FluvialGeomorph: Geomorphic Watershed Assessments

Christopher P. Haring, Research Physical Scientist, ERDC-River Engineering Branch, Vicksburg, MS, Christopher.P.Haring@usace.army.mil
Autumn S. Murray, Research Physical Scientist, ERDC-River Engineering Branch, Vicksburg, MS, Autumn.S.Murray@@usace.army.mil
Michael P. Dougherty, Geographer, USACE-Rock Island District, M*ichael.P.Dougherty@usace.army.mil*
Thomas A. Darby, Geographer, USACE-Rock Island District, Thomas.A.Darby@*usace.army.mil*
Alexi K. Karon, Geographer, USACE-Rock Island District, Alexi.K.Karon@*usace.army.mil*

Abstract

United States Army Corps of Engineers (USACE) planning and engineering studies require a rapid watershed assessment approach to meet current guidance and study initiatives. The FluvialGeomorph (FG) toolkit was developed to provide a rapid watershed assessment approach to identify stream channel bed and bank instability. The approach uses existing or recently acquired Light Imaging Detection and Ranging (LiDAR), other high-resolution terrain data or existing geomorphic field surveys to identify, locate, and map channel instability. The approach is used for single reach analysis that is combined into watershed level assessments. This paper summarizes the FG approach and provides case study example of the Level I analysis

Introduction

In 2004, Alan Gulso with the Illinois Department of Agriculture as part of the Streambank Stabilization and Restoration Program, reported that streambank erosion generated between 30% to 55% of the suspended sediment loads in Illinois streams (personal communication 2004). Similar numbers were reported by Schilling et al. (2011) for the Walnut Creek Watershed in south-central Iowa with 30% to 64% of the annual sediment load contributed from eroding streambanks. The Delta Headwaters Program (DHP) used the addition of grade-control structures to stabilize stream bed and banks and quantitatively reduce sediment delivery downstream by an average of 62% (Biedenharn and Watson 2011). Based on research of sediment contributions from stream bed and bank erosion, methods for locating, identifying, and treating these critical sediment supply sites are imperative for system-wide watershed stabilization. To assist with identifying erosion related sediment delivery and channel instability, a geomorphic assessment approach using terrain data was developed and tested to assist with identification of critical erosion sites.

FG is a geographic information system-based geomorphic analysis toolkit that assesses high-resolution terrain data to provide river-reach assessments for watershed studies. This report demonstrates the utility of FG to identify physical stream channel characteristics that are used to determine channel stability. FG is a remote-sensing approach based on light detection and ranging (lidar) data, designed to measure channel, floodplain, valley, and watershed metrics necessary for geomorphic assessments. Currently, channel slope and cross-sectional analysis and planform metrics are being evaluated with existing lidar data from different hydrophysiographic regions within the United States. Recent study areas include the Northwest, Southwest, South, Midwest, and upper Midwest of the United States.

Background

The FG toolkit is being developed through the USACE's Flood and Coastal Systems (FCS) Program to provide a rapid approach to detect riverine erosion and sedimentation and identify source locations within the of watershed. The rapid assessment approach was developed to quantify the benefits of streambank stabilization in Illinois River tributaries to protect mainstem floodplain habitats impacted by excessive sedimentation. The FG toolkit measures channel morphological features using lidar high-resolution digital elevation models (DEMs). The channel features include water-surface profile (channel bottom in ephemeral or in low-flow conditions), dimension (cross section), and pattern. The water-surface profile is used to identify nick points or areas along the profile that show extreme change in channel slopes. The cross sections are used to determine local channel and bank erosion and changes in channel location. Cross-section analysis is further expanded to include channel dimensions based on bankfull channel forming flow identification. The bankfull identification allows for the comparison of empirically derived relationships to be compared to actual lidar DEM-derived channel dimensions at each cross-section location. Channel stability assessments can then be compared to empirical data to determine channel stability. Channel stability values can then be mapped spatially based on each metric. In addition, channel pattern is derived from the channel-terrain data to assess stable planform conditions. Individual reach analysis is then combined and integrated to provide a comprehensive channel stability assessment to support watershed planning efforts. Haring et al. (2020) describes the background needs and requirements for US Army Corps of Engineers (USACE) watershed studies.

Technical Approach

The technical approach in the development of FG was focused on providing a platform to rapidly assess geomorphic and watershed data (Haring et al. 2020). With that focus, FG was developed as an Open-Source R package-based Geographic Information System (GIS) toolbox to assist in in watershed planning and assessments. Watershed studies provide a comprehensive approach to identifying and treating areas of concern. Such studies typically involve flood-risk management issues, critical habitat protection or enhancement opportunities, water-quality issues, excessive sediment delivery from erosion of streambanks, gullies and concentrated overland flow areas, land-use change, and protection for critical public infrastructure. The FG toolkit provides a five-step approach to investigate watersheds (Figure 1). The five steps include defining the purpose of the study, determining the extent of the study area, researching, and collecting available data, completing a rapid geomorphic assessment, and defining further studies as required.

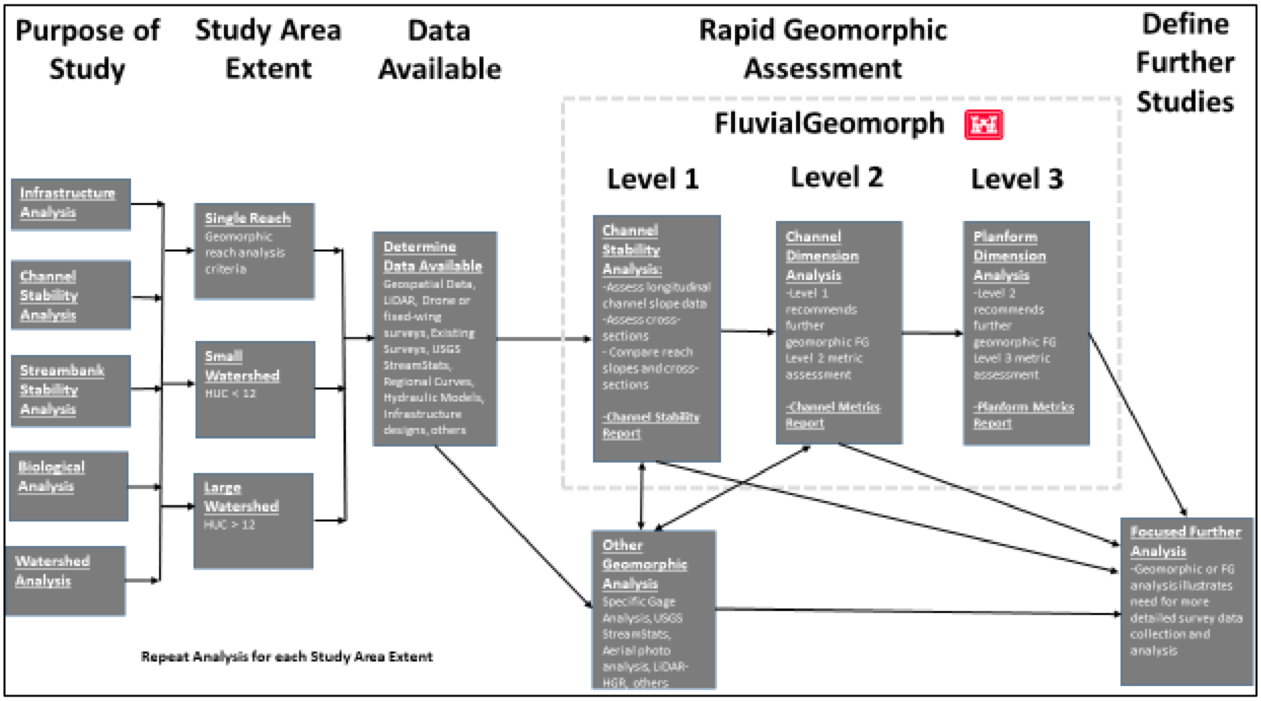

Figure 1. FluvialGeomorph (FG) rapid geomorphic assessment approach.

FG Level I: Channel Stability Analysis (CSA)

CSA analyzes the longitudinal water-surface slope profiles and cross sections. The CSA workflow is illustrated in Figure 2. Such an analysis provides a reconnaissance level of detail to identify potential areas of instability based on simple slope and cross-sectional area comparative analysis. The CSA provides a basis for identifying potential areas of interest where channel degradation, aggradation, or widespread channel changes are observed to determine if more detailed study is required. It is recommended that CSA should be completed prior to field site visits to allow for the focus on areas of concern based on existing information (Figure 3).

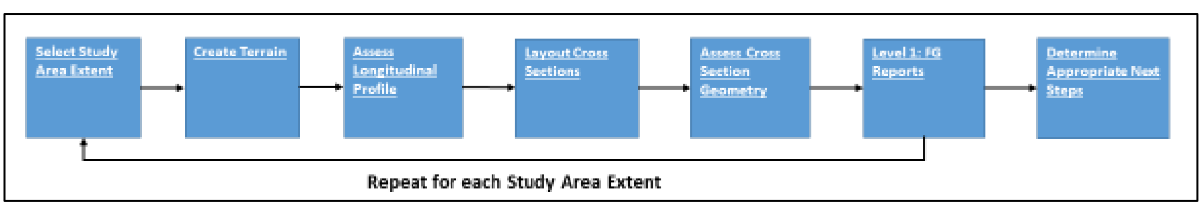

Figure 2. FG Level 1: channel stability analysis.

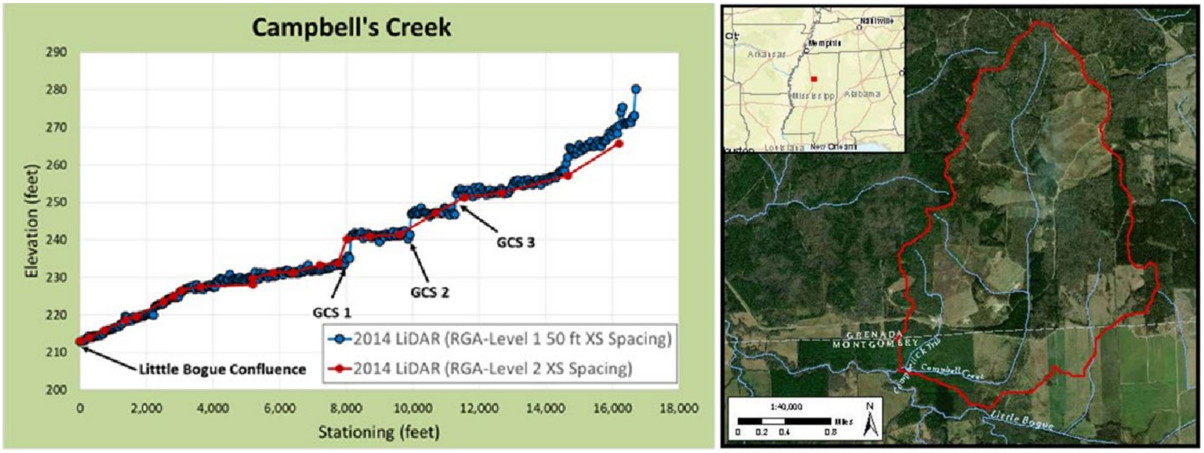

Figure 3. FG Level I-CSA analysis on Campbells Creek Watershed-Northern Mississippi (Haring and Biedenharn 2021). Left channel profile plot illustrates plotting resolution differences and the ability to locate existing grade control structures. Right map illustrates Campbell Creek Watershed location.

FG Level II-Channel Dimension Analysis (CDA)

CDA analyzes bankfull channel conditions based on lidar-derived DEMs to compare against empirically based data to assess channel stability (Figure 4). The final products of the CDA are reach-level reports that plot and map the metrics at a stream channel reach scale. The metrics are compared based on standard existing or user-defined

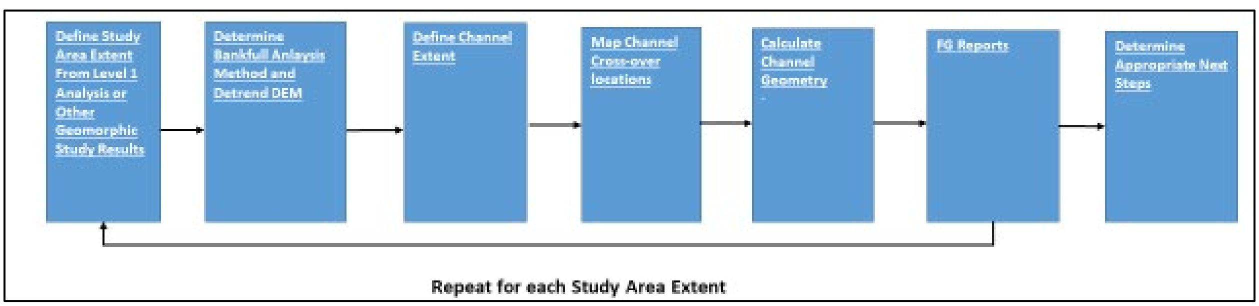

Figure 4. FG Level 2: Channel Dimension Analysis (CDA) workflow.

thresholds. An example bankfull elevation cross section is illustrated in Figure 5. Detrending of the terrain data is used to project the bankfull elevations through a reach and develop geomorphic metrics based on this parameter. This method is appropriate for identifying geomorphic channel indicators, berms, sediment bars, floodplain connections, terraces, and deriving width-to-depth ratios, channel entrenchment, stream power, shear stress, bankfull slopes and others. The metrics can then be mapped by color-coded signals (Figure 6).

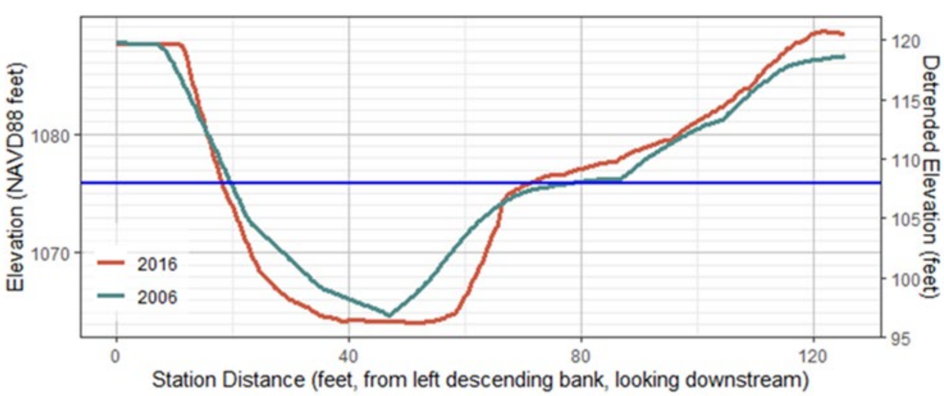

Figure 5. FG Level 2: CDA, example cross section illustrating bankfull identification

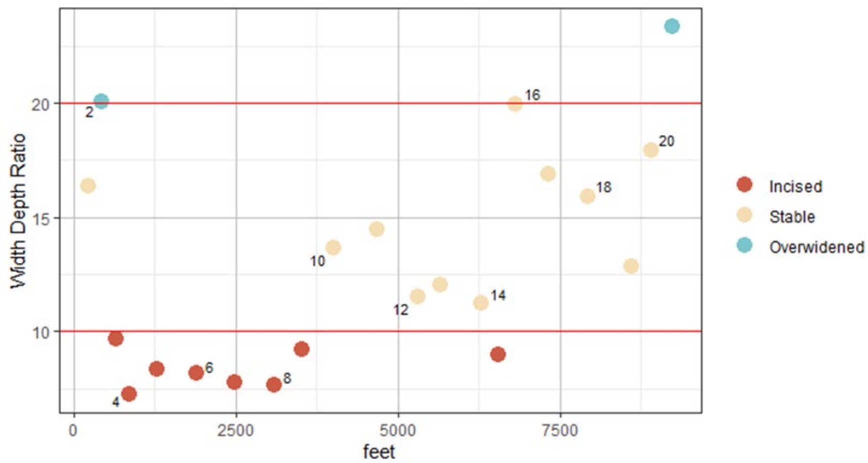

Figure 6. FG Level 2: CDA, example reach level determination of width-to-depth ratios. Incised threshold metrics set at <10, Stable 10 to 20 and Over-widened >20.

FG Level III-Planform Dimension Analysis (PDA).

PDA analyzes planform dimensions measured from the lidar-derived DEM to compare against empirically based data to further assess channel stability (Figure 7). The final products of the PDA are reach-level reports that plot and map the metrics at a stream channel reach scale. The metrics are compared based on standard existing or user-defined thresholds. The metrics are mapped by color-coded signals.

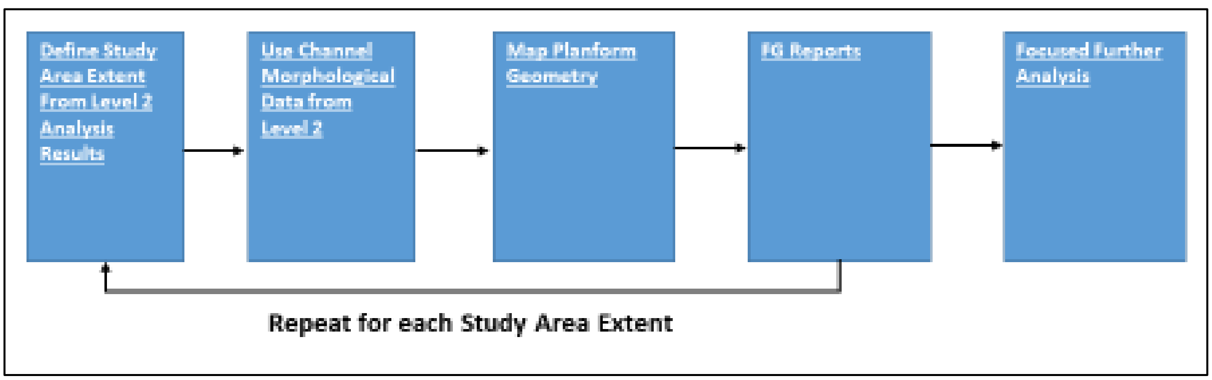

Figure 7. FG Level 3: Planform Dimension Analysis (PDA).

Depending on the level of detail needed for a particluar study, all three Levels of analysis are important for providing geomorphic assessments. The next section will provide an example of the FG Level I-CSA approach used for a watershed study on the Papillion Creek watershed in Omaha, Nebraska.

FG Level I-CSA
Case Study-West Papillion Creek, Omaha, NE

West Papillion Creek is a watershed (~133 square miles) within the overall Papillion Creek watershed located west of Omaha, NE. It generally flows from the northwest to the southeast (Figure 8) and merges with Big Papillion Creek (~232 square miles) approximately 900 ft downstream of South 36th Street Bridge to form Papillion Creek. The reaches in this study area are largely developed residential and industrial with some small pockets of agricultural land. The upstream end of the study is the South 132nd Street Bridge. The watershed upstream of Reach 5 is an additional 59 square miles and not part of this analysis.

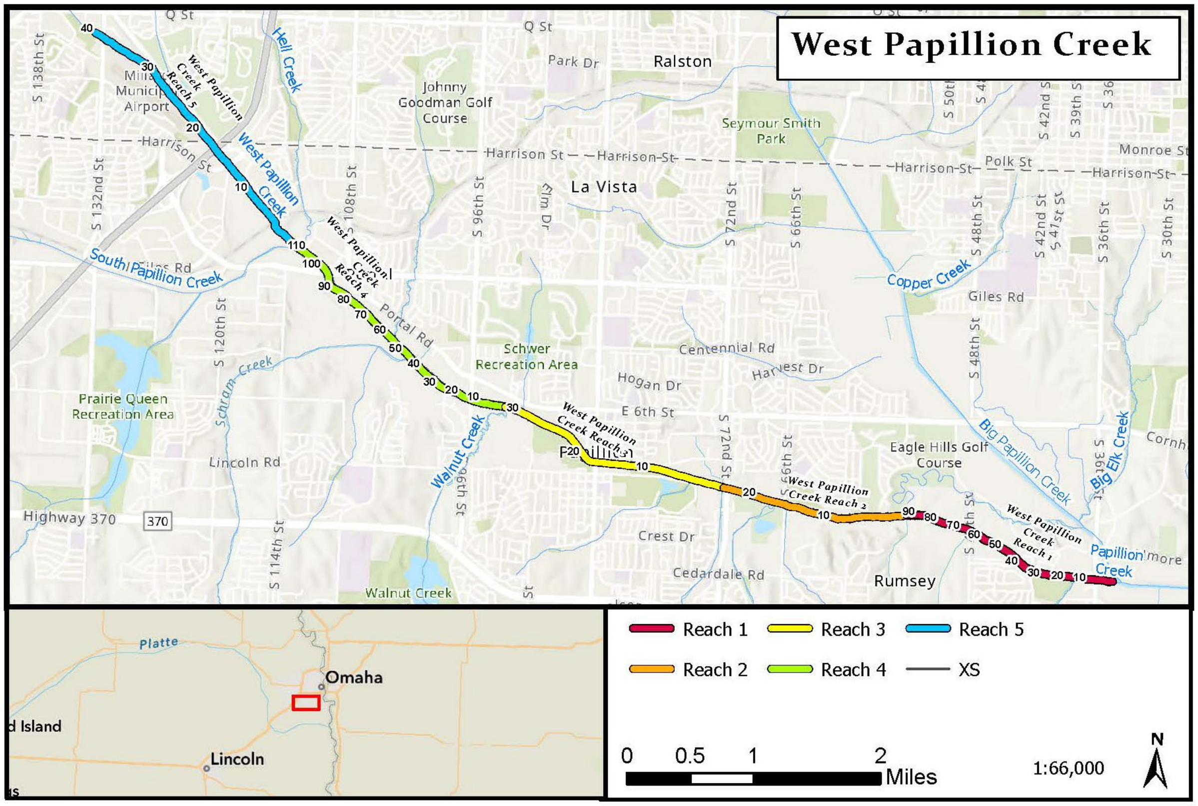

Figure 8. West Papillion Creek FG Level I Geomorphic Reaches (1-5).

FG Study Reaches and General Assessment

There are many sections of the creek that have some form of stabilization revetment, whether it is riprap or other materials present in the channel bed or banks. From field site visits, in most cases the presence of these materials is providing bed or bank stability. It is not known whether these structures and revetments were designed, or materials were placed in stream to protect utility crossings. In many locations, material has launched and formed Grade Control Structures (GCS) stabilizing the channel bed and banks in these locations. In some locations the lower Reaches (1-3), the original levee system design cut benches within the channel margins to provide flood flow relief. In other locations these benches or berms formed from sloughing or eroding banks restabilizing due to the presence of bed and bank revetments and reduced velocities (Figure 9). Compared to an incised channel (high banks with no floodplain), the berms provide access to the frequent flood events dissipating flow energy across a wider cross-sectional area. This is a common feature in the urbanized Papillion Creek watersheds visited during the field site visits.

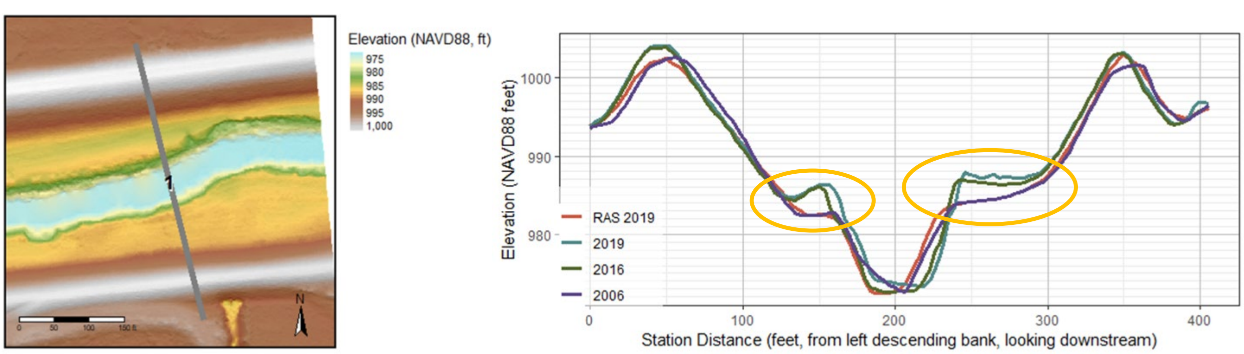

Figure 9. Floodplain Berms (orange circles) Developing Upstream of GCSs on West Papillion Creek.

The next section provides the channel reach profiles and individual Reach information developed for this study. The FG study reaches are defined in Figure 10 with individual FG Reach profile plots (2006/2016 LiDAR and HEC-RAS 2019 Thalweg Profiles) in each section. Some of these locations were field verified but others were not due to time restrictions on fieldwork. Each reach has bulleted descriptions based on geomorphic information collected from the field site visits and FG Level I analysis. The 6-stage Channel Evolution Model (Simon and Hupp, 1986) was used to provide geomorphic interpretation of channel stabilization trends.

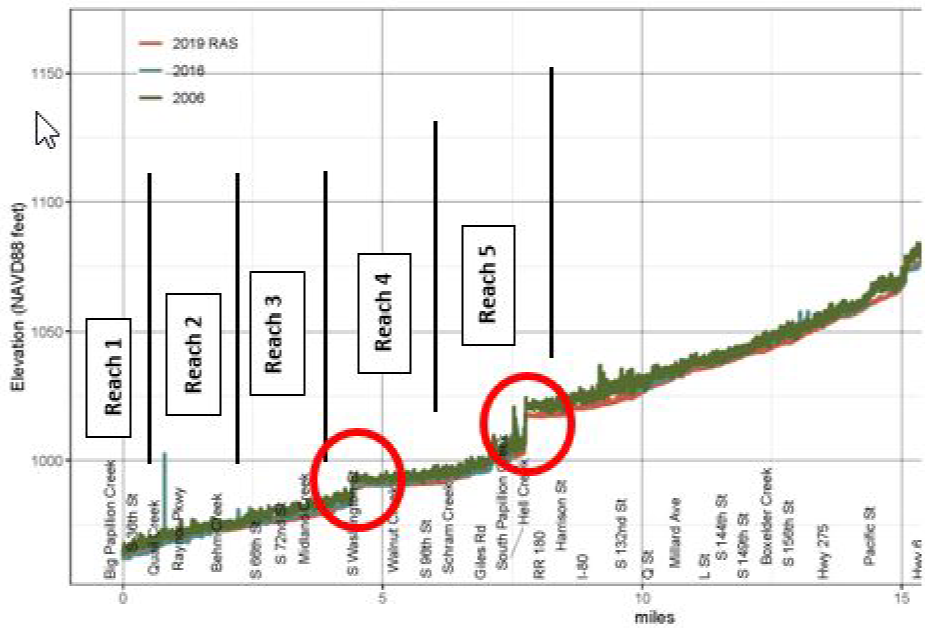

Figure 10. West Papillion Creek FG LiDAR Water Surface Profiles 2019 HEC-RAS Thalweg Profile. GCS locations are labeled in Reach 1-5 Figures (4-8).

Reach 1: Confluence of Big Papillion Creek to Behm Creek

Reach 1 starts at the confluence with Big Papillion Creek and is a highly modified with levees (confining the river floodplain), greenspace and recreational trails that separate the agricultural and residential activity from the stream channel (Figure 11). Based on aerial photo investigations, the agricultural areas are developing and will soon be replaced by residential development. The list below describes the assessment for the reach.

- Downstream of Raynor Parkway Bridge, the channel appears to show a trend of degradation. Much of the reach has bank revetments with a meandering pattern starting to form within the incised channel. Early stages of floodplain development are occurring with berms forming where bank slumps have stabilized. Bank failure and continued channel incision will likely continue with increased development in the upstream reaches increasing flows confined within the leveed floodplains.
- Upstream of Raynor Parkway bridge the channel is in a Type IV stage of the CEM where local bank stabilization measures limit the channel from evolving into a Type V-VI channel. Cluer and Thorne (2013) labeled this type of reach in a stage of “arrested degradation,” meaning the channel boundary conditions are stable enough to stabilize the reach at least temporarily. The revetments are providing this “arrested degradation” phase. Therefore, the channel will begin to 1) widen in locations where there is no bank protection and 2) potentially undermine current protection.

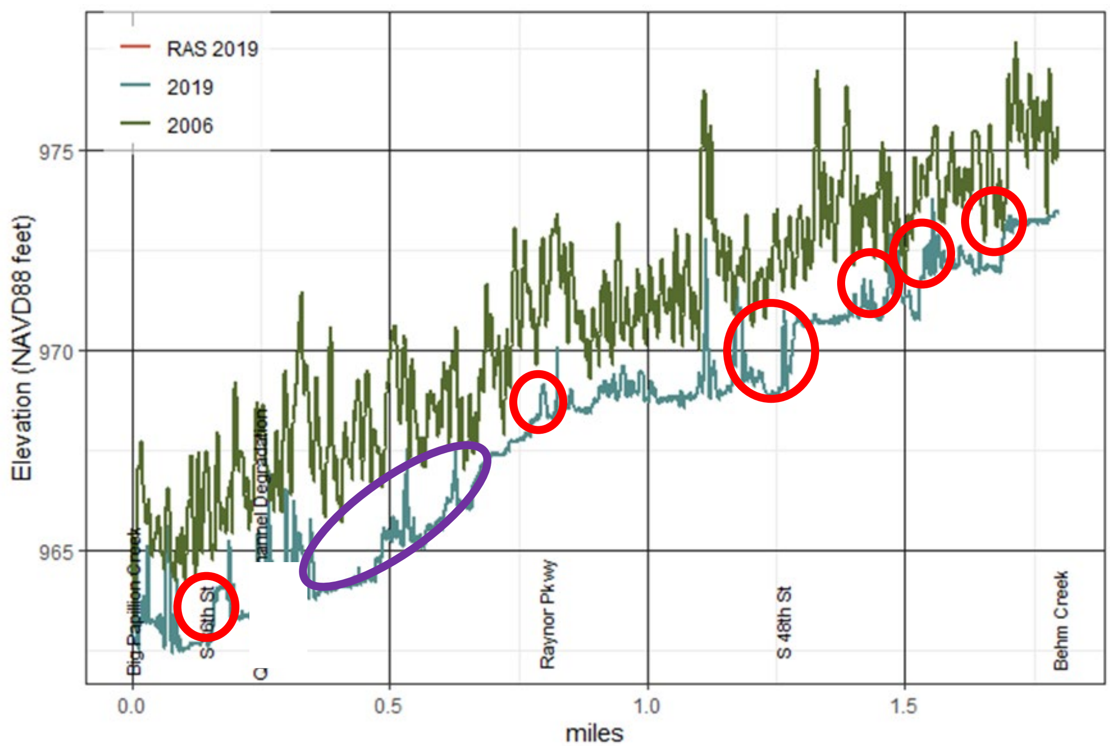

Figure 11. West Papillion Creek FG Reach 1. GCSs (red circles) or erosion resistant bed materials (purple oval) present.

- There are many locations within Reach 1 that would have access to an active floodplain if levees could be setback to provide more room for flood flows. This is still possible in areas where agriculture is present.
- Establishment of floodplain access areas to dissipate and store floodwater would be a great alternative to establish where applicable to the upstream reaches.

Reach 2 Behm Creek to Midland Creek

Reach 2 is a highly modified reach like Reach 1 with less agricultural areas. Levees are present with limited width floodplain/greenspace and recreational trails that limit floodplain access (Figure 12). The list below describes the FG and field assessment for the reach.

- Based on the LiDAR trends and comparing them to the RAS 2019 thalweg elevations, there appears to be channel degradation that has occurred in this reach especially at the South 66th Street Bridge (~Station 2.75 miles).
- GCSs are spaced out relatively evenly throughout (Figure 12). The structures are likely reworked revetment material or placed to protect utility crossings.

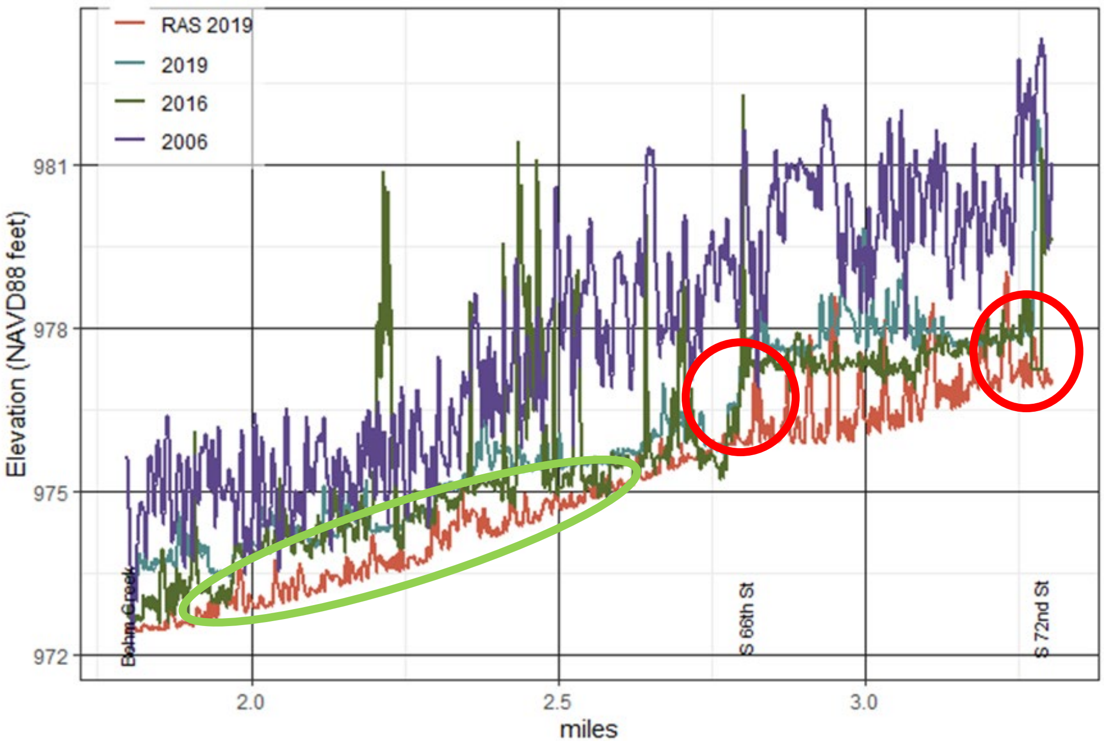

Figure 12. West Papillion Creek FG Reach 2. GCSs (red circles) or erosion resistant bed materials present, and GCS with continuous bank revetment in green.

- The reach 2 is in a CEM Stage IV displaying limited channel degradation and widening like reach 1.
- Based on the FG cross-sectional analysis, floodplain berms are building within the confined (by levees) floodplain. This reach is predominantly a sediment sink with new floodplain berms building with some areas of bank erosion through the bank revetments providing minor sediment sources for downstream reaches.
- The reach could be enhanced for flood water storage by increasing floodplain connection and access through series of levee setbacks. There are still some areas of agriculture that could be targeted. If sediment delivery to downstream reaches is a priority, then installation of additional bank erosion revetments is recommended.

Reach 3 Midland Creek to Walnut Creek

Reach 3 has greenspace with more encroachment on the floodplain and no adjacent agricultural land-use. Overall, the reach is trending degradational with local widening in areas without bank protection, primarily a type IV-V stage channel. The South Washington Street Bridge is serving as a GCS with ~6 ft of drop, creating a relatively deep incised channel downstream (Figure 13). The list below describes the FG and field assessment for the reach.

- Based on the FG-derived channel surface slope, Reach 3 appears to be over-steepened below South Washington Street. The reach is likely in CEM Stage III-IV and is having a difficult time eroding the bank revetments.
- Reach 3, like previous reaches, has extensive rock-line banks to keep the channel from meandering. Although by keeping the channel from meandering by hardening banks the channel can only adjust in the vertical direction – causing incision. Bank stabilization measures are forcing the channel to stay somewhat locked in place (Cluer & Thorne 2013).
- Continued channel degradation could cause failure of the concrete dam at South Washington Street and other bank stabilization projects if the over-steepened reach continues to incise. Based on the field site investigation, the dam appears to be in working order with no outward signs of erosion issues at the time of this assessment.

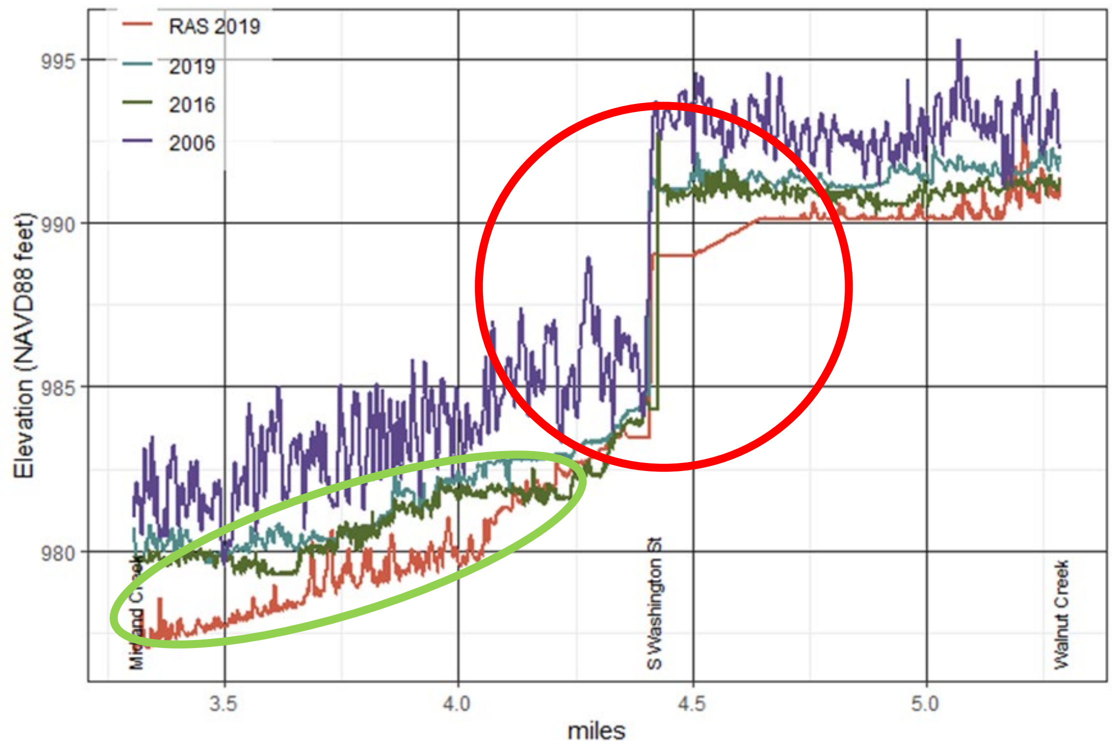

Figure 13. West Papillion Creek FG Reach 3. GCSs (red circles) or erosion resistant bed materials present, and GCS with continuous bank revetment in green.

- Based on the FG cross-section analysis, there is bank erosion in many sections of the reach. Additional bank protection revetments and developing a better understanding of the channel bed stability would be recommended. This reach would be considered a sediment source and areas with little or no erosion a sediment pathway.
- There are minimal locations available within the reach to expand access to floodplain areas behind the existing levees.

Reach 4 Walnut Creek to South Papillion Creek

Reach 4 has a highly confined channel and small floodplain between levees, with greenspace and pedestrian trails. The list below describes the FG and field assessment for the reach.

- GCSs are present at bridge locations and other locations within the reach likely from revetment launching revetment materials (Figure 14).

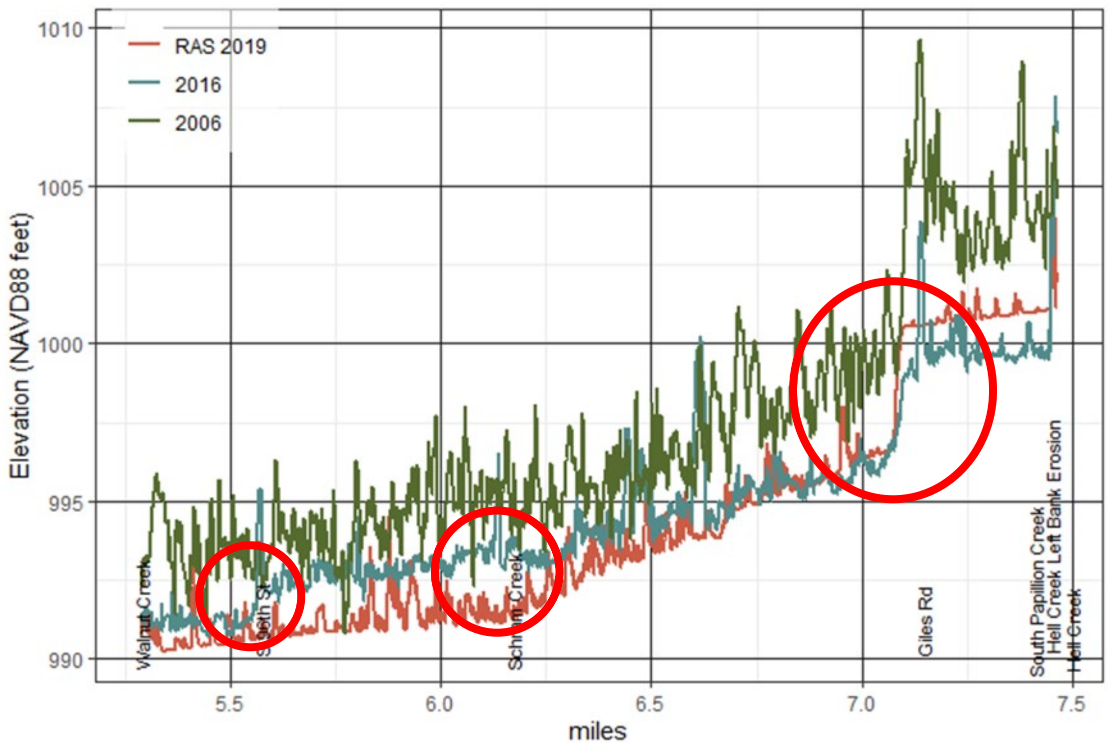

Figure 14. West Papillion Creek FG Reach 4. GCSs (red circles) or erosion resistant bed materials present.

- Based on the LiDAR channel slopes, Reach 4 appears to be in a CEM Stage V. The stream bed is stable and there is local bank erosion. New floodplain berms have developed in much of the reach showing a trend of stabilization.
- There is one GCS in the reach at Giles Road that is providing bed stability to the reach. The water surface elevation drop across the structure is approximately 5 ft in height and should be monitored for maintaining the channel slope.
- If there are any concerns for fish passage within the South Papillion Creek watershed, large GCS like this should be modified to allow reasonable channel slope transitions through these elevation drops.
- Reach 4, like Reach 3, has extensive rock-line banks to keep the channel from meandering. Although by keeping the channel from meandering and hardening banks, the channel can only adjust in the vertical direction – causing channel incision.
- There are locations behind the existing levees on the right terrace/floodplain available within the reach to expand access to floodplain areas behind the existing levees. If possible opening and reconnecting floodplain areas would provide flood flow storage.

Reach 5 South Papillion Creek to S 132nd St

Reach 5 is similar Reach 4 in floodplain development and urbanization but has more bank erosion throughout as there is less bank revetment protection. The areas downstream of the Railroad 180 GCS and upstream of Interstate 80 have the highest erosion rates. The Railroad 180 GCS has stabilized the reach immediately upstream for approximately ¾ of a mile with its backwater effects and floodplain berm connections. There are minimal levees in this reach and recreational trail access is only on the right bank. The list below describes the reach conditions and observations based on FG and field site visits.

- GCSs are present throughout with the largest at the Railroad 180 Bridge (Figure 15).

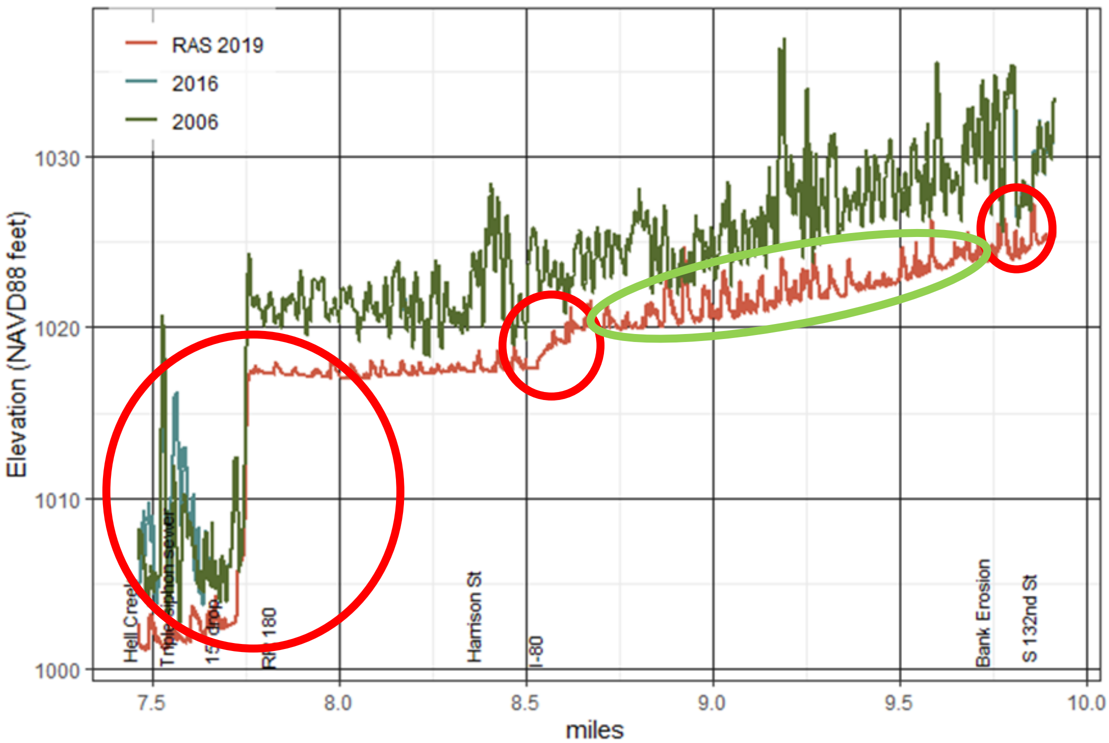

Figure 15. West Papillion Creek FG Reach 5. GCSs (red circles) or erosion resistant bed materials present, and GCS with continuous bank revetment in green**.**

- There are additional GCSs or other resistant bed materials located within the reach based on the Figure 8 profiles and aerial photo interpretation.
- The reach has a substantial amount of bank sloughing and erosion. Some of the erosion is threatening pipe outlets, pedestrian trail. Upstream of GCS locations the channel is in a CEM V-VI.
- Based on the FG analysis, this reach would be considered partially a sediment source and pathway.
- There are some locations on the right channel margins to expand access to floodplain. The locations are on the right terrace/floodplain upstream of the confluence with South Papillion Creek (lower reach) and upstream downstream of the S 132 Street Bridge.

Conclusion

This section is meant to provide the overarching recommendations for priorities based on the FG Level I analysis and assessment of the West Papillion Creek watershed. Based on the FG Level I CSA analysis the study recommendations are listed below (not in order of relevance).

Priority #1: Use existing GCS locations to continue to stabilize the channel. The structures whether designed or not are the basis for existing channel stability in the system.

Priority #2: Assess existing structures and other areas within the reaches that are providing channel and bank stability. This is especially important for the structures in Reach 2 (South Washington Street Dam) and Reach 5 (Railroad 180 GCS). If these structures are compromised rapid channel degradation (widening and deepening) will occur.

Priority #3: A comprehensive mapping system should be developed (if not already completed) to determine utility locations and crossing associated with the West Papillion Creek corridor. This can then be compared to constructed bank revetments, GCS locations (and those acting as GCs), bridges, resistive bed materials and other natural channel characteristics are providing stability to the reaches.

Priority #4: Where possible, increased floodplain connections should be re-established. There is limited space for these actions within Reaches 1-5, so targeting those areas to prevent land development should be considered further. Restoration options could include additional GCS construction to re-establish floodplain berms, levee setbacks or cut floodplain berms into the existing bank lines or a combination of all these options. If any work is completed, hydraulic analysis will need to be completed to assess potential impacts to flood flow and increasing flood stages.

Priority #5: Investigate more reaches upstream of Reach 5. Target upland areas for water and sediment retention structures where applicable in reaches upstream of Reach 5.

Priority #6: It is recommended to complete additional geomorphic analysis including FG level II and III assessments along with additional field site assessments. Additional Papillion Creek watershed analysis is also needed to better define a systems approach to stabilizing the watershed effectively through targeted restoration approaches. This is especially important with the rate of urbanization with the greater Omaha, Nebraska area.

In summary, the FG approach provides a relatively quick, thorough, geomorphic-based, watershed-wide assessment capability that has not been provided elsewhere to the best of our knowledge. Through the USACE FCS program, additional case studies and examples are being completed to provide more details and case study examples of FG Level II and III applications. In addition, more tools are being developed to develop more qualitative metrics, channel incision identification, bank erosion measurement, biological analysis and other analysis tools. Biological analysis may be particularly useful to support USACE habitat evaluations. The integration of the FG metrics with biological data provides a reproducible approach to assess habitat benefit models for nationwide application.

References

Cluer, B., & Thorne, C. 2013. A Stream Evolution Model Integrating Habitat and Ecosystem Benefits. River Research and Applications, DOI: 10.1002/rra.2631

Biedenharn, D. S. and C. C. Watson. 2011. Delta headwaters project: a review. Report to the Vicksburg District, U.S. Army Corps of Engineers

Gulso, A., 2004. Personal Communication-Illinois Department of Agriculture.

Haring, C. H., C. H. Theiling, and M. P., Dougherty. 2020. *Rapid Watershed Assessment Planning Tools Based on High-Resolution Terrain Analysis*. ERDC/CHL CHETN-VII-22. Vicksburg, MS: U.S. Army Engineer Research and Development Center. http://dx.doi.org/10.21079/11681/36714

Haring, C. H., and D. W. Biedenharn. 2021. *Channel Assessment Tools for Rapid Watershed Assessment.* ERDC/CHL CHETN-VII-24. Vicksburg, MS: U.S. Army Engineer Research and Development Center. *http://dx.doi.org/10.21079/11681/40379*

Schilling, K.E., T.M. Isenhart, J.A. Palmer and C.F. Wolter. 2011. Variations in suspended sediment transport with land cover change in two agricultural watersheds. Journal of the American Water Resources Association, DOI: 10.1111/j.1752-1688.2011.00533.

Simon, A.L., and Hupp, C.R., 1986. Channel Evolution in Modified Tennessee Channels, Proceedings of the Fourth Interagency Sedimentation Conference, March 1986, Las Vegas, NV, 2, 5-71 to 5-82.