the channel bed in the lower segment below station 2,000 ft.

Bank Stability

Banks are relatively stable along Lackman Tributary with only minor rates of channel meandering and enlargement occurring. Further, the presence of tree roots and bedrock bluffs reduce the risk of reach-scale bank instability along most reaches. There are some places where fill materials form channel banks and even these banks are relatively stable in low sinuosity segments. However, there are four reaches where active meandering is occurring and bank erosion rates are relatively high: (i) 6,650 to 6,940 ft; (ii) 4,400 to 4,420 ft; (iii) 2,300 to

2,700 ft; and (iv) below station 1,110 ft. In addition, bank erosion along a relatively straight reach related to meandering processes threatens bridge and path infrastructure at stations 1,775 to 1,975. Relatively large meanders with high, steep banks are located where the stream cuts through the floodplain deposits of Little Mill Creek between station 750 ft and the confluence. Healing meander cutoffs observed along this segment suggest that this is a long-term condition.

Natural bank materials along Lackman Tributary are usually composed of silt loam or clayey silt loam soils and are conditionally-stable to stable where excessive meandering is not occurring. Some cut banks expose gravel deposits of previous channel positions in the lower half of the bank. In places, fill materials composed of silty soil mixed with larger bedrock blocks produced during the development period are exposed in bank cuts. In other places, natural bedrock and fluvial cobble deposits protect the bank toe. In bedrock-controlled reaches, the channel often gets pinned up against bedrock along one side of the valley and does not appear to migrate laterally. The availability of weathered limestone at the surface and relatively narrow valley width also favor bank stability since meandering channels cannot easily develop.

Along several reaches, a well expressed active bankfull floodplain has formed and bankfull benches are common throughout suggesting that a stable planform is developing over time. There are some meandering reaches where bank erosion and point bar deposition is obvious, but the risk to infrastructure is low. Management should favor the natural development of a low floodplain. To build a new floodplain, the stream channel needs to be free to meander, erode banks, and deposit fines on bar surfaces. However, there are a few places where bank erosion is occurring at a fast rate and we recommend these should be addressed.

Bedrock and Soil Influence

There is a strong influence from bedrock and bedrock residuum on channel form and substrate in Lackman Tributary (Table 2; Figure 3). The locations of relatively stable knick-points and head-cuts are probably controlled by horizontal layers of more resistant limestone beds. Knick-points in more resistant limestone develops as steps, small cascades, or falls across the bed of the stream. In longitudinal profile, bedrock knickpoints indicate locations where channel erosion is slowly lowering bed elevation by retreat of the step through block plucking, scour of weathered material, and joint failure. Since bedrock erosion rates are orders of magnitude less than for soil materials and alluvial deposits, knick-point response can lag behind other geomorphic adjustments and so they can function as natural slope controls for the stream. On the other hand, unstable head-cuts tend to have a similar form in longitudinal profile, but usually occur in less resistant materials such as weaker shale units or soil materials. Since unstable head-cuts are in more erodible materials, they generally migrate or cut headward at a faster rate compared to bedrock knick-point counterparts. It is possible that head-cuts form first, initially erode rapidly in weaker shale or weathered limestone, and then stall out as shale units pinch out. Field observation suggest that larger knick-points and head-cuts (up to 7 ft of local drop) are associated with thicker underlying shale units such as found in the Vilas and Lane Shale units (Table 2).

In most segments of Lackman Tributary below station 6,250 ft, the channel bed is at or near bedrock elevation. This condition is probably inherited to some degree from the pre-development channel system. A low order channel flowing through an unglaciated area across a steep bluff line to reach the base-level of a larger river (i.e. Little Mill Creek) would be expected to erode to bedrock in places. Further, the stream channel would develop characteristics reflecting differential resistance of bedrock units. This attribute is exhibited by the seven bedrock steps (3 to 7 ft drop) or knick-points found along the stream course below station 6,000 ft in the Plattsburg and Wyandotte Limestones (Table 2, Figure 3). These steps are effectively stable and are presently eroding at a slow rate of relatively little concern. However, further inspection of knick-point condition to look for indicators of erosion rate would be helpful to further support this opinion.

There is a natural tendency for the stream to be bedrock-controlled in Lackman Tributary. However, this condition has also been influenced by a long history of watershed disturbance by agriculture followed by urbanization. Soil erosion rates typically increased greatly during the early agricultural period. Thus, the expectation is that fine-grained sediment loads and overbank deposition increased early on and then stabilized after conservation practices were invoked. There may have been an early period of aggradation as bank heights increased due to floodplain storage of excess fine sediment load. The thickness of bed deposits may have also increased in places during this period.

Over the past 30 years of urbanization, runoff rates probably increased again with a net decrease in sediment load causing channel bed incision in most places, maybe up to 1 to 2 feet in some reaches. This most recent period of incision has probably reactivated some of the limestone knick-points to a slight degree, but more importantly is has resulted in the formation several head-cuts in weaker shale units in the channel above station 5,750 in the Stranger Formation, Vilas Shale, and Stanton Limestone (Table 2). Head-cuts observed along the upper segment are not steep (<3 ft drop) and are formed in thin shale beds or silty soil material (stations 7,360 and 6,380 ft). However, there is a large, relatively active head-cut formed in the thicker Vilas Shale at stations 5,830 to 5,890 ft (4 ft drop) followed by a knick-point at stations 5,770 to 5,820 ft (5 ft drop). In addition, a smaller head-cut (not tabulated in the assessment here) has formed at the confluence of a sub-tributary drainage way flowing in from the south at station 5,830 ft. The head-cuts and knick-point in the stream segment from stations 5,800 to 5,900 ft should be inspected further to evaluate short-term migration risk and potential stabilization measures.

Soil characteristics along Lackman Tributary are influenced by the spatial distribution of bedrock (residuum/colluvium) and transported parent materials (Pleistocene loess, alluvium) (Table 2; appendix). Soil materials generally affect sediment supply, bed substrate conditions, bank composition, and stability of a stream channel. Above station 6,200 ft, relatively thick Pleistocene Loess deposits cover uplands and summits (Grundy and Chillicothe series). In this upland area, the channel generally flows over silty soil material and was probably classified as a colluvial channel prior to development. Today, a colluvial channel exists upstream of the

grouted channel at station 7,200 ft. Colluvial channels are eroded into soil materials with little alluvial fill present and respond to overland flow and mass-wasting processes where true channel development is limited. Between stations 4,800 and 6,100 ft, residual/colluvial bedrock soils are found in association with the Vilas Shale and Plattsburg Limestone (Oska-Martin and Sogn-Vinland series). Within this residual soil zone, weathered bedrock is at the surface and the stream cuts across the edges of exposed horizontal beds to form steps and mobilize rock for fluvial transport. Thus, there is ample supply of limestone clasts for bedload transport and bedrock features are common (i.e. 6 of the 10 knick-points/head-cuts identified are located here) (Table 2).

Loess deposits again cover uplands and terraces along the valley floor along the lower half of the stream system from stations 4,800 to 600 ft (Ladoga series). Riffle-pool bedforms are better developed in this segment due to the affects of increased finer sediment loads, waning effects of bedrock influence, and lower channel slopes in general (note deep, >2 ft maximum depth, residual pool distribution in Figure 3). Natural overbank levees composed of silty and sandy sediment are formed along the channel from stations 3,750 to 2,700 ft in response to increased flooding, riparian vegetation trapping, and (maybe) the addition of fine-grained sediment delivered from eroded loess deposits or cut banks. At the lower end of Lackman Tributary, the channel cuts through floodplain deposits of Little Mill Creek below station 600 ft (Kennebec series). Here, the channel develops well formed meanders and cut-off scars in this zone since (i) channel slope breaks due to base-level control; (ii) banks are relatively high and unstable; and (iii) bedrock control, if it occurs, is limited to the relatively weak Lane Shale.

Large Woody Debris Effects

Large woody debris (LWD) are relatively large pieces of wood that are >5 ft in length and 0.25 ft in diameter not attached to the banks and free to be moved by flood flows. Typically, LWD is composed of whole trees, trunks and limbs (stems), root wads, and artificial wood such as building timbers, rail-road ties, and fence posts. In some instances, “wood jams” composed of three or more pieces of LWD are deposited in one place and form a pile, channel obstacle, or natural dam that can deflect flow, increase flooding, or cause bank erosion. Sources of LWD to the Lackman Tributary channel include bank erosion of riparian forests areas, mass movement and erosion of valley bluff slopes, wind and ice storm damage, natural mortality, and land clearing, pruning, and dumping by local residents. While the cross-sections studied for this assessment did not contain measureable LWD, there are some reaches that contain debris and jams that influence local flow conditions and channel form. Relatively large jams tend to form on the upstream side of bridge and culvert openings, tight channel bends, and around existing obstacles such as large stone blocks, fence crossings, or low hanging or fallen trees. In order to reduce the possibility of LWD causing flood and channel instability, log jams should be removed in accordance with urban forest management programs. The channel should be inspected annually and after large floods for log jams.

REACH CLASSIFICATION

Below is a reach classification based on channel geomorphology for Lackman Tributary. Reach classes are based on channel form, occurrence of dominant processes, nature of disturbance factors, and history of geomorphic stability (Table 7).

R-1: Colluvial Channel (Station 7,870 - 7,200 ft)
The stream emerges from a curb inlet box downstream of 83rd Street and passes though a narrow riparian corridor and several small culverts under the walking path. This area probably lacked a definite channel in the pre-development period. The channel is presently forming by scour and erosion into a loess soil with weathered shale near the surface (Grundy/Chillicothe Series).

Concern rating: Low. This reach is out of the study area. If scour and channel deepening continue in the future, this reach would be a source of fine-grained sediment and present risk to infrastructure.

SR-1-A: Typical colluvial channel (Station 7,870-7,350 ft)- The stream bed and banks consist of silty material with occasional construction debris, such as asphalt and crushed limestone, being deposited on the bed. Forced riffles caused by roots, utility crossings, and walking path culverts cause small scour-hole formation locally, but there is no evidence of systemic instability. Cross-section site 1 is in this sub-reach (Photos 1-2)

SR-1-B: Enlarged colluvial channel (Station 7,350-7,200 ft)- The reach begins below a head cut in silty soil which drops about 2.5 ft from stations 7,360 to 7,330 ft. The channel increases in cross-section area by about 4x compared to SR-1-A. Evidence of fine-grained deposition on the bed and along “mud bars” is present with some meandering where the stream slope flattens out. A narrow riparian corridor is present on both sides of the stream. (Photo 3)

R-2: Grouted, rip-rap channel (Station 7,200-7,050 ft)
This sub-reach consists of a grouted rip-rap channel that emerges from riparian corridor and makes a sharp 90 degree turn before it flows toward 81st Street. Channel banks are graded to a 2:1 slope with joints in the rip-rap sprouting weeds and grass. This segment was probably a colluvial channel during the predevelopment period, but was modified to develop adjacent properties and allow for drainage under 81st street (Photo 4).

Concern rating: Low. This reach is out of the present study area. However, this structure should be inspected and repairs made if required.

R-3: 81st Street Culvert (Station 7,050 – 6,940 ft)
This reach is a CMP culvert under 81st street Culvert (Photo 4). A colluvial channel probably occupied this location during predevelopment time since deep loess soils are mapped in the area.

Concern rating: Low. Culverts should be inspected for failure and erosion problems.

R-4: Meandering reach (Station 6,940 – 6,650 ft)
This reach is also within the zone of deep loess soil and was probably a colluvial channel or grass waterway prior to development. The stream was probably channelized to some extent to make room for the culvert under 81st street, thus creating an entrenched appearance. Channel slope is locally lower compared to the steep, headwater location allowing the channel freedom to meander in order to recover from a lower upstream flow line and channelization by depositing a relatively wide floodplain. Banks are relatively high here and sometimes composed of fill material with frequent tree root protection along back property lines on channel right. An active floodplain is forming by lateral channel migration in the reach. A riffle-pool bed is present and is relatively stable at present. The size of the substrate is relatively small reflecting sediment source influences of loess material overlying residuum with little bedrock contact. This channel has meandering pattern as follows: sinuosity, 1.21; meander wavelength, 60 ft; and meander belt width, 20 ft.

Concern rating: Moderate. While the meandering channel is releasing sediment to the stream and may cause local bank failures, the formation of an active floodplain indicates that recovery is occurring and the stream is tending to a more stable system.

R-5: Plane-bed reach (Station 6,650-6,400 ft)
This reach represents the transition of the stream as it flows from areas of deep upland soil and colluvial valley influence into an area of shale and limestone bedrock control. The bed consists of small cobble and gravel (Photo 5). A positive sediment budget is produced by: (i) relatively low slope; (ii) local supply of relatively coarse sediment by limestone bedrock weathering on the channel bed; and (iii) excess supply of finer bed material delivered from lateral channel erosion upstream in R-4. However, within the plane-bed channel, there is also a periodicity in bedform suggesting that it is really an inter-grade between riffle-pool and plane bed channel types.

Concern rating: Moderate. This reach is stable, however it should be monitored to see if deposition continues or bed sedimentation rates and bed form stabilize.

R-6: Bedrock-Controlled Reach (Station 6,400 – 5,150 ft) (Photos 6-7)
This reach contains bedrock exposures along the bed and several bedrock knickpoints. Two shallow (<2 ft), slowly migrating headcuts occur in the thin shale layer of the Stanton Formation at stations 6,375 and 5,990 ft. A deeper head cut (4 ft drop) is formed at station 5,890 ft near a tributary confluence in the thicker shale bed of the Vilas Formation. Four other limestone-capped bedrock knickpoints with bed drops ranging from 3 to 5 ft are located at stations 5,820, 5,615, 5,565, and 5,210 ft in the middle section of the Vilas Formation.

Concern rating: High. The head-cut at station 5,890 ft should be stabilized and additional head-cuts upstream and knick-points downstream further inspected and evaluated for stability controls. Another head-cut is also extending up a small sub-tributary immediately below the mainstem head-cut and this cut should be stabilized too. The shallow (2 ft drop) head-cut at station 6,375 ft is probably a “precursor” head-cut that marks the upstream limit of slope effect on flow and sediment transport due to the drop in channel elevation across cut steps. However, this cut is generally also located in the boundary zone between upstream colluvial and downstream bedrock/alluvial valley segments. Thus, this step may be an active,

younger head-cut moving upstream into the less resistant bed material. If so, then this cut may threaten upstream path bridge at station 6,500 ft.

<u>SR-6-A: Steep riffle-pool channel (6,400-6,200 ft)</u>- This is a relatively stable reach below a shallow head-cut at station 6,370 ft.

<u>SR-6-B- Step-pool channel (6,200-6,000 ft)</u>- This sub-reach has a step-pool form with bedform spacing of 3 channel widths or less. The channel is probably cutting across a resistant limestone bed (in contrast to weaker shale).

<u>SR-6-C- Bedrock controlled channel with frequent Knick-points (6,000-5,150 ft)</u>
The stream flows across the Vilas Shale and Plattsburg Limestone in this section. Five well expressed knick-points are formed in this unit with bed elevation drops from 3 to 5 ft. The Vilas shale beds are relatively thick and erodible. Thus, knick-points tend to form when overlying limestone beds fail after underlying shale support is removed by erosion. Only the upstream knick-point at station 5,890 ft seems to be head-cutting upstream at timescales of potential concern, albeit slowly. A smaller extension of this head-cut is moving up a small tributary. The limestone unit here is relatively thin over a thick shale unit. The others are formed in relatively thickly-bedded limestone where shale layers are thinner maybe have pinched out. (Photos 8-10)

R-7: Road Culvert (Station 5,150 – 4,950 ft)

Concern rating: Low. Culverts should be inspected for failure and erosion problems.

R-8: Plane-bed Reach (Station 4,950 – 4,420 ft)
This reach is affected by scour below the culvert and tributary inflow from the south. The lower segment B was described several years ago as a braided reach in a geomorphic assessment by Intuition and Logic. However, now the reach has a single-thread channel suggesting recovery to the present plane-bed form and a more stable riffle-pool channel in the near future.

Concern rating: Moderate. This reach appears to be conditionally stable and possibly the lower reach is recovering a bit from earlier disturbances. However, the moderate rating here is to underscore the need to monitor this reach for future instability or recovery.

SR-8-A: Scoured Reach (Station 4,950-4,800 ft)- The channel condition is erosional and the bed is scoured with little fine gravel deposition, probably due to the steepness of the channel bed and culvert discharge rate.

SR-8-B: Plane-bed Reach (Station 4,800-4,420 ft)- This sub-reach is affected by both delivery of sediment from bed and bank scouring in SR-8-A and tributary inflow and sediment load at station 4,800. The channel is classified as a plane-bed but it also has riffle bed-forms.

R-9: Meandering Reach (Station 4,420-4,000 ft)- The culvert at Lackman Road acts provides base-level control for this reach and appears to backwater flood the reach too. In addition, channel slope decreases within the reach. The result is that fine-grained sedimentation,

channel meandering, and bank erosion is degrading this reach. Relatively high erosion rates are indicated by freshly exposed tree roots. This channel has meandering pattern as follows: sinuosity, 1.21; meander wavelength, 100 ft; and meander belt width, 40 ft.

Concern rating: High. Bank erosion is a problem here. The channel should be stabilized and banks protected.

R-10: Lackman Road Culvert (Station 4,000-3,800)

Concern rating: Low. Culverts should be inspected for failure and erosion problems.

R-11: Step-pool Reach Station (3,800-3,500 ft)- This reach is affected by culvert scour and has been channelized and repositioned previously. It is relatively stable but is eroding into colluvial toe slopes on channel right and mixed-fill on channel left.

Concern rating: Moderate. This reach should be inspected for long-term stability and stabilized with low bank protection.

R-12: Riffle-Pool reach (Station 3,500-2,700 ft)- This reach is relatively stable and is bedrock controlled in the mid-reach by a knick-point (3.5 ft drop) at station 3,000 and a precursor head-cut (1 ft drop) at station 3,100 ft.

Concern rating: Low. Bedrock control is stabilizing this reach. There is some minor bank erosion occurring, however, this can be said about all reaches below Lackman Road.

R-13: Meandering Reach (Station 2,700-2,300 ft)- Slope is reduced in this reach due to the influence of base-level control by the limestone bed that is exposed at the downstream knick-point at station 2,070 ft. Sediment loads are finer than upstream due to loess soil inputs and delivery of fine gravel from higher energy reaches upstream. The response of the channel has been to increase meandering and bank erosion. This channel has meandering pattern as follows: sinuosity, 1.10; meander wavelength, 150 ft; and meander belt width, 30 ft.

Concern rating: Moderate to High. A cross-section was not placed in this reach so we only have geomorphic information from OA survey and visual inspection. This reach should be inspected to determine if stabilization measures are needed to prevent bank erosion.

R-14: Riffle-Pool Reach (Station 2,300-1,100 ft)- The reach has the lowest knick-point at station 2,070 ft. Finer gravel is accumulating in bars and riffle-pool bed forms are getting better organized. Large blocks from bedrock plucking are present and bedrock-control adds stability to the reach. There is a pile or mound of fill on the valley floor on the right bank from St. 1,750 to 1,800 ft. Floodplains are forming along the lower third of this reach.

Concern rating: Low for sub-reaches A and C; <u>High</u> for sub-reach B. This reach is stabilized by bedrock along the bed and banks in many areas.

<u>SR-14-A: Riffle-Pool Reach with bedrock control (Station 2,300-2,050 ft)</u>-This sub-reach includes the bedrock channel that is above the major (7 ft drop) knick-point at station 2,070).

<u>SR-14-B: Riffle-Pool reach with confined valley (Station 2,050-1,750 ft)</u>- This sub-reach is located within a confined valley area with bedrock bluffs on the left side and finer-grained alluvium or

colluvium on the right bank. In addition, there is a pile of fine-grained fill on the valley floor near station 1,775 ft. The fill material appears to have been deposited by human action on the valley floor to a depth of 5+ ft during the early construction phase of the area since there are some relatively large trees rooted in it. It is composed of relatively weathered soil material from older colluvial or residual soil sources compared to the younger floodplain soils exposed in a bank cut below it. Bank erosion along the right side of the stream at station 1,970 ft is threatening the bridge abutment at station 1,978 ft. About 200 ft below the bridge, lateral channel erosion into the right bank has formed another steep cut at station 1,775 ft. This cut has mobilized both valley floor material and overlying artificial fill. Early stages of mass failure have been detected in soils upon which the walking trail is located on the upper valley floor surface at station 1,775 ft.

SR-14-C: Riffle-Pool Reach with bedrock control (Station 1,750-1,100 ft)- This sub-reach begins below obvious influence of the knick-point where the valley begins to widen slightly. There are relatively well formed floodplains found in several places along this reach.

R-15: Meandering Confluence Reach (Station 1,100-0 ft)- This reach is affected by base-level control of Mill Creek and the higher banks of its floodplain. At the confluence, Little Mill Creek is flowing over shale bedrock, possibly the Lane Shale. The break in slope and backwater influence during flood results in a meandering planform. Channel banks are high and steep. Bank erosion rates are relatively high here, but not excessive. There is evidence of old channel cutoffs that are filling with sediment suggesting that this is a long-term and maybe even natural form of the stream channel at this location. However, observations of cut bank soil exposures indicate that over 4 feet of historical overbank alluvium was deposited on the floodplains along Little Mill Creek since the middle 1800s. Thus, while the planform may be natural to this reach, the bank conditions (i.e. composition, height) are not.

Concern rating: Moderate to High. This reach needs to be monitored for excessive bank erosion. Stabilization measures aimed at reducing the channel migration rates would reduce the effect of fine-sediment loading from bank erosion. However, the meandering planform present today may be similar to the pre-development channel.

SR-15-A: Lower Sinuosity (Station 1,100-750 ft)- This reach indicates where the stream first starts to respond to the influence of Mill Creek base-level or backwater control. Meandering is not as well developed as in sub-reach B: sinuosity, 1.13; Meander wavelength, 175 ft, and meander belt width, 50 ft.

SR-15-B: Higher Sinuosity (Station 750-0 ft)- This reach is fully affected by Little Mill Creek base-level and back-water control. The channel is more entrenched than sub-reach A and has a fully expressed meandering pattern: sinuosity, 1.67; meander wavelength, 120 ft; and meanderbelt width, 75 ft.

RECOMMENDATIONS

(1) The following reaches are identified for further action (after Table 7):

R-4: Meandering reach (St. 6,940 – 6,650 ft): Bank stabilization
R-5: Plane-bed reach (Station 6,650-6,400 ft): Monitor recovery
R-6: Bedrock-Controlled Reach (St. 6,400 – 5,150 ft): Head-cut stabilization
R-8: Plane-bed Reach (St. 4,950 – 4,420 ft): Monitor recovery
R-9: Meandering Reach (St. 4,420-4,000 ft): Bank Stabilization
R-11: Step-pool Reach (St. 3,800-3,500 ft): Monitor recovery, low bank protection
R-13: Meandering Reach (St. 2,700-2,300 ft): Inspect reach and evaluate for bank stabilization
R-14-B: Riffle-pool Reach (St. 2,050-1,750 ft): Bridge protection and bank stabilization
R-15: Meandering Confluence Reach (Station 1,100-0 ft): Bank stabilization

(2) All bridge crossings should be inspected for erosion and undermining along the lower segment below 79th street. There does not appear to be any acute problems, however erosion conditions do exist at these places.

(3) The head-cut at station 5,890 ft is high priority for stability measures. In addition, the head-cut at station 6,375 ft should be inspected to evaluate for its potential to migrate upstream and for stabilization needs. The risk of this head-cut was not directly evaluated.

(4) There are many places in the channel where large boulders are providing increased roughness and flow deflection in the channel resulting in local erosion. These come from escaped rip-rap, bedrock slabs, and mobilized fill. Maybe an effort should be made to reduce the source of these materials to the channel so that these frequent local disturbances do not

(5) In following with Intuition and Logic recommendations, an urban forestry program aimed at reducing the amount of large wood supplied to the channel and stabilizing banks should be implemented. In addition, inspections should be made annually or after large storms to locate and remove large wood jams.

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Table 1. GPS Points for Cross-Sections

XS #	Station (ft)	Northing (ft)	Easting (ft)
1	7,600	251,587.556	2,230,670.575
2	6,840	252,214.751	2,230,885.177
3	6,530	252,420.714	2,231,052.002
4	6,020	252,797.246	2,231,364.907
5	5,835	252,895.574	2,231,480.876
6	5,640	253,023.575	2,231,633.133
7	5,280	253,272.125	2,231,867.343
8	4,750	253,538.038	2,232,289.790
9	4,560	253,684.726	2,232,362.339
10	4,260	253,832.694	2,232,565.041
11	3,710	254,095.274	2,232,977.367
12	3,220	254,417.208	2,233,242.046
13	2,780	254,764.543	2,233,431.170
14	2,140	255,209.048	2,233,381.952
15	1,530	255,788.308	2,233,577.272
16	890	256,192.247	2,233,968.717
17	320	256,468.031	2,234,305.585

Table 2. Soil and Bedrock

Station (ft)	Geology	Knicks	Deep Pools	Parent Material	Soils	Station (ft)
8,000					Grundy	8,000
7,750	Stanger Formation (probably shale)					7,750
7,500						7,500
7,250		x		Glacial Loess	Chillicothe	7,250
7,000	Stanton Limestone					7,000
6,750						6,750
6,500						6,500
6,250		x				6,250
6,000						6,000
5,750		xxx			Oska-Martin	5,750
5,500	Vilas Shale	xx		Bedrock Residuum		5,500
5,250		x			Sogn-Vinland	5,250
5,000	Plattsburg Limestone					5,000
4,750						4,750
4,500						4,500
4,250			o			4,250
4,000						4,000
3,750		x				3,750
3,500			o			3,500
3,250						3,250
3,000	Lane Shale	x			Ladoga	3,000
2,750			o	Glacial Loess		2,750
2,500						2,500
2,250						2,250
2,000		x				2,000
1,750	Wyandotte Limestone					1,750
1,500						1,500
1,250			o			1,250
1,000						1,000
750						750
500						500
250				Alluvium	Kennebec	250
0			o			0

Table 3. Bankfull Geometry and Discharge

Section #	Station (ft)	Ad (ac)	Width (ft)	D (BF) (ft)	D (mean) (ft)	R (ft)	A (ft^2)	Wp (ft)	Slope (ft/ft)	Mannings "n"	Mean V (ft/s)	Q (ft^3/s)
Section 1	7,600	11.5	3.9	0.48	0.17	0.16	0.672	4.19	0.0150	0.036	1.51	1.02
Section 2	6,840	29.5	2.09	0.85	0.58	0.42	1.22	2.94	0.0170	0.039	2.81	3.44
Section 3	6,530	37.6	6.18	1.2	0.90	0.79	5.56	7.00	0.0160	0.021	7.69	42.76
Section 4	6,020	49.2	7.09	1	0.70	0.64	4.93	7.71	0.0267	0.030	6.06	29.91
Section 5	5,835	69.3	5.13	1	0.84	0.69	4.31	6.26	0.0330	0.034	6.16	26.57
Section 6	5,640	74.6	9.69	1.5	1.03	0.93	10.00	10.81	0.0240	0.033	6.59	65.94
Section 7	5,280	78.4	8.86	1	0.82	0.76	7.28	9.52	0.0167	0.036	4.53	32.97
Section 8	4,750	118	6.7	1.14	0.95	0.82	6.38	7.83	0.0080	0.032	3.65	23.30
Section 9	4,560	119	8.75	2	1.32	1.09	11.57	10.60	0.0133	0.030	6.11	70.72
Section 10	4,260	204	14.84	1.48	1.09	1.02	16.19	15.84	0.0100	0.033	4.55	73.59
Section 11	3,710	227	14.35	2.02	1.56	1.44	22.43	15.58	0.0144	0.038	6.05	135.64
Section 12	3,220	257	19.73	2.51	1.50	1.41	29.57	20.98	0.0067	0.034	4.53	134.08
Section 13	2,780	285	21.72	1.81	1.25	1.21	27.05	22.36	0.0100	0.045	3.75	101.54
Section 14	2,140	299	14.37	2.11	1.55	1.43	22.3	15.63	0.0050	0.027	4.96	110.50
Section 15	1,530	317	17.63	2.07	1.42	1.33	25.05	18.85	0.0100	0.031	5.77	144.61
Section 16	890	331	13.71	2.1	1.59	1.43	21.76	15.24	0.0100	0.044	4.33	94.12
Section 17	320	379	17.22	2.84	1.63	1.47	28.07	19.04	0.0144	0.042	5.56	156.07

Table 4. Total Channel Geometry and Discharge

Section #	Station feet	Ad (ac)	Width feet	D (TC) feet	D (mean) feet	R feet	A $feet^2$	Wp feet	Slope ft/ft	Mannings "n"	Mean V ft/s	Q ft^3/s
Section 1	7,600	11.5	16.27	1.21	0.49	0.48	8.03	16.68	0.0150	0.051	2.21	17.74
Section 2	6,840	29.5	13.6	5.8	3.13	2.30	42.53	18.52	0.0170	0.068	4.95	210.33
Section 3	6,530	37.6	22.17	3.35	1.62	1.51	35.81	23.78	0.0160	0.045	5.49	196.51
Section 4	6,020	49.2	21.22	3.82	2.10	1.93	44.59	23.06	0.0267	0.054	6.97	310.67
Section 5	5,835	69.3	24	3.00	1.45	1.34	34.84	26.06	0.0330	0.064	5.12	178.47
Section 6	5,640	74.6	24.28	4.85	2.50	2.22	60.70	27.39	0.0240	0.059	6.62	401.53
Section 7	5,280	78.4	34.44	4.21	2.33	2.23	80.39	36.12	0.0167	0.066	4.95	397.67
Section 8	4,750	118	40.4	4.88	2.77	2.58	111.80	43.35	0.0080	0.057	4.37	488.49
Section 9	4,560	119	67.83	4.03	1.19	1.15	80.90	70.10	0.0133	0.070	2.70	218.29
Section 10	4,260	204	54.44	5.33	2.63	2.52	143.20	56.77	0.0100	0.063	4.36	623.72
Section 11	3,710	227	29.88	6.71	4.23	3.61	126.5	35.02	0.0144	0.056	7.45	942.76
Section 12	3,220	257	31.09	5.10	3.14	2.86	97.63	34.1	0.0067	0.043	5.68	554.43
Section 13	2,780	285	38.13	4.77	3.28	3.09	125.2	40.56	0.0100	0.056	5.60	700.93
Section 14	2,140	299	59.4	6.30	2.77	2.66	164.5	61.9	0.0050	0.051	3.94	647.77
Section 15	1,530	317	28.86	7.24	5.07	4.13	146.3	35.4	0.0100	0.041	9.27	1356.33
Section 16	890	331	51.57	7.35	3.49	3.25	179.9	55.39	0.0100	0.059	5.50	988.60
Section 17	320	379	37.22	7.02	3.42	3.01	127.4	42.36	0.0144	0.057	6.49	826.58

Table 5. Pebble Counts

Section	Station (ft)	D25 (mm)	D50 (mm)	D84 (mm)	Dmax (mm) (mobile)	Dmax (mm) (Largest)
Section 1	7,600	12	13	20	50	-
Section 2	6,840	12	15	30	88	100
Section 3	6,530	7	11	20	110	147
Section 4	6,020	9	35	68	77	180
Section 5	5,835	43	80	100	157	303
Section 6	5,640	49	60	120	210	317
Section 7	5,280	41	50	81	293	507
Section 8	4,750	21	58	103	177	230
Section 9	4,560	14	50	80	153	177
Section 10	4,260	20	30	59	200	313
Section 11	3,710	15	30	73	240	387
Section 12	3,220	28	80	120	327	543
Section 13	2,780	30	55	123	280	363
Section 14	2,140	23	35	85	253	347
Section 15	1,530	11	70	98	293	380
Section 16	890	28	45	79	207	253
Section 17	320	11	35	54	170	343

Table 6. Sediment Transport

Section #	Shear (lbs/ft^2)	Stream Power	Critical Dia1 (mm)	Critical Dia2 (mm)	Reynold's #	GeoMean Dia (m)	Shields Parameter	Dcbf mm	RBS	LRBS
Section 1	0.15	0.95	11	38	1,164	0.014	0.025	18	3.060	0.486
Section 2	0.44	3.64	33	83	2,422	0.017	0.026	49	.728	-0.138
Section 3	0.79	42.69	61	128	2,294	0.012	0.026	89	.208	-0.682
Section 4	1.07	49.84	83	159	4,653	0.021	0.028	114	.529	-0.277
Section 5	1.42	54.72	112	197	15,595	0.061	0.029	146	.745	-0.128
Section 6	1.39	98.76	110	193	16,924	0.067	0.029	142	1.086	0.036
Section 7	0.80	34.36	62	129	8,622	0.045	0.028	83	1.850	0.267
Section 8	0.41	11.63	31	78	5,065	0.037	0.028	43	1.203	0.080
Section 9	0.91	58.69	70	141	6,536	0.032	0.028	96	.634	-0.198
Section 10	0.64	45.92	49	109	4,456	0.026	0.027	69	.397	-0.401
Section 11	1.29	121.88	102	184	5,614	0.023	0.028	137	.184	-0.735
Section 12	0.59	56.06	45	103	7,249	0.044	0.028	62	1.185	0.074
Section 13	0.75	63.36	58	124	7,831	0.042	0.028	79	1.328	0.123
Section 14	0.45	34.48	34	84	4,725	0.033	0.028	48	.432	-0.365
Section 15	0.83	90.24	64	132	6,449	0.033	0.028	88	.647	-0.189
Section 16	0.89	58.73	69	140	7,698	0.038	0.028	93	.606	-0.217
Section 17	1.32	140.24	105	187	4,940	0.02	0.028	142	.258	-0.589

Table 7. Reach Classification

Reach	Sub-Reach	Station ft	Channel Type	Slope %	Sinuosity ft/ft	W:D Ratio ft/ft	Bed Material	Boulders (> 300 mm)	Bed Stability
R1	R1-A	7,870-7,350	Colluvial	1.8	1.19	22.6	Medium Gravel	-	0.486
	R1-B	7,350-7,200	Enlarged colluvial	1.8	1.05	-	-	-	-
R2		7,200-7,050	Rip-rap	4.3	-	-	Rip-rap	-	-
R3		7,050-6,940	Culvert	6.4	-	-	Culvert	-	-
R4		6,940-6,650	Meandering	1.5	1.21	3.6	Medium Gravel	-	-0.138
R5		6,650-6,400	Plane-bed	1.6	1.05	6.9	Medium Gravel	-	-0.682
R6	R6-A	6,400-6,200	Steep riffle-pool	2.7	1.01	-	-	-	-
	R6-B	6,200-6,000	Step-pool	2.5	1.05	10.2	Very Coarse Gravel	-	-0.277
	R6-C	6,000-5,150	Bedrock	3	1.05	9.7	Very Coarse Gravel	Yes	-0.128 - 0.267
R7		5,150-4,950	Culvert	1.5	-	-	Culvert	-	-
R8	R8-A	4,950-4,800	Scour	2.1	1.01	-	-	-	-
	R8-B	4,800-4,420	Plane-bed	1.9	1.02	6.6	Very Coarse Gravel	-	-0.198
R9		4,420-4,000	Meandering	0.9	1.21	9.6	Course Gravel	Yes	-0.401
R10		4,000-3,800	Culvert	1.3	-	-	Culvert	-	-
R11		3,800-3,500	Step-pool	1.9	1.38	6.7	Course Gravel	Yes	-0.735
R12		3,500-2,700	Riffle-pool	1.7	1.25	16.5	Small Cobble	Yes	0.099
R13		2,700-2,300	Meandering	1.2	1.18	-	-	-	-
R14	R14-A	2,300-2,050	Riffle-pool	0.5	1.04	-	-	-	-
	R14-B	2,050-1,750	Riffle-pool	1.5	1.08	-	-	-	-
	R14-C	1,750-1,100	Riffle-pool	1.4	1.06	12	Very Coarse Gravel	Yes	-0.189
R15	R15-A	1,100-750	Low Sinuosity	1.1	1.13	8.2	Very Coarse Gravel		-0.217
	R15-B	0-750	High Sinuosity	1.1	1.67	10.6	Very Coarse Gravel	Yes	-0.589

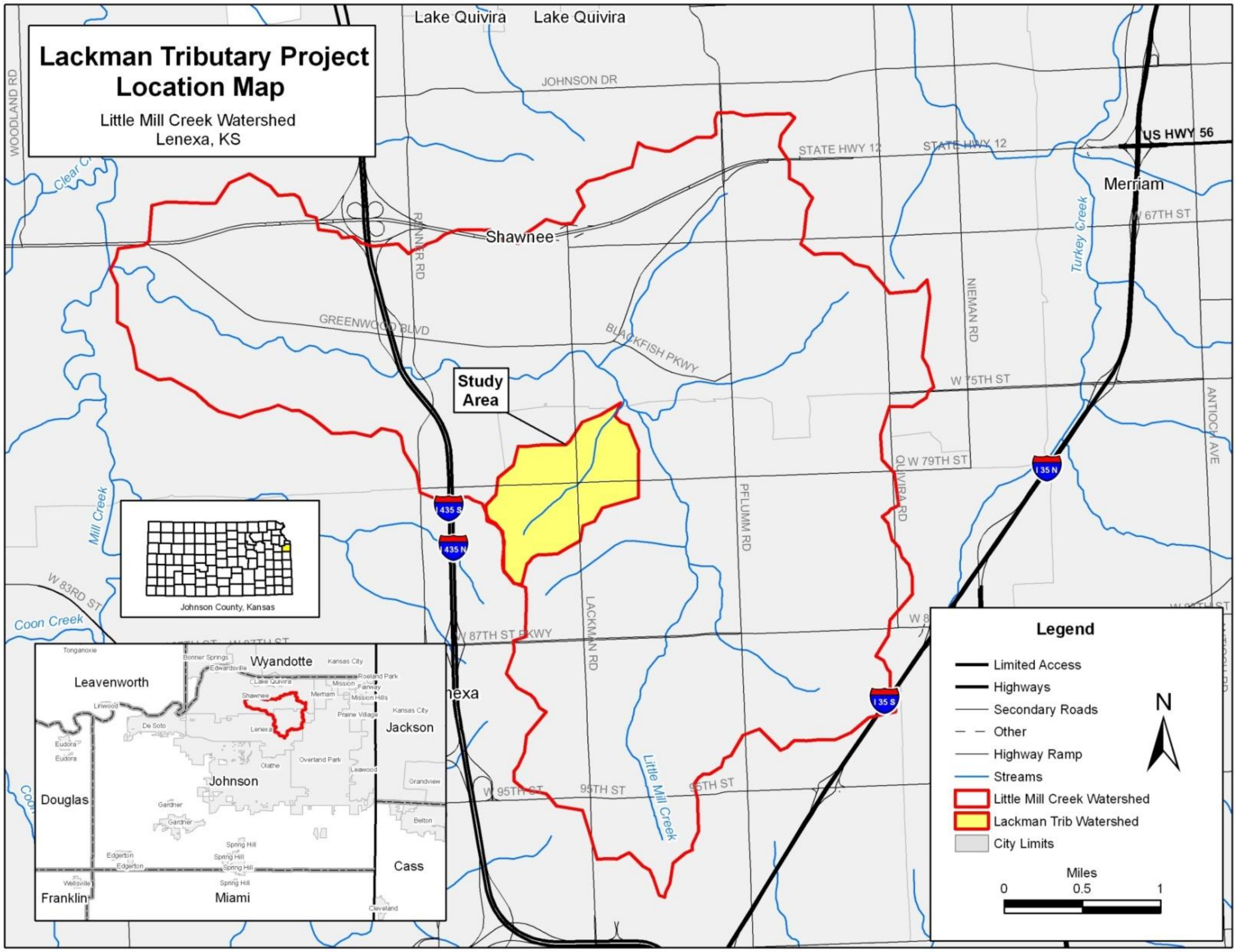


Figure 1. Lackman Tributary, Little Mill Creek Watershed

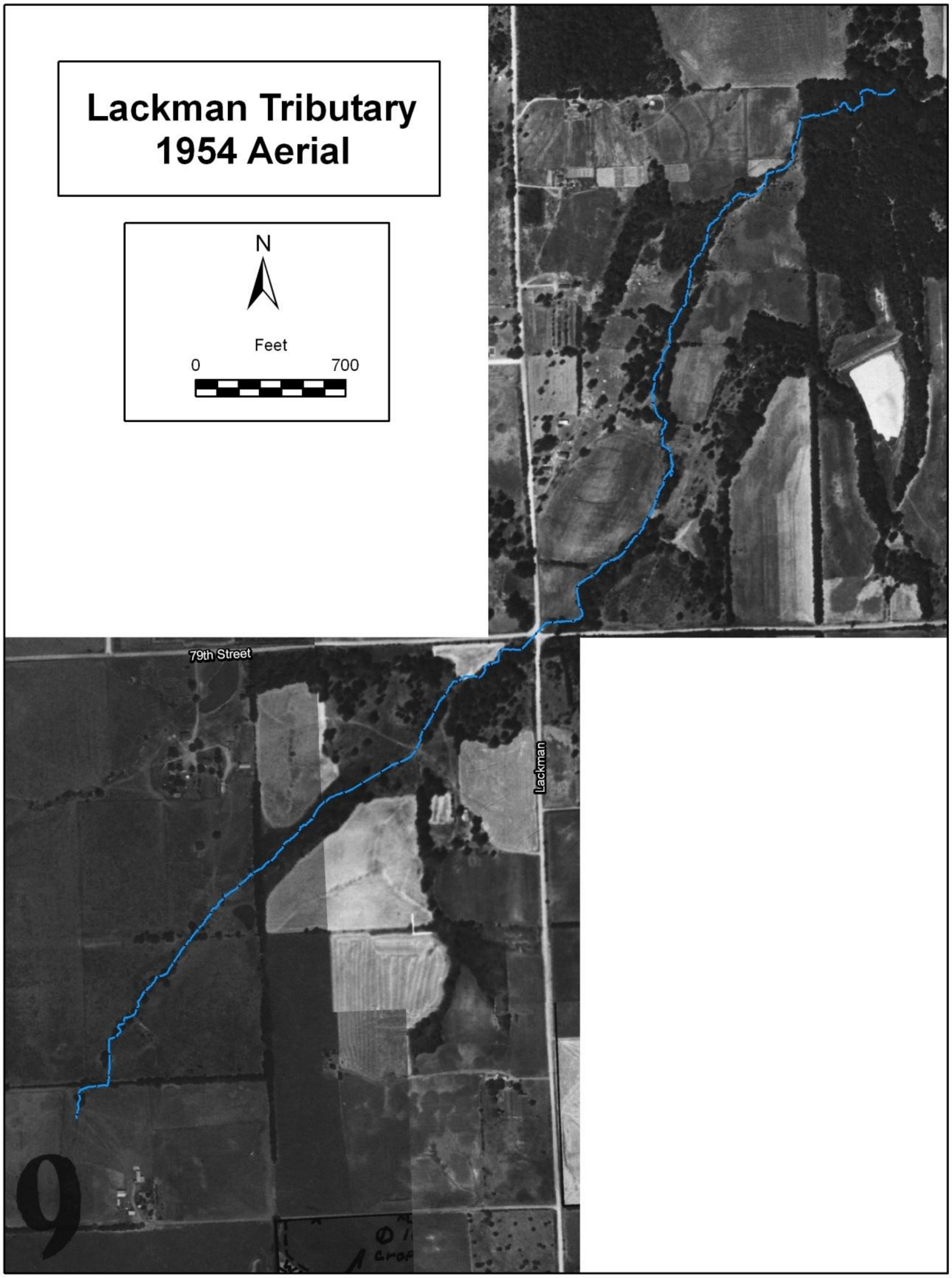


Figure 2. 1954 Aerial of Lackman Tributary

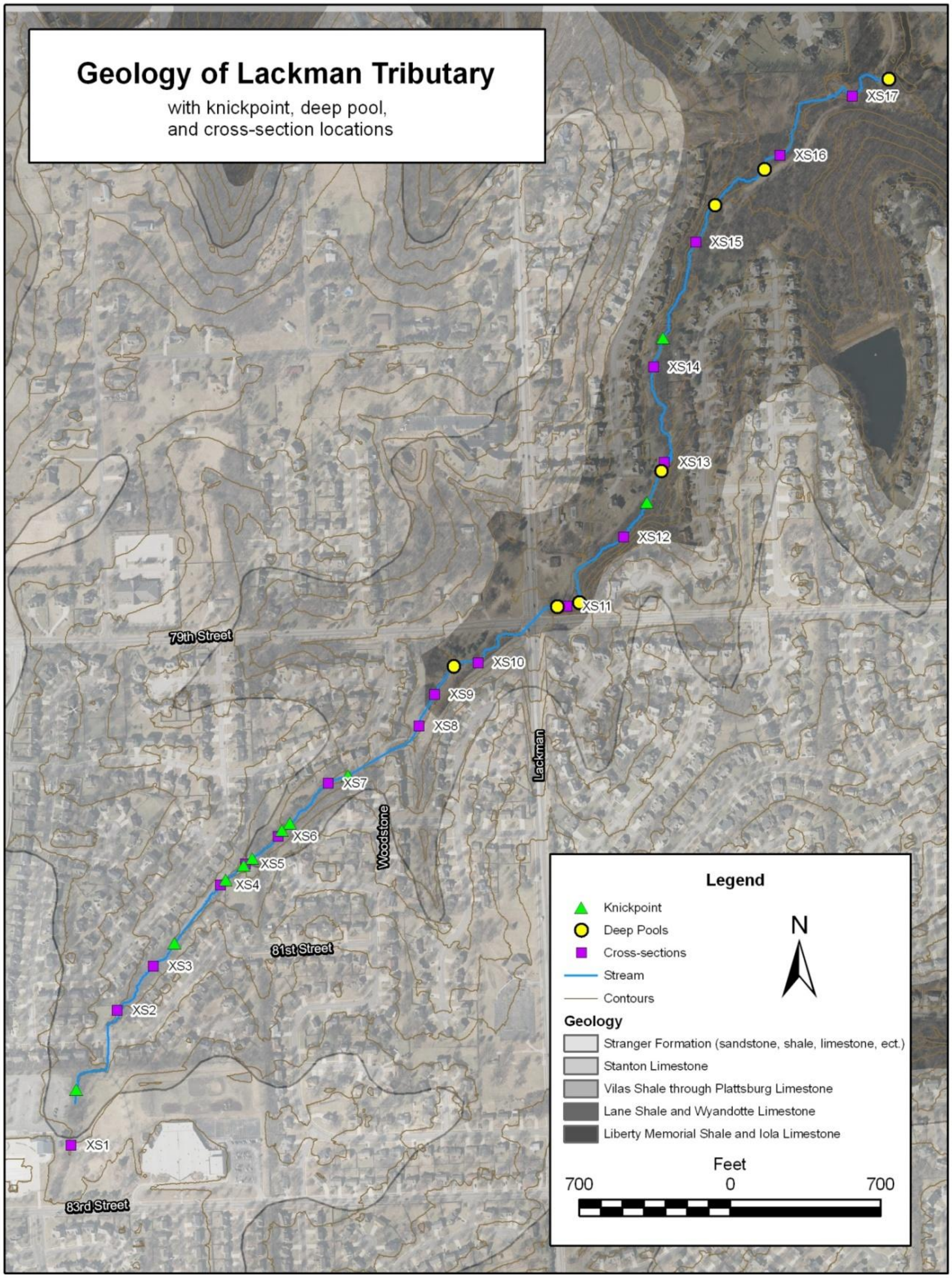


Figure 3. Geology of the Lackman Tributary with knickpoints and deep pool locations

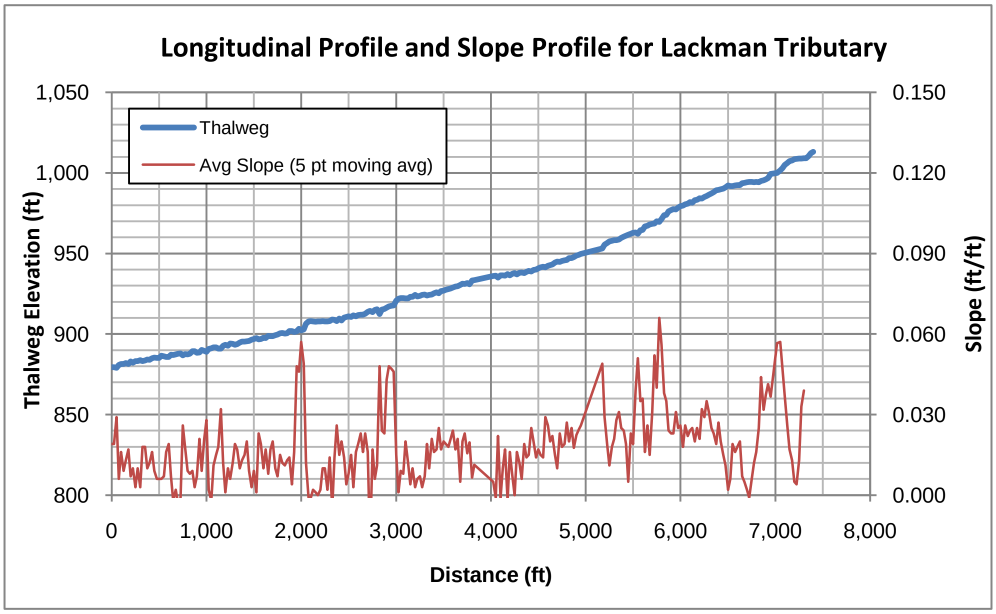


Figure 4. Longitudinal Profile and Avg. Slope

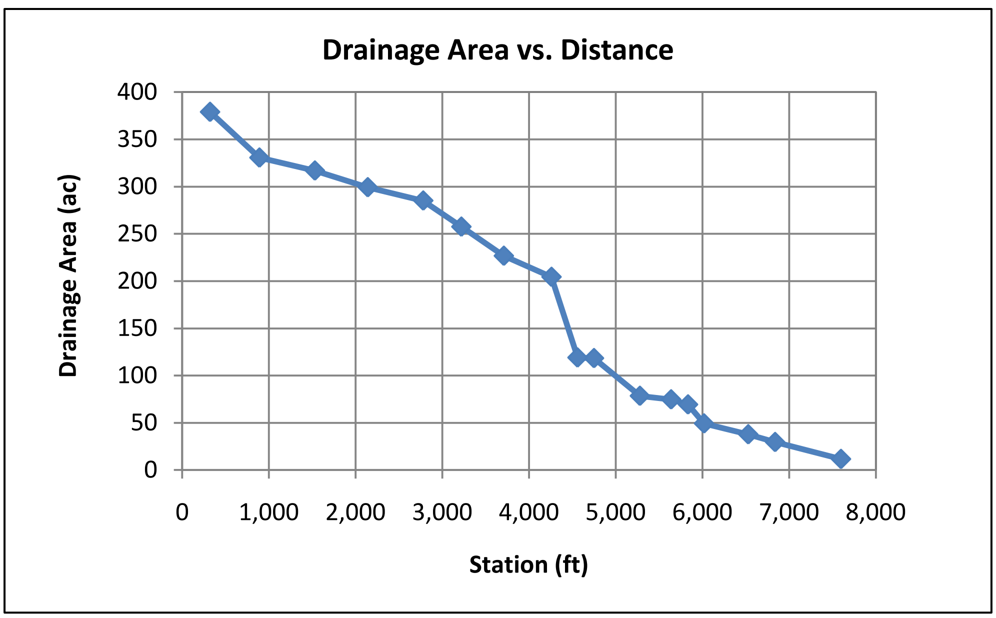


Figure 5. Downstream changes in drainage area

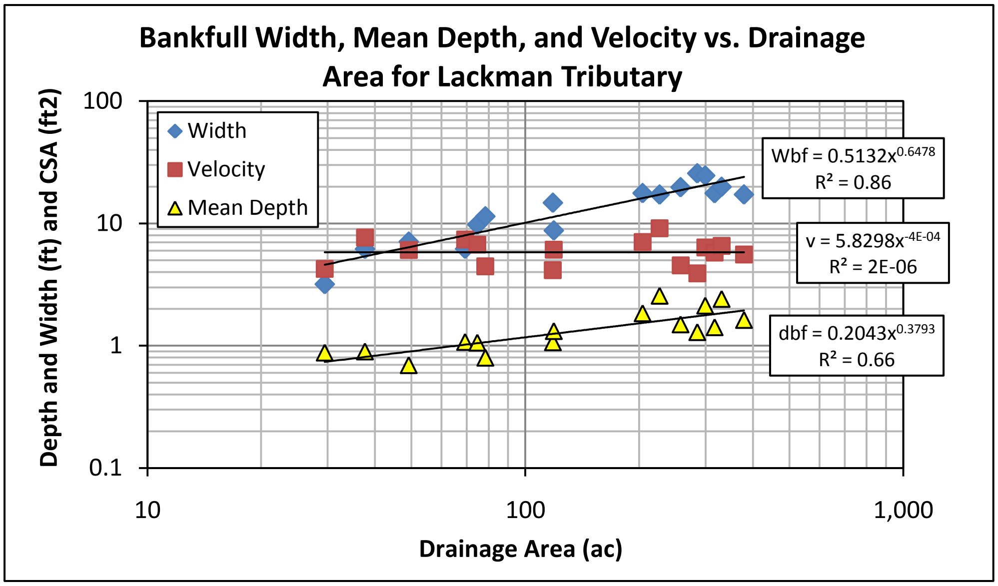


Figure 6. Bankfull hydraulic geometry

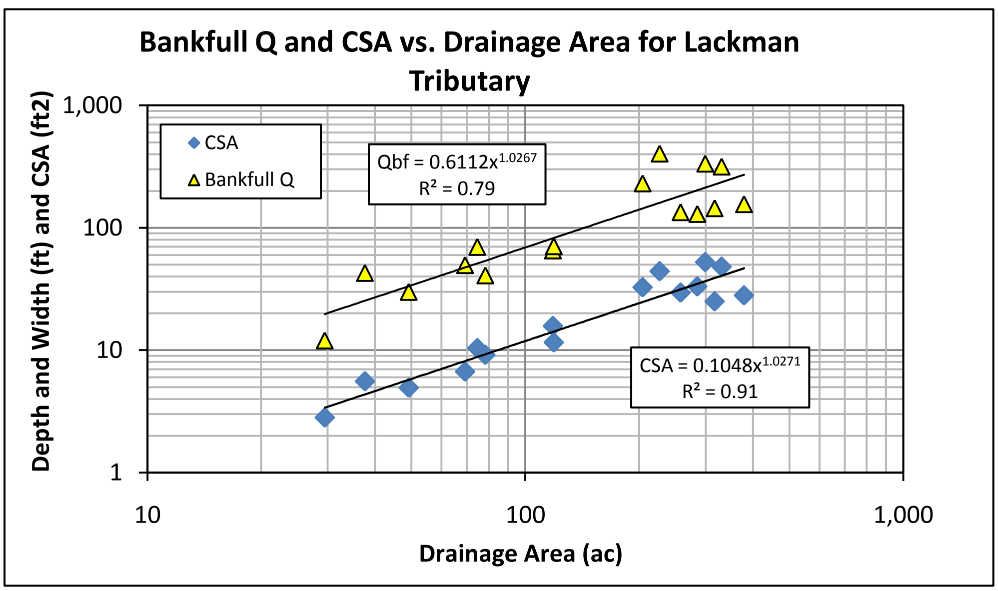


Figure 7. Bankfull Discharge and CSA

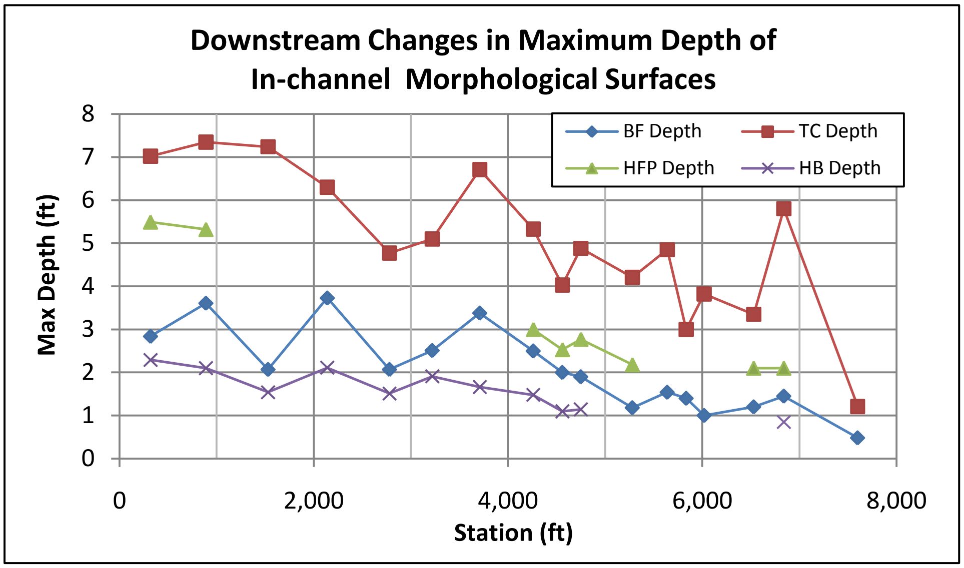


Figure 8. Downstream changes in depth

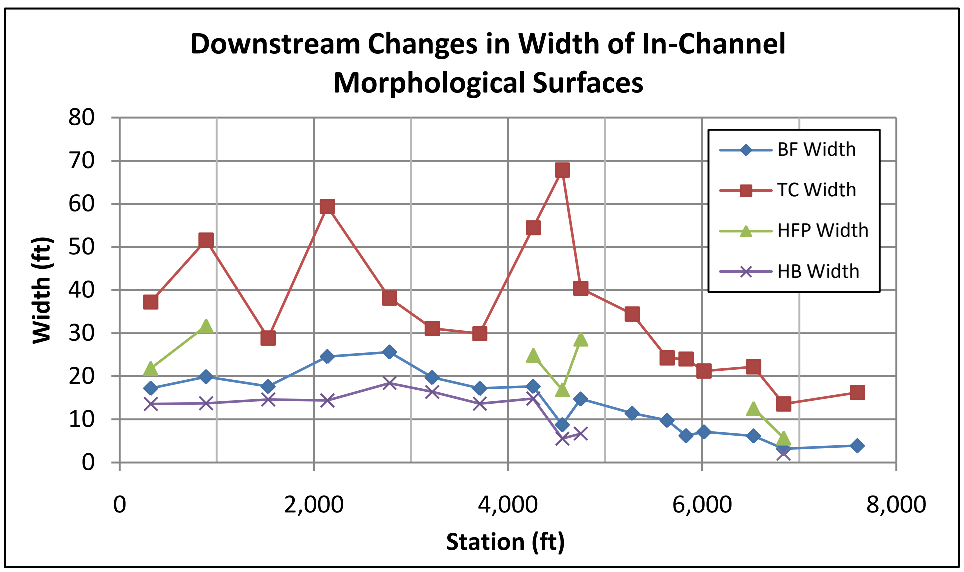


Figure 9. Downstream changes in width

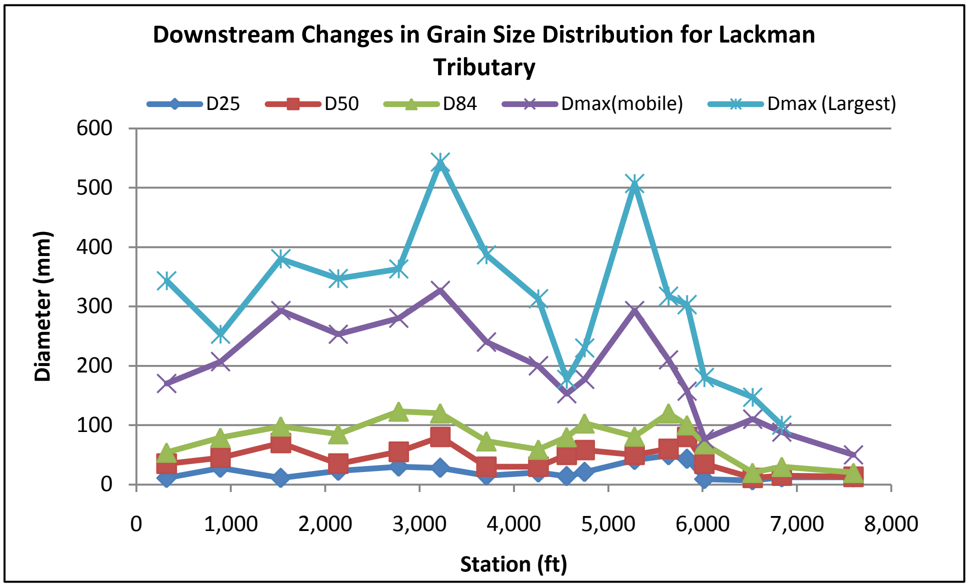


Figure 10. Downstream changes in grain size distribution

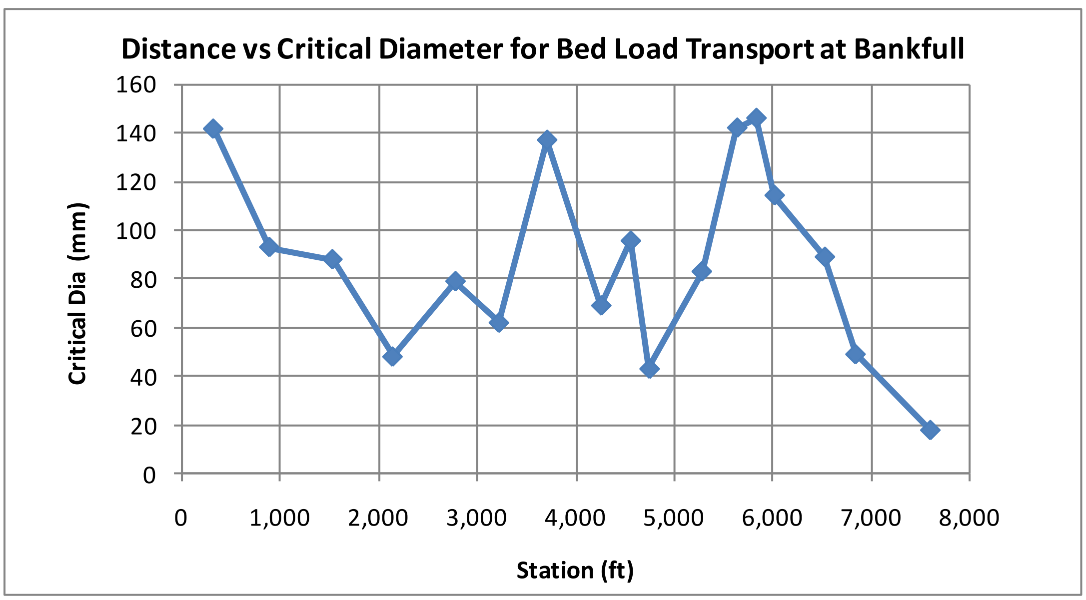


Figure 11. Downstream changes in critical diameter for bed load transport

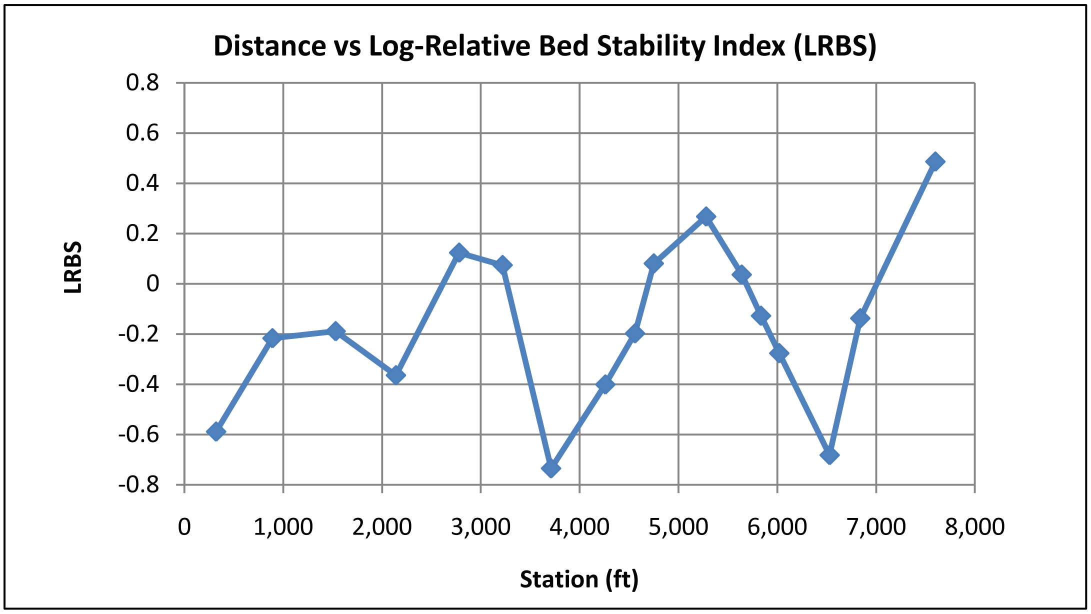


Figure 12. Downstream changes in the Log-Relative Bed Stability Index (LRBS)

Photo 1. R1-A Start of Project St. 7,870 ft looking downstream (Sept. 2009)

Photo 2. R1–A Path at St. 7,550 looking downstream (Sept. 2009)

Photo 3. R1-B Channel St. 7,300 looking downstream (Sept. 2009)

Photo 4. R3 - Rip-rap and culvert inlet St. 7,030 looking upstream (Sept. 2009)

Photo 5. R4 – xs 2, St. 6,840, looking upstream (Sept. 2009)

Photo 6. R4 – xs 2, St. 6,840, looking downstream (Sept. 2009)

Photo 7. R5 – xs 3 St. 6,530 ft looking downstream (Sept. 2009)

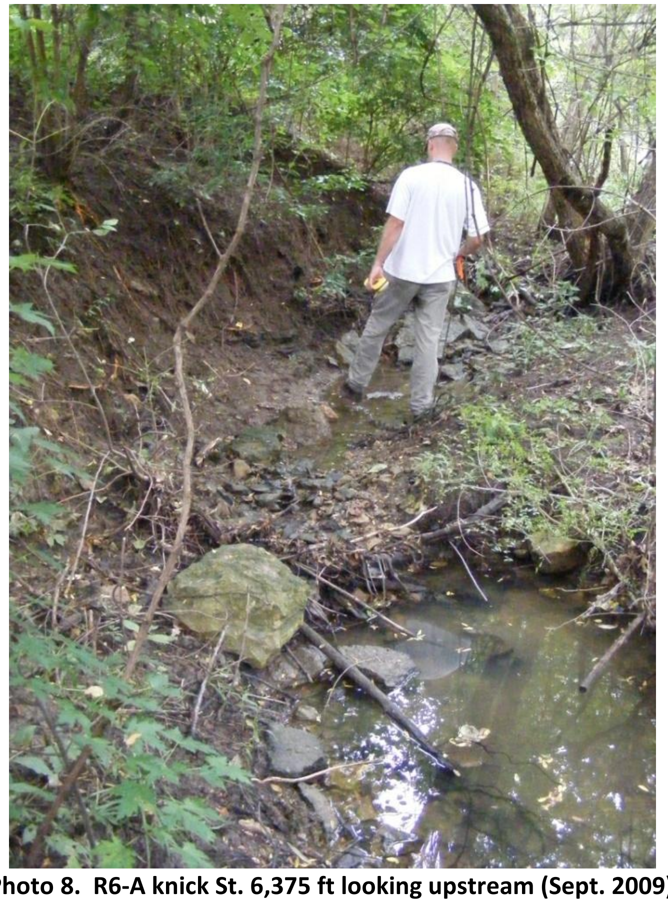


Photo 8. R6-A knick St. 6,375 ft looking upstream (Sept. 2009)

Photo 9. R6-B xs 4 St. 6,020 ft looking upstream (Sept. 2009)

Photo 10, R6-C xs 5 St. 5,835 looking upstream (Sept. 2009)

Photo 11. R6-C Knick St. 5,800 looking upstream (Sept. 2009)

Photo 12. R6-C xs 6 St. 5,640 ft looking upstream (Sept. 2009)


Photo 13. R6-C xs 6, St. 5,640 ft looking downstream (Sept. 2009)


Photo 14. R6-C knick St. 5,550 looking upstream (Sept. 2009)


Photo 15. R6-C xs 7 St. 5,280 ft looking upstream (Sept 2009)


Photo 16. R6-C – xs 7, St. 5,280 ft looking downstream (Sept. 2009)

Photo 17. R6-C knick St. 5,175 ft looking upstream (Sept. 2009)

Photo 18. R8-B xs 8 St. 4,750 ft looking downstream (Sept. 2009)

Photo 19. R8-B xs 9 St. 4,560 ft looking upstream (Sept. 2009)

Photo 20. R8-B xs 9, St. 4,560 ft looking downstream (Sept. 2009)

Photo 21. R9 – xs 10, St. 4,260 ft looking upstream (Sept. 2009)

Photo 22. R9 – xs 10 St. 4,260 ft looking downstream (Sept. 2009)

Photo 23. R9 – xs 10 St. 4,260 ft left bank (Sept. 2009)

Photo 24. R11 – xs 11, St. 3,710 ft looking upstream (Sept. 2009)

Photo 25. R11 – xs 11 St. 3,710 ft looking downstream (Sept. 2009)

Photo 26. R11 - xs11 St. 3,710 ft left bank (Sept. 2009)

Photo 27. R11 - xs 11, St. 3,710 ft right bank (Sept. 2009)

Photo 28. R12 – xs 12, St. 3,220 ft looking upstream (Sept. 2009)


Photo 29. R12 – xs 12 St. 3,220 ft looking downstream (Sept. 2009)


Photo 30. R12 – xs 12 St. 3,220 ft left bank (Sept. 2009)

Photo 31. R12 – xs 12, st. 3,220 ft right bank (Sept. 2009)

Photo 32. R12 - above knick St. 3,000 ft looking downstream (Sept. 2009)

Photo 33. R12 – xs 13 St. 2,780 ft looking upstream (Sept. 2009)

Photo 34. R12 – xs 13 St. 2,780 ft looking downstream (Sept. 2009)


Photo 35. R12 – xs 13 St. 2,780 ft left bank (Sept. 2009)


Photo 36. R12 – xs 13 St. 2,780 ft right bank (Sept. 2009)

Photo 37. R14 – xs 14 St. 2,140 ft looking upstream (Sept. 2009)

Photo 38. R14 – xs 14 St. 2,140 ft looking downstream (Sept. 2009)

Photo 39. R14 – xs 14 St. 2,140 ft left bank (Sept. 2009)

Photo 40. R14 – xs 14 St. 2,140 ft right bank (Sept. 2009)

Photo 41. R14 - knick St. 2,050 ft looking upstream (Sept. 2009)

Photo 42. R14 – xs 15 St. 1,530 looking upstream (Sept. 2009)

Photo 43. R14 – xs 15 St. 1,530 ft looking downstream (Sept. 2009)

Photo 44. R14 – xs 15 St. 1,530 ft left bank (Sept. 2009)

Photo 45. R14 – xs 15 St. 1,530 ft right bank (Sept. 2009)

Photo 46. R15-A xs 16 St. 890 ft looking upstream (Sept. 2009)

Photo 47. R15-A – xs 16 St. 890 ft looking downstream (Sept. 2009)

Photo 48. R15-A xs 16 St. 890 ft left bank (Sept. 2009)

Photo 49. R15-A xs 16 St. 890 ft right bank (Sept. 2009)

Photo 50. R15-B xs 17 St. 320 ft looking upstream (Sept. 2009)

Photo 51. R15-B xs 17 St. 320 ft looking downstream (Sept. 2009)

Photo 52. R15-B xs 17 St. 320 ft left bank (Sept. 2009)

Photo 53. R15-B xs 17 St. 320 ft right bank (Sept. 2009)

Photo 54. R15-B confluence with Little Mill Creek St. 0 ft looking upstream (Sept. 2009)

Appendix

Geology

The area is underlain by interbedded Pennsylvanian age limestones and shales that are outcropped along the stream corridor both in the bed and along the banks, especially at strath terraces in the lower sections of the stream (O'Conner, 2000). Mapped geological units within the watershed are the Stanger Formation, Stanton Formation, Vilas Shale/Plattsburg Limestone Formation, and the Lane Shale/Wyandotte Limestone Formation (Figure ?). Descriptions of these formations along with details of the individual members are discussed here (Figure ?).

<u>Stranger Formation</u>
The Stranger Formation contains sandstone, shale, and a minor amount of limestone, coal, and conglomerate. The thickness ranges from 100 to 180 feet, generally increasing southward. The Stranger is divided into five members (O'Connor, 1963). The Weston Shale Member and the latan Limestone Member were formerly included in the Pedee Group.

Vinland Shale Member
This unit consists of gray to greenish-gray, clayey, calcareous shale, sandy shale, and sandstone. North of Anderson and Coftey counties, where the Westphalia Limestone Member is absent, the top of the upper Sibley coal is regarded as marking the base of the Vinland Shale. A persistent zone of septarian concretions occurs in the upper middle part of the member in northeastern Kansas. A faunal zone containing abundant mollusks, particularly myalinid clams, characterizes the upper part of the Vinland Shale. The thickness of the Vinland ranges from about 2 to 50 feet.

Westphalia Limestone Member
The Westphalia Limestone Member comprises brown, flaggy-bedded, argillaceous limestone about 1 to 5 feet thick from northern Anderson County southward to northeastern Chautauqua County. The upper part of the member contains fusulinids, *Osagia,* and mollusks. In Anderson County and northward, the member is a discontinuous, gray, laminated, carbonaceous limestone 0 to 1.5 feet thick that directly overlies the upper Sibley coal bed.

Tonganoxie Sandstone Member
Generally lenticular, massive, crossbedded sandstone and more continuous sandy shale, containing several discontinuous coal beds, occupy the middle part of the Stranger Formation in most places. The *upper* and *lower Sibley coal beds,* in the northern part of the outcrop area, are distinctive units. Locally, there is a disconformity at the base of the Tonganoxie where it cuts through the lower members of the Stranger and into the top of the underlying Stanton Limestone. In other places, where the intervening latan Limestone Member is absent, the lower contact is gradational into the Weston Shale Member. The thickness ranges from 0 to 120 feet.

Formerly the base of the Tonganoxie Sandstone was regarded as marking the base of the Douglas Group and of the Virgilian Stage. The Douglas Group has been expanded to include beds downward to the top of the Stanton Limestone (O'Connor, 1963). Ball (1964) has shown that there is no persistent disconformity on which the Tonganoxie Sandstone was deposited.

Iatan Limestone Member

The Iatan Limestone Member outcrops in Kansas only in Leavenworth County, where it ranges in thickness from 0 to 14 feet. It is a dense, light-gray limestone, which locally contains *Archaeolithophyllum* and *Osagia,* as well as fusulinids, brachiopods, bryozoans, crinoids, and corals.

Weston Shale Member
The Weston Shale Member is a grayish-blue to medium-gray, clay shale that weathers yellowish-gray to light olive-gray. It is generally unfossiliferous, but locally it may contain thin fossiliferous zones. In many places ironstone concretions are abundant. Plant remains are present locally in the middle or upper beds. In southeastern Kansas, where the Iatan Limestone Member is absent, and where there are no massive sandstones to mark the base of the Tonganoxie Sandstone Member, the upper boundary of the Weston is difficult to define. The thickness ranges from 0 to 140 feet.

<u>Stanton Limestone</u>
The Stanton Limestone contains three limestone and two shale members. Northward from Anderson County the Stanton is rather uniform in thickness and character. In Anderson County and southward the formation has many facies variations. Northern exposures are commonly 30 to 50 feet thick, whereas southern outcrops of the formation range from 15 to 130 feet in thickness.

South Bend Limestone Member - The upper member of the Stanton is a medium- to thick-bedded, dense, fine-grained, medium- to dark-gray or bluish-gray, fossiliferous limestone that weathers yellowish-gray to yellowish-brown. The lower part commonly is sandy or conglomeratic. The South Bend ranges from about 1 to 6 feet in thickness along its outcrop except in Montgomery County, where it is as much as 27 feet thick.

Rock Lake Shale Member - Gray and olive-gray argillaceous to sandy shale and sandstone that weathers yellowish-gray to yellowish-orange comprise most of this member. The sandstone contains *Myalina* and *Aviculopecten.* Locally the Rock Lake includes a conglomerate; elsewhere a thin black shale or thin coal overlain by a thin, laminated gray limestone is present. The thickness ranges from about 1 to 15 feet in most of eastern Kansas but is as much as 30 feet locally in Montgomery County.

Stoner Limestone Member - The Stoner Limestone Member comprises thin to medium beds of medium-gray to very light-gray wavy-bedded limestone. It is 10 to 20 feet thick throughout most of eastern Kansas. The uppermost beds locally may be brecciated or nodular-appearing or calcarenitic. The member includes much fine- to medium-grained light-gray mottled limestone containing abundant coarsely crystalline calcite and some oolitic limestone in southern outcrops. It has a maximum thickness of about 50 feet in northern Montgomery County.

Eudora Shale Member - The Eudora Shale Member ranges from 2 to 11 feet in thickness in eastern Kansas, except in Montgomery County, where it ranges from 0 to 70 feet in thickness. In most exposures the middle part of the Eudora comprises 1 to 5 feet of grayish-black fissile shale that contains small phosphatic nodules. The grayish-black shale overlies a thin bed of greenish-gray calcareous shale and is overlain by 1 to 6 feet of light- to dark-gray shale. In Montgomery County the member is chiefly gray calcareous and fossiliferous shale locally containing a few inches to a few feet of grayish-black fissile shale near its base.

Captain Creek Limestone Member - The lower member of the Stanton Limestone comprises 4 to 11 feet of limestone having even to slightly uneven, thin to medium bedding. It is chiefly light-gray to medium-gray, fine- to medium-grained, fossiliferous limestone that weathers light gray. The upper 2 feet may be

brecciated and mottled. Southern outcrops of the Captain Creek may be as much as 64 feet thick and contain beds of coarsely crystalline algal limestone and oolitic limestone.

Vilas Shale and Plattsburg Limestone

From Anderson County northward the Vilas ranges from about 1 to 35 feet in thickness and comprises sandy, silty, and carbonaceous gray shale which weathers yellowish-gray. Locally the formation contains beds of sandstone and a fossiliferous sandy limestone. In Wilson and Montgomery counties the Vilas ranges from 5 to 120 feet in thickness, is fossiliferous in the uppermost part, and contains beds of ironstone concretions.

The Plattsburg Limestone consists of two limestone members separated by a shale member. The upper is the thicker of the two limestone members, except locally, as in eastern Franklin County. In Wilson County the Plattsburg forms marine limestone banks (Harbaugh, 1959) and attains its maximum thickness of 115 feet. The formation disappears near the Oklahoma state line. Thickness of the Plattsburg Limestone in Kansas averages about 25 feet.

Spring Hill Limestone Member - The Spring Hill Limestone Member is chiefly gray, fine-grained, even to slightly wavy-bedded limestone that weathers yellowish-orange. Along most of its outcrop in eastern Kansas it has a fine- to medium-grained texture and contains abundant fossils. Oolitic limestone comprises part of the middle or upper beds. In Wilson County the middle part of the member is coarsely crystalline limestone containing *Archaeolithophyllum* (Wray, 1964). The lower part is a fragmental, pelletal limestone, and the upper part is a calcarenite (Harbaugh, 1959). The member has a thickness of 7 to 23 feet in northern outcrops and ranges from 0 to 88 feet in southern outcrops.

Hickory Creek Shale Member - The Hickory Creek Shale Member in central and northern outcrops comprises 0.1 foot to 6 feet of calcareous light olive-gray shale. Locally the member includes a thin bed of greenish-black or very dark-gray shale. Outcrops of the Hickory Creek in southern Kansas range from 0 to 40 feet in thickness. Where thickest it comprises gray calcareous shale interbedded with thin fragmental limestones and contains abundant crinoids, sponges, and bryozoans.

Merriam Limestone Member - In central and northern outcrops in eastern Kansas, the Merriam consists of a light-gray to yellowish-gray limestone bed characterized by mollusks, *Composita,* and abundant *Osagia* and oolites in the upper part. This bed is overlain by a fine-grained gray limestone containing fusulinids, brachiopods, and crinoids. The Merriam commonly is 1 to 3 feet thick except locally where the oolitic or *Osagia*-bearing limestone expands the thickness to as much as 11 feet. In southern outcrops the Merriam is a single thin fossiliferous limestone generally having a thickness of 1 foot or less.

Wyandotte Limestone and Lane Shale

The Wyandotte Limestone contains three limestone and two shale members. The lower two limestones and the intervening shale are more constant in lithologic character and thickness, but the entire formation, which is prominent in northeastern Kansas and especially along the Kansas River, disappears in or near northwestern Anderson County. Thickness ranges from 0 to about 100 feet.

The Lane Shale consists of dark bluish-gray shale, locally containing rather abundant marine fossils, gray and yellowish-brown unfossiliferous sandy shale, and thin-bedded sandstone. The thickness ranges from about 7 to 108 feet, averaging about 50 feet. Southward from the point where the Wyandotte

Limestone pinches out in Anderson County, the Lane and Bonner Springs shales cannot be differentiated.

Farley Limestone Member - This member comprises an extremely variable assemblage of limestone and shale beds that is recognized definitely only north of southern Johnson County. Many types of limestone are represented, but oolitic or pelletal limestone, limestone breccia or conglomerate, and dense, mottled, pinkish-gray limestone are characteristic. Crossbedding is common. The algal or oolitic facies commonly are in massive beds; the breccias and conglomerates are slabby. Detrital beds are mostly in the upper part. Wavy and thin-bedded, mottled, dense limestone, chiefly in the lower part, is somewhat similar to the underlying Argentine Limestone. The Farley Limestone is abundantly fossiliferous. Thickness ranges from 0 to about 35 feet.

Island Creek Shale Member - The Island Creek Shale Member is a gray, yellow, and bluish-gray clayey shale of highly variable thickness. Locally in Wyandotte County, several feet of sandstone, which seems to be a channel filling, occupies this position. Thickness ranges from 0 to perhaps as much as 40 feet.

Argentine Limestone Member - This is a prominent escarpment-forming light bluish-gray, wavy-bedded limestone, much of which weathers very light gray or yellowish-gray. Clay partings are numerous in some outcrops. Marine fossils are plentiful. Thickness ranges from 0 to 37 feet.

Quindaro Shale Member - The Quindaro Shale Member is chiefly a yellowish-gray to greenish-gray calcareous shale, locally interbedded with gray, nodular limestone. Both the shale and the limestone are fossiliferous. In some localities, the Quindaro contains a thin dark-gray to black fissile shale at the base. In parts of Johnson and Miami counties the member is absent or cannot be distinguished. The thickness ranges from 0 to 8 feet, but it is commonly 2 to 5 feet thick.

Frisbie Limestone Member - The Frisbie Limestone Member is a bluish-gray to dark-blue, massive limestone, locally containing numerous marine fossils. Thickness commonly ranges from 1 to 3 feet.

Soils

Generally, upland soils are derived from loess, while hillslope soils are weathered from residuum and colluvial parent material and all soils in this watershed are classified as mollisols (Evans, 2005). The upper 1/4 of the stream is located in the uplands and transitions to the hillslope landscape position for the majority of its length until it meets the valley floor of Little Mill Creek over the final 1/10 of the stream. Mapped soil units within the watershed consist of the Grundy silt loam, Chillicothe silty clay loam, Oska-Martin Complex, Sogn-Vinland Complex, Ladoga silt loam, and the Kennebec silt loam that are described in detail below (Figure ?). Soil description information can be found at the NRCS website http://ortho.ftw.nrcs.usda.gov/cgi-bin/osd/osdname.cgi.

Grundy silt loam *(Fine, smectitic, mesic Aquertic Argiudolls)*

The Grundy series consists of very deep, somewhat poorly drained soils formed in loess. These soils are on divides and interfluves. Slope ranges from 0 to 9 percent

Chillicothe silty clay loam *(Fine, smectitic, mesic Oxyaquic Vertic Argiudolls)*

The Chillicothe series consists of very deep, moderately well drained, soils that formed in loess or loess and residuum from limestone or shale. These soils are on gently sloping ridgetops and upper side slopes of hills. Slopes range from 2 to 14 percent.

Oska silty clay loam (Fine, smectitic, mesic Vertic Argiudolls)
Martin silty clay loam (*Fine, smectitic, mesic Aquertic Argiudolls)*
The Oska series consists of moderately deep well drained soils that formed in residuum derived from limestone. These soils are on uplands. Slopes range from 1 to 9 percent.

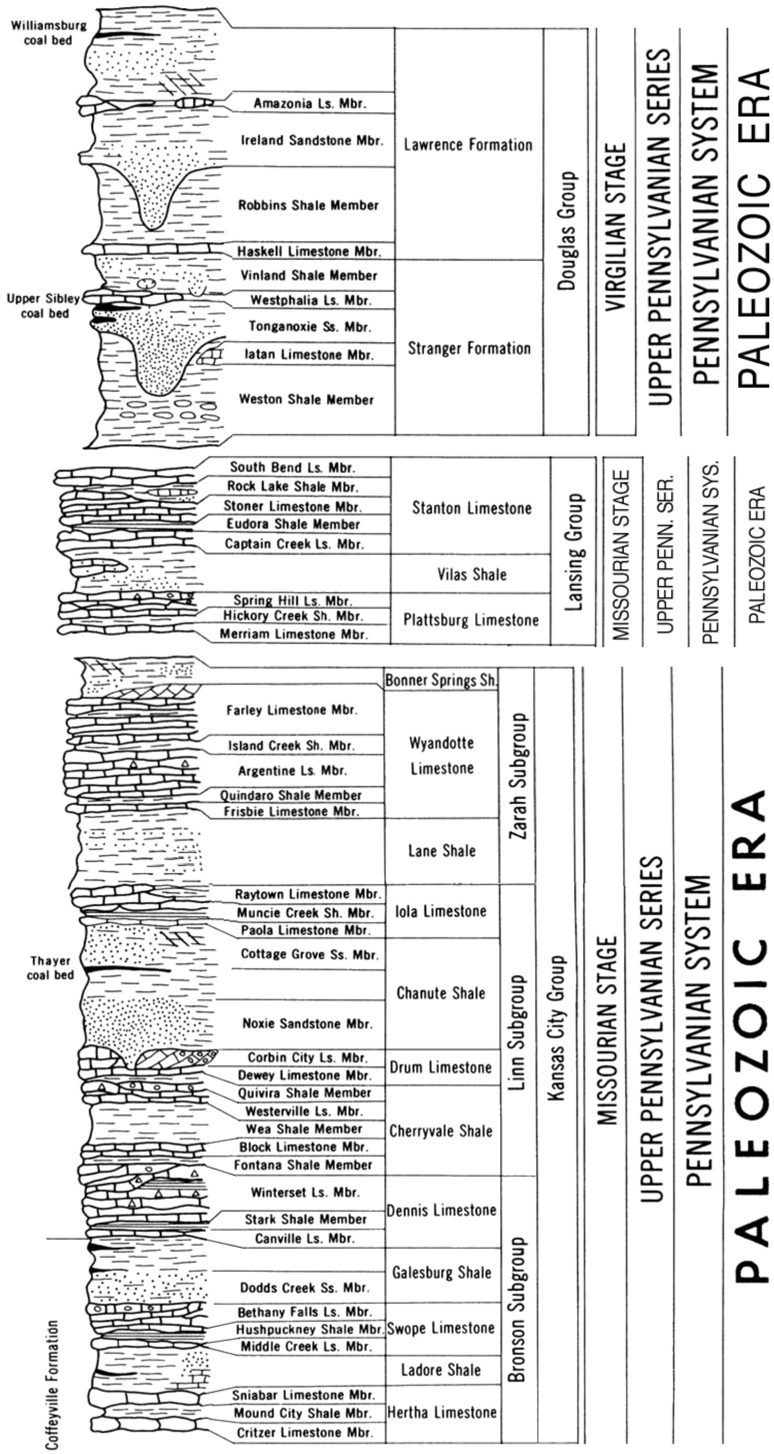
The Martin series consists of deep and very deep, moderately well drained soils on uplands. They formed in colluvium and/or residuum from interbedded silty and clayey shales, limestone, and clay beds. Slopes range from 0 to 12 percent.

Sogn silty clay loam *(Loamy, mixed, superactive, mesic Lithic Haplustolls*)
Vinland silty clay loam *(Loamy, mixed, superactive, mesic, shallow Typic Hapludolls)*
The Sogn series consists of shallow and very shallow, somewhat excessively drained, soils that formed in residuum weathered from limestone. Sogn soils are on uplands. Slopes range from 0 to 20 percent.

The Vinland series consists of shallow over shale, somewhat excessively drained upland soils formed in residuum weathered from interbedded sandy and silty shales. Slopes range from 4 to 30 percent.

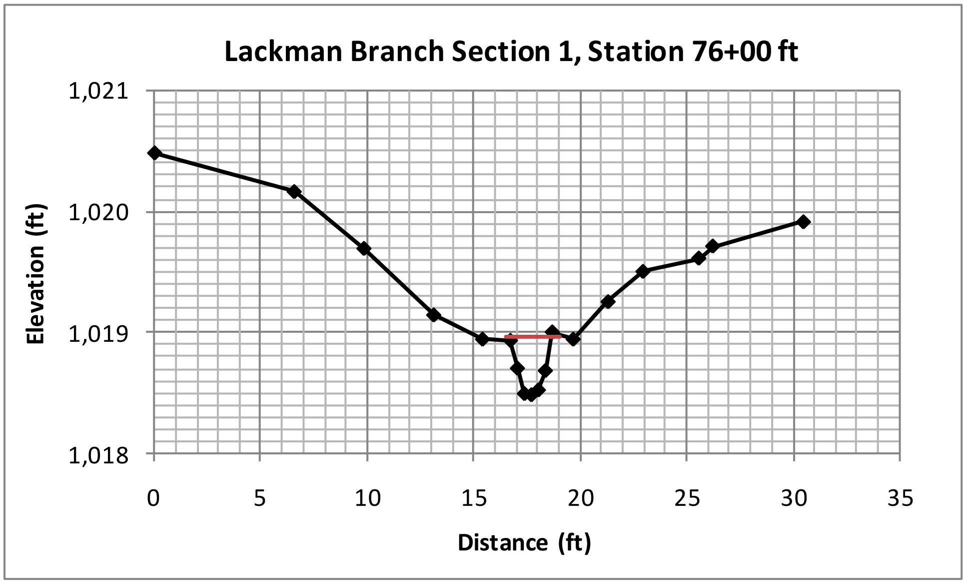
Ladoga silt-loam *(Fine, smectitic, mesic Mollic Hapludalfs)*
The Ladoga series consists of very deep, moderately well drained soils formed in loess. These soils are on convex summits of interfluves, side slopes, and nose slopes on dissected till plains and treads and risers on stream terraces. Slope ranges from 0 to 30 percent.

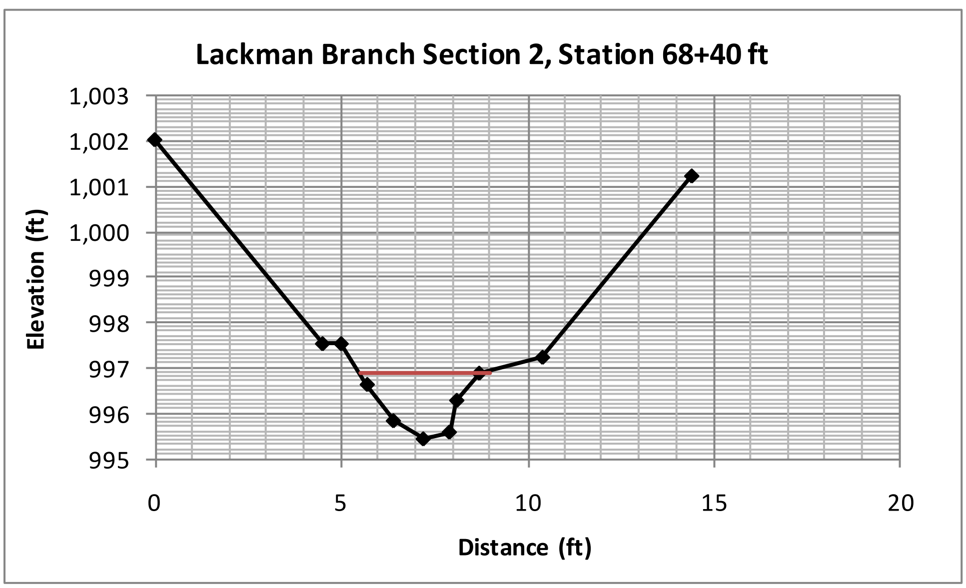
Kennebec silt-loam *(Fine-silty, mixed, superactive, mesic Cumulic Hapludolls)*
The Kennebec series consists of very deep, moderately well drained soils formed in alluvium. These soils are on flood plains in river valleys and on drainageways on uplands. Slope ranges from 0 to 5 percent.

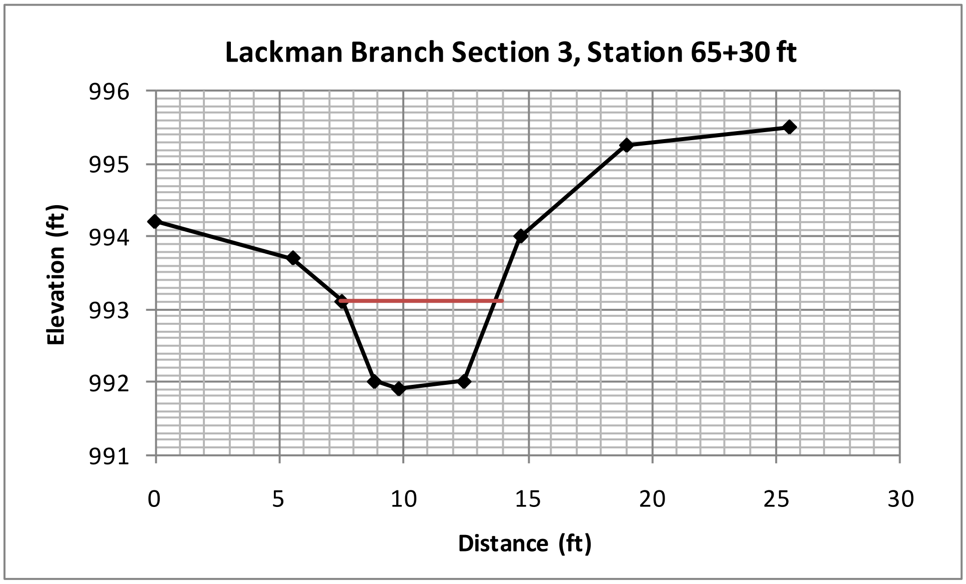


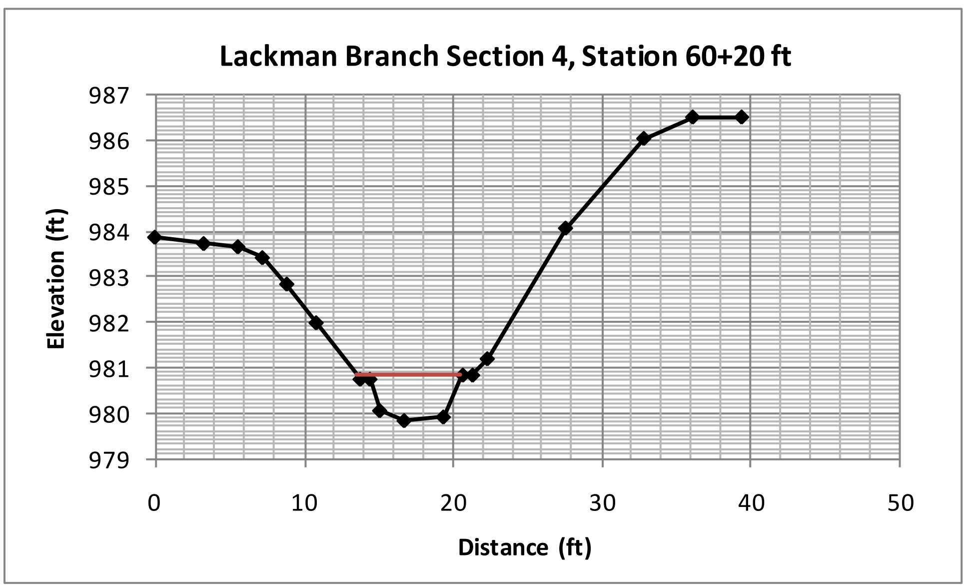
Williamsburg coal bed
Amazonia Ls. Mbr.
Ireland Sandstone Mbr.
Robbins Shale Member
Haskell Limestone Mbr.
Vinland Shale Member
Upper Sibley coal bed
Westphalia Ls. Mbr.
Tonganoxie Ss. Mbr.
Iatan Limestone Mbr.
Weston Shale Member
Lawrence Formation
Stranger Formation
Douglas Group
VIRGILIAN STAGE
UPPER PENNSYLVANIAN SERIES
PENNSYLVANIAN SYSTEM
PALEOZOIC ERA
South Bend Ls. Mbr.
Rock Lake Shale Mbr.
Stoner Limestone Mbr.
Eudora Shale Member
Captain Creek Ls. Mbr.
Spring Hill Ls. Mbr.
Hickory Creek Sh. Mbr.
Merriam Limestone Mbr.
Stanton Limestone
Vilas Shale
Plattsburg Limestone
Lansing Group
MISSOURIAN STAGE
UPPER PENN. SER.
PENNSYLVANIAN SYS.
PALEOZOIC ERA
Bonner Springs Sh.
Farley Limestone Mbr.
Island Creek Sh. Mbr.
Argentine Ls. Mbr.
Quindaro Shale Member
Frisbie Limestone Mbr.
Wyandotte Limestone
Lane Shale
Zarah Subgroup
Raytown Limestone Mbr.
Muncie Creek Sh. Mbr.
Paola Limestone Mbr.
Iola Limestone
Thayer coal bed
Cottage Grove Ss. Mbr.
Noxie Sandstone Mbr.
Chanute Shale
Corbin City Ls. Mbr.
Dewey Limestone Mbr.
Drum Limestone
Quivira Shale Member
Westerville Ls. Mbr.
Wea Shale Member
Block Limestone Mbr.
Fontana Shale Member
Cherryvale Shale
Linn Subgroup
Kansas City Group
Winterset Ls. Mbr.
Stark Shale Member
Canville Ls. Mbr.
Dennis Limestone
Dodds Creek Ss. Mbr.
Galesburg Shale
Bethany Falls Ls. Mbr.
Hushpuckney Shale Mbr.
Middle Creek Ls. Mbr.
Swope Limestone
Ladore Shale
Sniabar Limestone Mbr.
Mound City Shale Mbr.
Critzer Limestone Mbr.
Hertha Limestone
Bronson Subgroup
Coffeyville Formation
MISSOURIAN STAGE
UPPER PENNSYLVANIAN SERIES
PENNSYLVANIAN SYSTEM
PALEOZOIC ERA

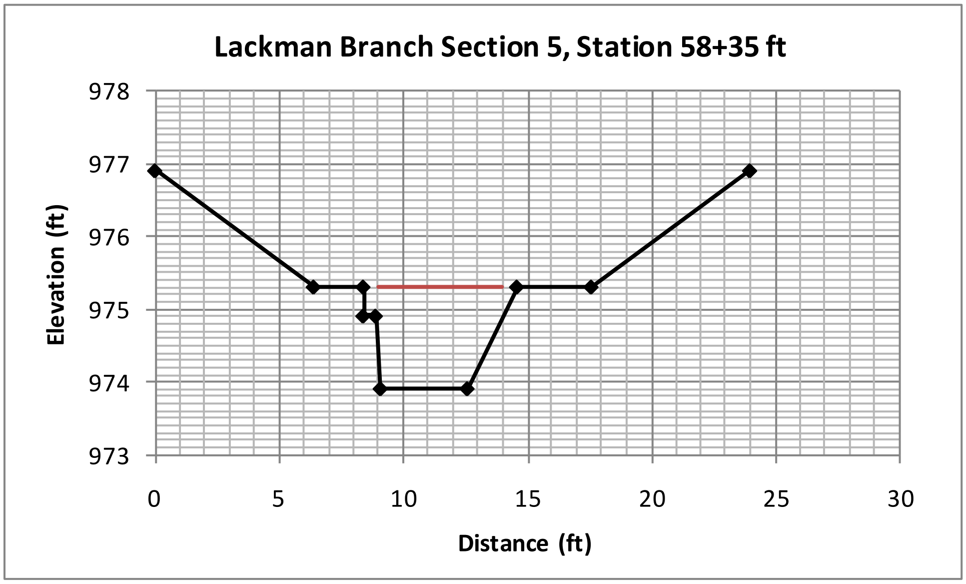
Channel Cross Sections

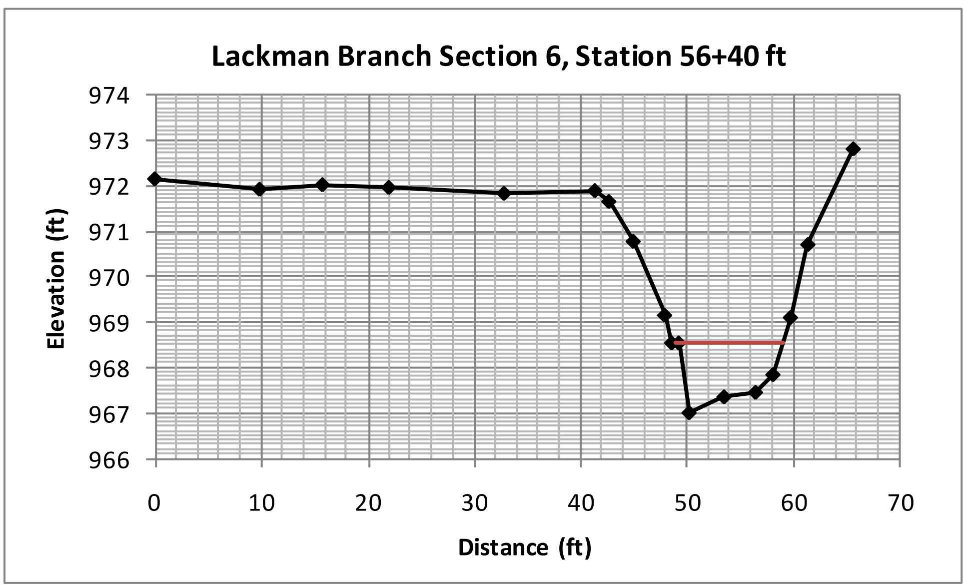


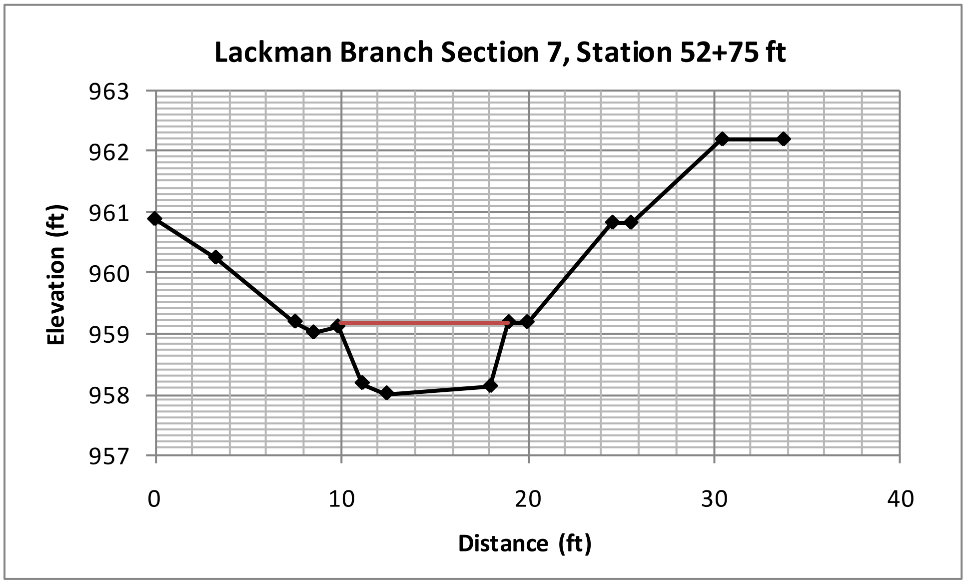


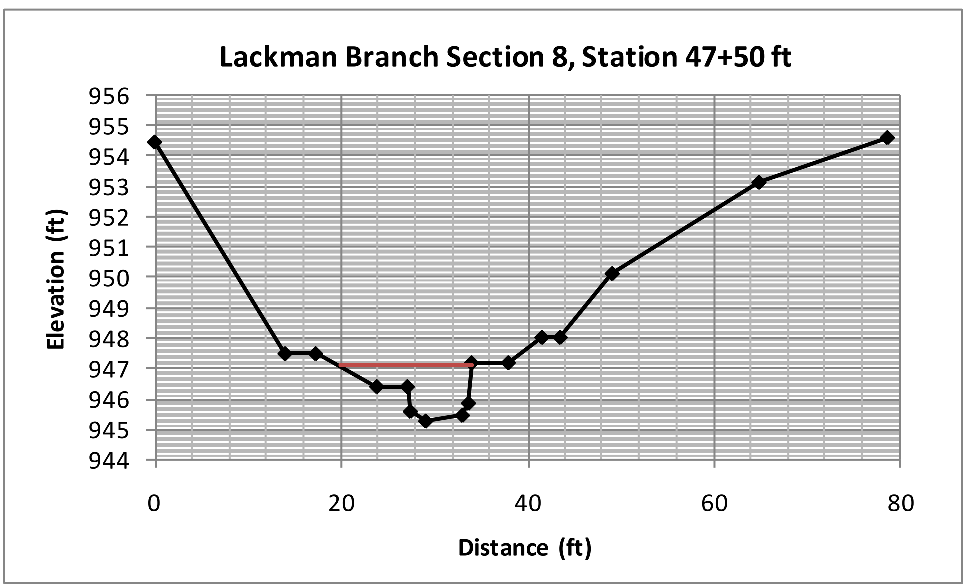

Lackman Branch Section 3, Station 65+30 ft
Elevation (ft)
996
995
994
993
992
991
0
5
10
15
20
25
30
Distance (ft)

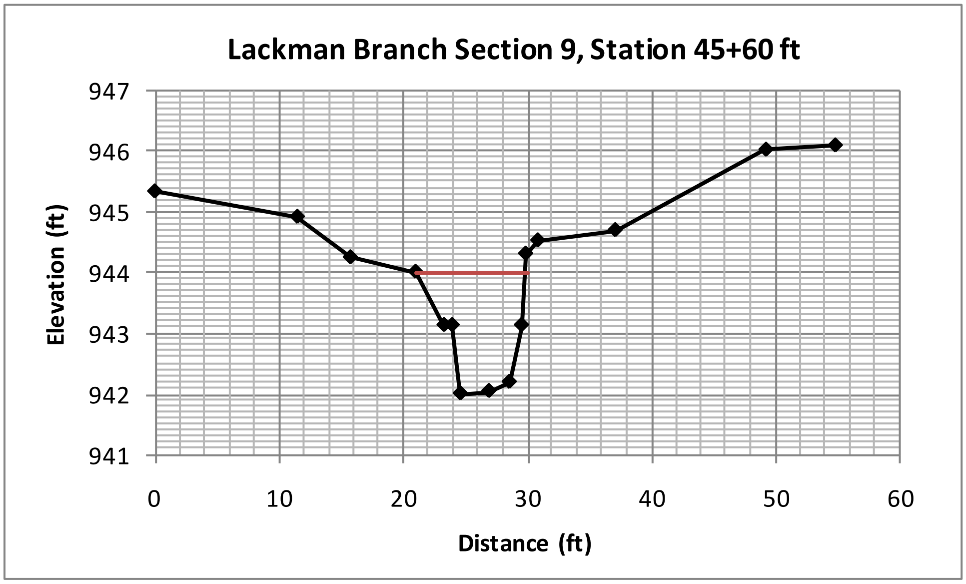

Lackman Branch Section 4, Station 60+20 ft
Elevation (ft)
987
986
985
984
983
982
981
980
979
0
10
20
30
40
50
Distance (ft)


Lackman Branch Section 5, Station 58+35 ft
978
977
976
975
974
973
Elevation (ft)
0
5
10
15
20
25
30
Distance (ft)

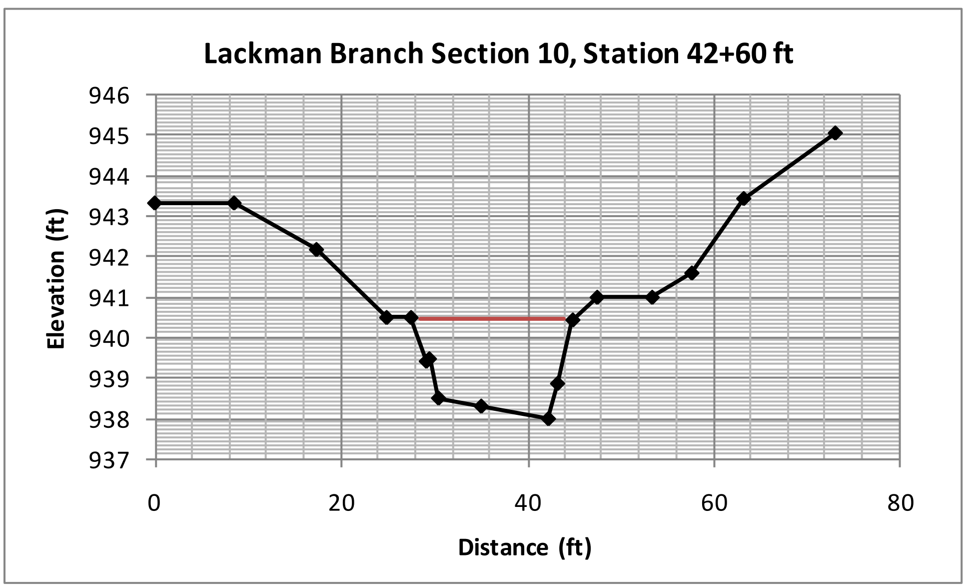

Lackman Branch Section 6, Station 56+40 ft
974
973
972
971
970
969
968
967
966
Elevation (ft)
0
10
20
30
40
50
60
70
Distance (ft)


Lackman Branch Section 7, Station 52+75 ft
963
962
961
960
959
958
957
0
10
20
30
40
Elevation (ft)
Distance (ft)

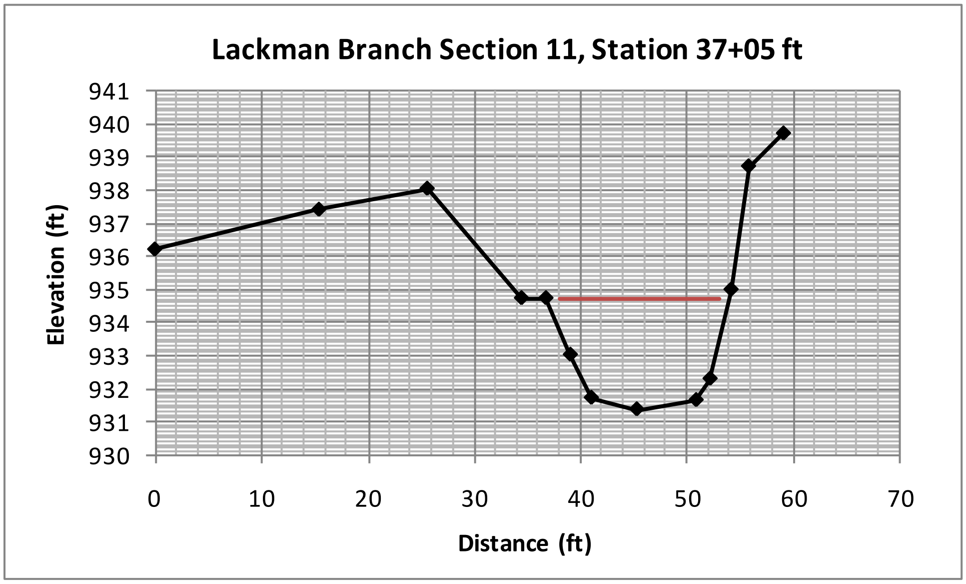

Lackman Branch Section 8, Station 47+50 ft
956
955
954
953
952
951
950
949
948
947
946
945
944
0
20
40
60
80
Elevation (ft)
Distance (ft)

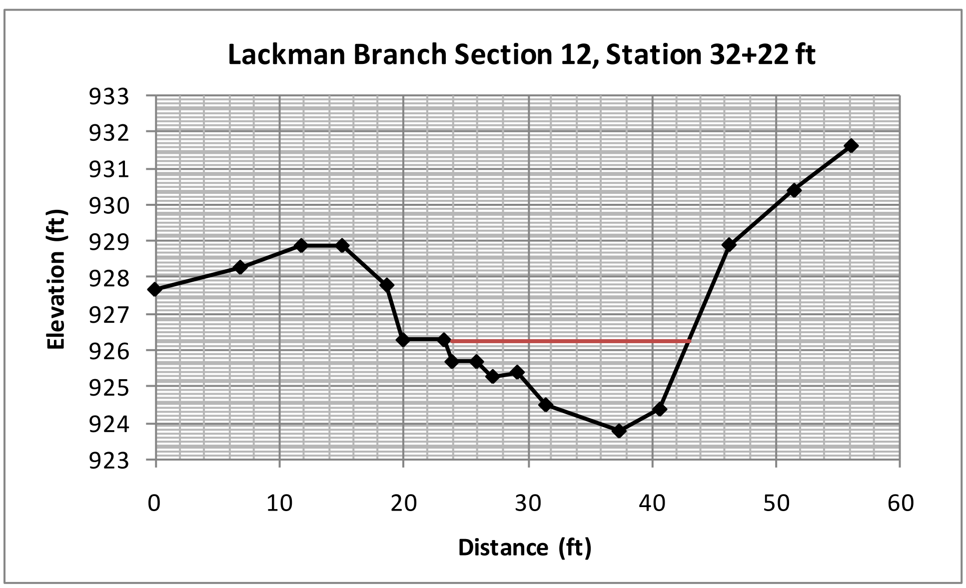


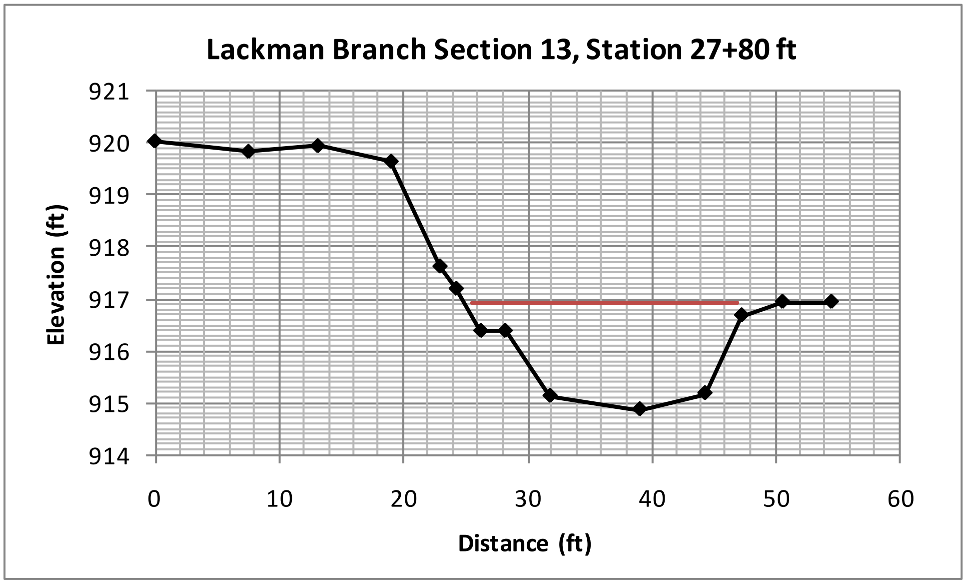
Lackman Branch Section 9, Station 45+60 ft
Elevation (ft)
947
946
945
944
943
942
941
0
10
20
30
40
50
60
Distance (ft)

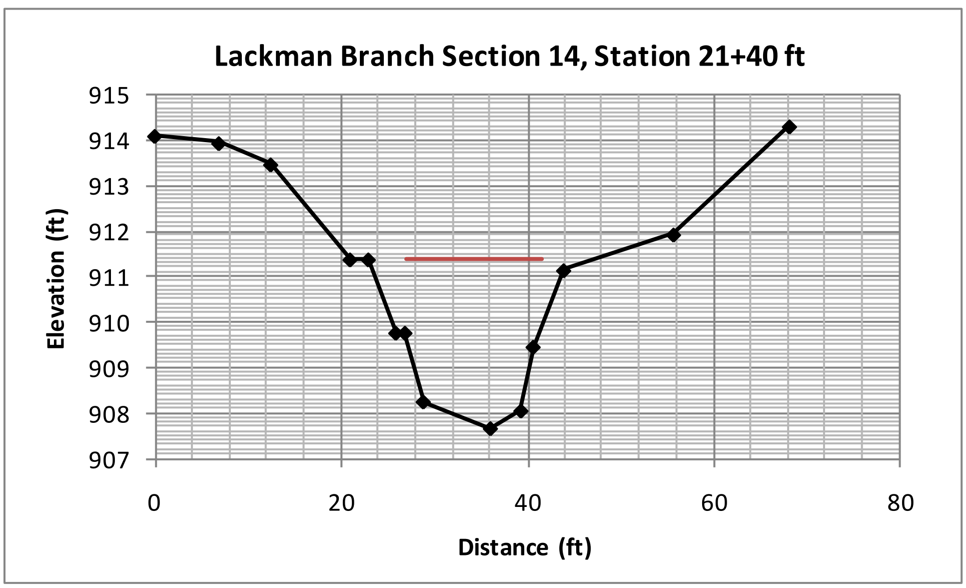


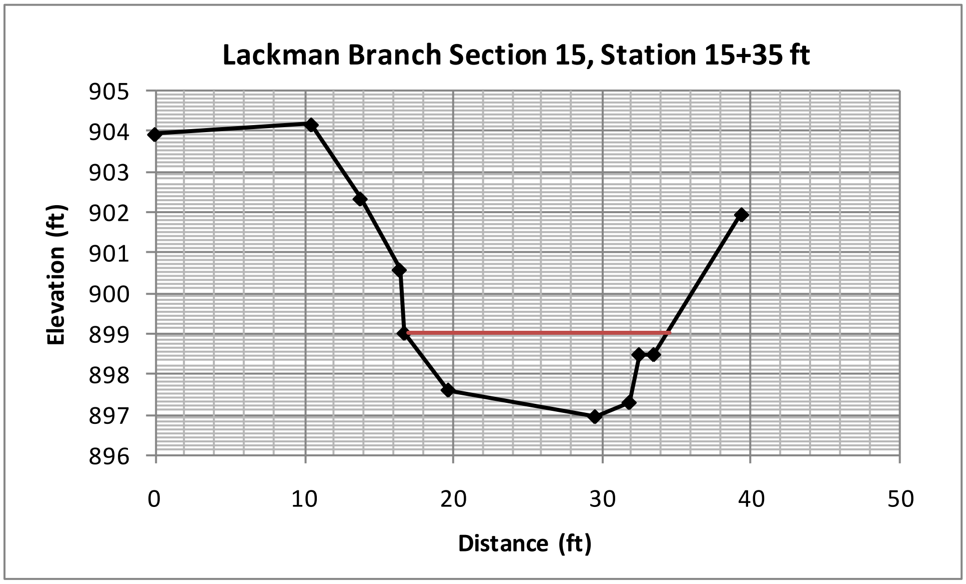
Lackman Branch Section 10, Station 42+60 ft
Elevation (ft)
946
945
944
943
942
941
940
939
938
937
0
20
40
60
80
Distance (ft)

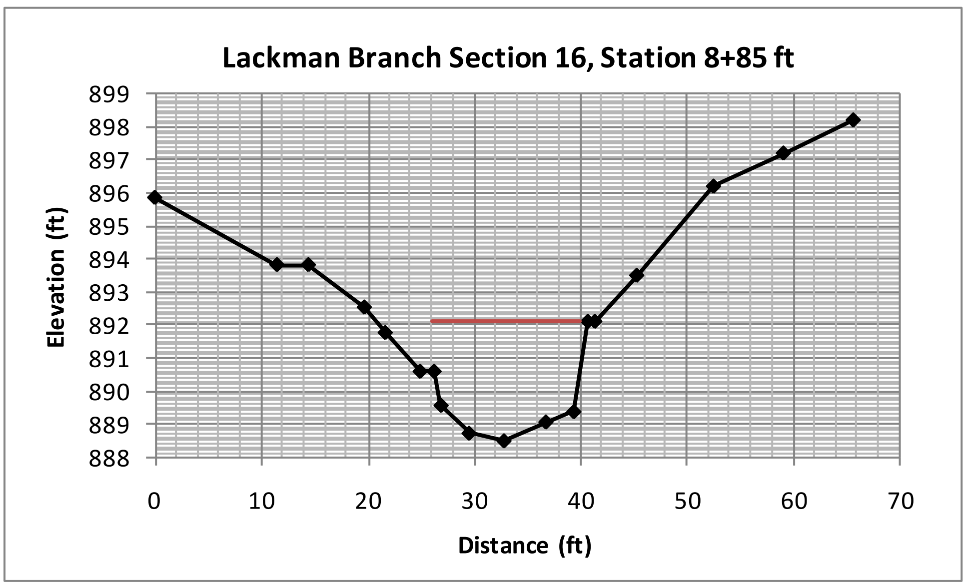

Lackman Branch Section 11, Station 37+05 ft
Elevation (ft)
941
940
939
938
937
936
935
934
933
932
931
930
0
10
20
30
40
50
60
70
Distance (ft)

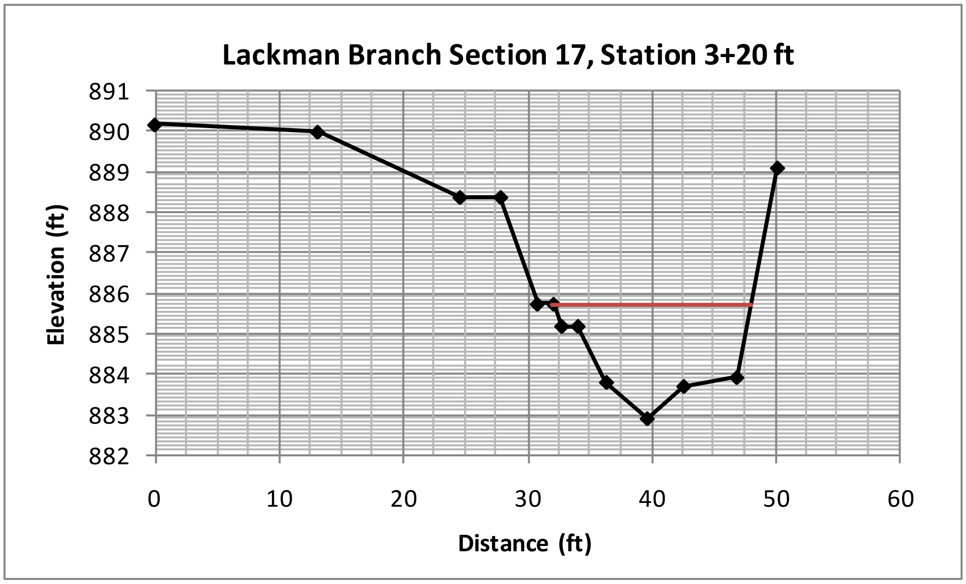

Lackman Branch Section 12, Station 32+22 ft
Elevation (ft)
933
932
931
930
929
928
927
926
925
924
923
0
10
20
30
40
50
60
Distance (ft)


Lackman Branch Section 13, Station 27+80 ft
921
920
919
918
917
916
915
914
Elevation (ft)
0
10
20
30
40
50
60
Distance (ft)


Lackman Branch Section 14, Station 21+40 ft
915
914
913
912
911
910
909
908
907
Elevation (ft)
0
20
40
60
80
Distance (ft)


Lackman Branch Section 15, Station 15+35 ft
905
904
903
902
901
900
899
898
897
896
Elevation (ft)
0
10
20
30
40
50
Distance (ft)


Lackman Branch Section 16, Station 8+85 ft
899
898
897
896
895
894
893
892
891
890
889
888
Elevation (ft)
0
10
20
30
40
50
60
70
Distance (ft)


Lackman Branch Section 17, Station 3+20 ft
891
890
889
888
887
886
885
884
883
882
Elevation (ft)
0
10
20
30
40
50
60
Distance (ft)