Hydraulic geometry relationships and the development of bankfull regional curves for Iowa streams

by

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The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this thesis. The Graduate College will ensure this thesis is globally accessible and will not permit alterations after a degree is conferred.

Iowa State University

Ames, Iowa

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DEDICATION

To Allisyn,

For taking the leap and exploring new opportunities in unknown places.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

NOMENCLATURE

AGL	Applied Geomorphology Lab
CV	Coefficient of Variation
HLR	Hydrologic Landscape Region
IDNR	Iowa Department of Natural Resources
IRR	Iowa Rivers Revival
ISU	Iowa State University
NED	National Elevation Dataset
NHD	National Hydrography Dataset
NCLD	National Landcover Dataset
USDA	United States Department of Agriculture
USGS	United States Geological Survey
WBD	Watershed Boundary Dataset

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ABSTRACT

Regional curves relate bankfull stream dimensions to drainage area and are assumed to represent stable alluvial channel form under the prevailing hydrological and sediment regime. Preliminary regional curve data has been collected, but no bankfull regional curve analysis has been presented for Iowa streams. Channel geometry data was collected from 20 gaged and 34 ungaged reaches throughout Iowa. Data collected included channel cross-sectional geometry, longitudinal profile, and streambed material particle size distribution. Additionally, basin characteristics were assembled and analyzed for each reach. Bankfull discharge was then estimated for all gaged and ungaged reaches. Data analysis included two alternative stratification schemes. Channel geometry data was first stratified by non-urban (≤10% total impervious cover) and urban (>10% total impervious cover) cover types for comparison with the combined regional dataset. The dataset was also stratified by flood region to compare three independent regional curves with the combined non-urban dataset. Regional curves were developed by multiple linear regression analysis of log-transformed variables and the relationship between drainage area and cross-sectional area, width, mean depth, and discharge for the bankfull channel. Stratifying by flood region improved the explanatory power of the regional equations for some bankfull parameters. However, flood regions are not significantly different for bankfull cross-sectional area, width, and mean depth, and the justification for stratification was not met. Analysis of non-urban and urban cover types improves the explanatory power of the regional equations for all bankfull parameters compared to the combined regression equations, with differences between slopes and intercepts for non-urban and urban streams. Results justify the dataset's stratification into regional curves for non-urban and urban cover types. Additional analysis provided evidence that regression equations for bankfull cross-sectional area, width, and discharge can be improved

by including percent impervious surface and mean annual precipitation as continuous variables in the urban and non-urban models, respectively.

CHAPTER 1. INTRODUCTION

Stream restoration is an increasingly common technique used by local, state, federal, and private landowners and organizations to stabilize and improve the biological integrity of impaired channels. This process generally includes restoring a channel's geomorphic pattern and shape to be in dynamic equilibrium where it neither aggrades nor degrades. Dynamic equilibrium can be achieved when the sediment supply and sediment transport capacity is balanced (Lane, 1955). The relationship between these variables was developed by Lane (1995) and follows the general form:

$$Q_s \cdot D_{50} \propto Q_w \cdot S \qquad \text{(Equation 1)}$$

Where Q_s is the sediment discharge, D_{50} is the sediment particle size, Q_w is the stream flow, and S is the channel slope. Equation 1 is a proportionality equation between the four independent variables where the change in one variable requires an increase or decrease in the others to maintain equilibrium. Assuming dynamic equilibrium, a healthy and functioning stream should exhibit geomorphic stability while providing habitat for fish, waterfowl, and other aquatic organisms. Restoration methods based on natural-channel design utilize channel classification techniques and dimensionless ratios describing the geometry of stable streams as reference conditions for restoration plans (Rosgen, 1994). These methods use bankfull channel geometry (cross-sectional area, width, and mean depth) and bankfull discharge as the foundations of channel design to properly construct instream features and hydraulic gradients, and establish riparian vegetation.

Channel-Forming Discharge

Natural-channel design hinges on the concept of channel-forming discharge, which has been defined in numerous ways by different researchers. Copeland et al. (2000) defined channel-forming discharge as a "theoretical discharge that if maintained indefinitely would produce the same channel geometry as the natural long-term hydrograph" and can be estimated by one of three methodologies.

Bankfull discharge is one method to estimate channel-forming flows, which relies on identifying bankfull stage and the corresponding discharge associated with that stage. The most common definition of bankfull used in identifying the bankfull stage is the elevation of the active floodplain (Wolman & Leopold, 1957). Others have identified bankfull stage as the elevation at which the width-depth ratio is minimized (Wolman, 1955), the height of the lower limit of perennial vegetation (Schumm, 1960), and the middle bench in rivers with several overflow surfaces (Woodyer, 1968). Identifying bankfull stage in the field is often difficult and varies among streams (Juracek & Fitzpatrick, 2003; Williams, 1978). Due to the inherent heterogeneity among streams, bankfull stage is often difficult to recognize and may be misidentified. Identification of the bankfull stage has become a source of concern amongst practitioners and scientists due to its important role in hydraulic geometry development (Leopold & Maddock, 1953) and natural channel design (Lave, 2009; Rosgen, 1996).

Effective discharge is one way channel-forming discharge can be estimated and is defined by Andrews (1980) as "the increment of discharge that transports the largest fraction of the annual total sediment load over a period of years." The concept was first introduced by Wolman & Miller (1960), where they attempted to relate channel-forming discharge as a function of magnitude and frequency of geomorphic events. Other researchers have improved upon their process by utilizing suspended sediment and discharge data to construct sediment rating curves (Andrews, 1980; Benson & Thomas, 1966; Doyle et al., 2007; Emmett & Wolman, 2001). However, this process requires multiple years of data (Andrews, 1980; Benson & Thomas, 1966; Copeland et al., 2000; Emmett & Wolman, 2001) and requires intensive data collection and analysis (Doyle et al., 2007). Andrews (1980) identified other factors such as climate, geologic, and physiographic characteristics that can refine estimates of effective discharge. Doyle et al. (2007) found that streams in different hydrologic settings yield different effective discharge return intervals. In particular, they found that flashy, incised channels broadened the range of observed return intervals for effective discharge where there is an observed departure between bankfull discharge and effective discharges. Given the need for multiple years of data and region-specific factors that affect estimates of effective discharges, Emmett & Wolman (2001) acknowledged the difficulty of accurately estimating effective discharge.

Recurrence interval discharge is another methodology that is used to estimate channel-forming flows. Due to the difficulty in identifying bankfull stage, some researchers have related channel-forming discharges to a range of recurrence intervals. The 1.5-year return interval is an average return period for bankfull discharge (Dunne & Leopold, 1978). However, this method does not always accurately predict channel-forming discharge and may not yield accurate results (Andrews, 1980; Doyle et al., 2007).

Dunne & Leopold (1978) defined bankfull discharge as the "discharge at which channel maintenance is most effective, that is, the discharge at which moving sediment, forming or removing bars, forming or changing bends and meanders, and generally doing work that results in the average morphologic characteristics of channels." This definition captures the essence of channel-forming discharge and, excluding inherent uncertainty with its identification, is the most practical way to estimate its discharge for a given reach. Therefore, the definition of bankfull discharge described by Dunne & Leopold (1978) is used in this study. Multiple field indicators should be used to identify the bankfull stage as a best practice in estimating bankfull discharge to reduce the uncertainty associated with identification.

Hydraulic Geometry and Regional Curves

Many degraded streams that are targets for restoration will lack reliable bankfull indicators. Regional curves are one of the more commonly used tools to estimate bankfull discharges and channel dimensions in such reaches. Dunne & Leopold (1978) showed a strong correlation between bankfull channel parameters such as cross-sectional area, width, and depth to the accompanying drainage area. This concept follows from earlier works on stable channel geometry by Leopold & Maddock (1953) that developed the empirical power functions using discharge as the independent variable. These hydraulic geometry equations follow the general form:

$$W = aQ^b \qquad \text{(Equation 2)}$$

$$D = cQ^e \qquad \text{(Equation 3)}$$

$$V = fQ^g \qquad \text{(Equation 4)}$$

Where W, D, and V are bankfull parameters width, depth, and velocity, respectively. These equations are based on the continuity equation $Q = WDV$, where the product of the coefficients equals one, and the summation of the exponents equals one (Leopold et al., 1995).

Like hydraulic geometry equations, regional equations are empirically derived to estimate bankfull channel cross-sectional area, width, depth, and discharge as a function of drainage area or discharge. Statistically, bankfull discharge is a more reliable independent variable than drainage area because discharge is the driving force in creating observed channel geometry, and drainage area is used as a surrogate (FISRWG, 1988). However, the most unique and appealing feature of regional equations is that they represent numerous streams within a region, while hydraulic geometry equations represent a single stream or reach. Regional equations have gained popularity due to their simplicity in estimating design parameters in channels where bankfull indicators are absent. These equations were created under the assumption that all channels within a region share similar morphological characteristics. Regional equations follow the general form:

$$Y_{bkf} = mA_w^{\,b} \qquad \text{(Equation 5)}$$

Where Y_{bkf} is the bankfull parameter (area, width, depth, or discharge), A_w is the watershed drainage area, and m and b are fitting parameters for the regression equation. Decades of dredging, straightening, and draining the landscape in agricultural environments have led to many impaired and incised streams in Iowa. These activities have altered the pattern, profile, and shape of many channels, thereby pushing them out of equilibrium and producing unintended effects on the state's water resources. Often impaired streams do not have available streamflow data and may not show obvious evidence of bankfull stage. This poses a challenge to stream restoration practitioners who rely on streamflow data and bankfull identification to properly size channel dimensions.

Regional Curve Studies

Numerous studies have been conducted to test and develop regional curves across the U.S. Many of these studies were conducted in the eastern U.S. within a single physiographic province like the Piedmont of Pennsylvania and Maryland (Cinotto, 2003), Valley and Ridge of

Maryland, Virginia, and West Virginia (Keaton et al., 2005), North Carolina Coastal Plain (Doll et al., 2003), Piedmont of North Carolina (Harman et al., 1999), Florida Coastal Plain (Metcalf et al., 2009). These studies reported a strong relationship between watershed drainage area and bankfull channel parameters. In addition to these studies, others have found there to be an influence of other factors on bankfull channel parameters such as percent carbonate rock (Chaplin, 2005), impervious cover (Doll et al., 2002), and riparian vegetation (Hession et al., 2003). Most regional curve studies use the coefficient of determination (R^2) to assess the model's ability to estimate bankfull parameters. However, some have used other statistical methods to test for interactions between urban or rural cover types (Doll et al., 2002), urban and forested cover types (Hession et al., 2003), physiographic regions (Chaplin, 2005), sub-regions that are within the Bluegrass Region of Kentucky (Brockman et al., 2012), and regional curves from other studies (Brockman et al., 2012; Johnson & Fecko, 2008).

While many studies commonly develop regional equations by adding new data to improve the representation of a single physiographic region, others have combined and compared regional curves among larger regions (Bieger et al., 2015; Blackburn-Lynch et al., 2017). Bieger et al. (2015) examined regional regression equations throughout the U.S. published by almost 50 authors over the past 50 years. They concluded that provincial-level regional equations performed better than the division-level models in some provinces. Blackburn-Lynch et al. (2017) conducted a similar study examining the development of regional curves for hydrologic landscape regions (HLR) in the Contiguous United States. They found that stratifying physiographic provinces significantly increased regional curve performance. From these two studies, stratifying regional datasets to account for various influential parameters such as land use, landform, geology, climate, and vegetation was found to increase the reliability of regional datasets.

The Effects of Urbanization on Channel Morphology

Urbanization and the associated increases in impervious surfaces can affect the quantity and timing of water delivered to a stream. The resulting change from pre-development conditions can influence stormwater runoff, flood frequency, peak discharges, and sediment transport (Booth, 1991; Schueler, 1995; Wolman, 1967). As little as 10% impervious cover within a watershed can cause stream degradation and the impairment of aquatic ecosystems (Booth, 1991; Booth & Jackson, 1997; Schueler, 1995). Impervious cover due to urbanization has also been shown to affect channel morphology by altering channel cross-sections (Hammer, 1972; Leopold, 1973) and increasing channel size (Hession et al., 2003; Pizzuto et al., 2000; Trimble, 1997). Additional studies have evaluated the impact of urbanization on flood frequency and found that an increase in impervious surfaces reduces the return period of various flood intervals (Huang et al., 2008; Villarini et al., 2009).

Numerous studies relating urbanization and channel morphology have assessed changes in the bankfull channel (Booth & Jackson, 1997; Doll et al., 2002; Hammer, 1972; Hession et al., 2003; Kang & Marston, 2006; Pizzuto et al., 2000; Trimble, 1997), flow regime (Booth, 1991; Huang et al., 2008; Leopold, 1968; Schueler, 1995; Villarini et al., 2009) floodplain inundation (Anim et al., 2018), channel evolution models (Booth & Fischenich, 2015; Hawley et al., 2012), geomorphic and habitat features (Anim et al., 2018; Cianfrani et al., 2006; Hawley et al., 2013; Pizzuto et al., 2000; Segura & Booth, 2010), and sediment transport (Schoonover et al., 2007; Trimble, 1997; Wolman, 1967). By utilizing urban-drainage area interactions, studies found that bankfull channel widths and cross-sectional areas are larger in urban watersheds (Hession et al., 2003; Pizzuto et al., 2000; Trimble, 1997). In the Piedmont of North Carolina, Doll et al. (2002) compared hydraulic geometry data of urban streams to a rural streams dataset collected by Harman et al. (1999). The analysis showed no statistical evidence that the slopes of the regressions differed between urban and rural curves. However, a statistically significant difference in the intercept of urban curves indicated an enlargement with urban streams of similar drainage areas (Doll et al., 2002). Comparing against rural regional curves, they computed enlargement ratios for urban streams such that they were expected to have 2.65, 2.91, 1.66, and 1.57 times greater bankfull area, discharge, width, and mean depth, respectively (Doll et al., 2002). These results are comparable to other studies that estimated the urbanization derived enlargement of channel cross-sectional area to be 0.7 to 3.8 (Hammer, 1972). Additionally, Hession et al. (2003) found urbanization to have a significant effect (different slopes and intercepts) on bankfull channel widths and cross-sectional areas, but not depths. While there is a significant body of work analyzing the influence of urbanization on stream morphology, not all yielded similar outcomes. For instance, Cianfrrani et al. (2006) found that streams in southeastern Pennsylvania with up to 24% impervious cover did not show significant enlargement of bankfull width or mean depth when compared to streams with 10% impervious cover or less. Brockman et al. (2012) found that impervious area had minimal effect on bankfull channel parameters in the Inner and Outer Bluegrass regions of Kentucky. The extent of riparian vegetation in urban streams is thought to affect the channel morphology independent of urbanization (Hession et al., 2003) and is presumed to be the reason Cianfrrani et al. (2006) and Brockman et al. (2012) did not find a significant effect of impervious cover on bankfull channel parameters. These studies suggest that the impact of urbanization on channel morphology should be evaluated when utilizing regional curves to size channels during stream restoration activities.

Stratifying reaches into discrete groups characterized by the percent total impervious cover in their upstream basin may provide a more detailed framework for restoring streams within non-urban and urban watersheds.

Flood Regions Delineated by Exceedance-Probability Discharges

Three Iowa flood regions (Figure 3) have been delineated in a United States Geological Survey (USGS) study to more accurately estimate annual exceedance probability discharges for ungaged reaches. An analysis of preliminary statewide regressions for 510 stream gages in Iowa and the surrounding states was conducted to better understand flood risk hazards in Iowa streams. Stream gages were grouped based on the difference in plotted residual values between annual exceedance probability discharges to delineate general flood regions (Eash et al., 2013). A cluster analysis method called “portioning around medoids” was then used to help account for the variability in the residual mapping. Cluster analysis was based on basin characteristics previously identified as significant variables in the preliminary statewide regression analysis equations (Eash et al., 2013). Significant variables include drainage area, percent of basin underlain by the Des Moines Lobe, and constant of channel maintenance; however, this analysis did not include drainage area because it is not a unique characteristic of one cluster. An analysis of co-variance regression was used to determine statistically significant differences between flood regions. Such analysis was deemed suitable in defining flood regions for Iowa due to the statistical significance in grouping regions by annual exceedance probability discharges and using cluster analysis to improve groupings by including basin characteristics. Furthermore, flood regions are defined primarily based on Iowa's landform and soil regions. Using flood regions to stratify the regional curve dataset presented in this study may improve the predictive capability of the regression equations while leveraging additional exceedance probability regression equations developed by Eash et al. (2013). This could provide practitioners with numerous tools to aid in-stream restoration projects while providing consistency between three different regional equations.

Relevance for Iowa Streams

Effects of urbanization or total impervious cover on channel morphology have been well studied, and it can be expected that stream restoration projects in urban environments are more likely to be negatively affected by changes in hydrology, riparian vegetation, floodplain restrictions, and channelization. Therefore, understanding how urbanization affects bankfull channel parameters is critical to aid restoration practitioners in properly designing channels in urban settings. Extreme care must be exercised to properly size channels in urban settings to ensure negative consequences do not impact the health and safety of people and property in such settings. It is therefore essential to explore this relationship when developing regional curves for Iowa streams.

Stratification of regional curves to finer spatial scales has increased the predictive capability of regional regression equations for most bankfull parameters (Bieger et al., 2015; Blackburn-Lynch et al., 2017). Furthermore, Blackburn-Lynch et al. (2017) found that using hydrologic landscape regions (HLR) as a basis for stratifying physiographic provinces improved regional curves' predictive capabilities. Eash et al. (2013) delineated flood region boundaries that are more generalized and do not necessarily align with HLRs but share similar parameters. For example, flood regions were defined by the annual exceedance probability discharges, landform, and soil region bounders in Iowa. Both HLRs and flood regions define hydrologic regions with similar basin characteristics. In light of the results presented by Blackburn-Lynch et al. (2017), grouping regional curves by flood regions was thought to be a vital stratification technique to test if the state-wide regional curves could be improved. Evaluating regional curves stratified by HLRs in Iowa was investigated, but with 20 defined HLRs, the dataset was not large enough in individual regions to provide meaningful analysis.

The primary objectives of this study were to: (1) develop bankfull regional curves for the state of Iowa in collaboration with the Iowa Department of Natural Resources (IDNR) for use in Iowa's River Restoration Toolbox; (2) identify and test key stratification schemes to determine if alternative methods of stratification can improve the predictive capability of the regression equations; (3) compare hydraulic geometry regression equations between significant groups identified during the stratification processes; (4) document the range of recurrence interval discharges for the bankfull channel.

CHAPTER 2. METHODS

Study Area

The study area includes Iowa's five most extensive landform regions (Figure 1), which are all part of the Central Lowland Physiographic Province (Fenneman, 1946). The majority of locations have most of their watershed area underlain by the Des Moines Lobe landform region. Other landform regions in which data was collected include the Northwest Iowa Plains, Southern Iowa Drift Plain, Iowan Surface, and Paleozoic Plateau.

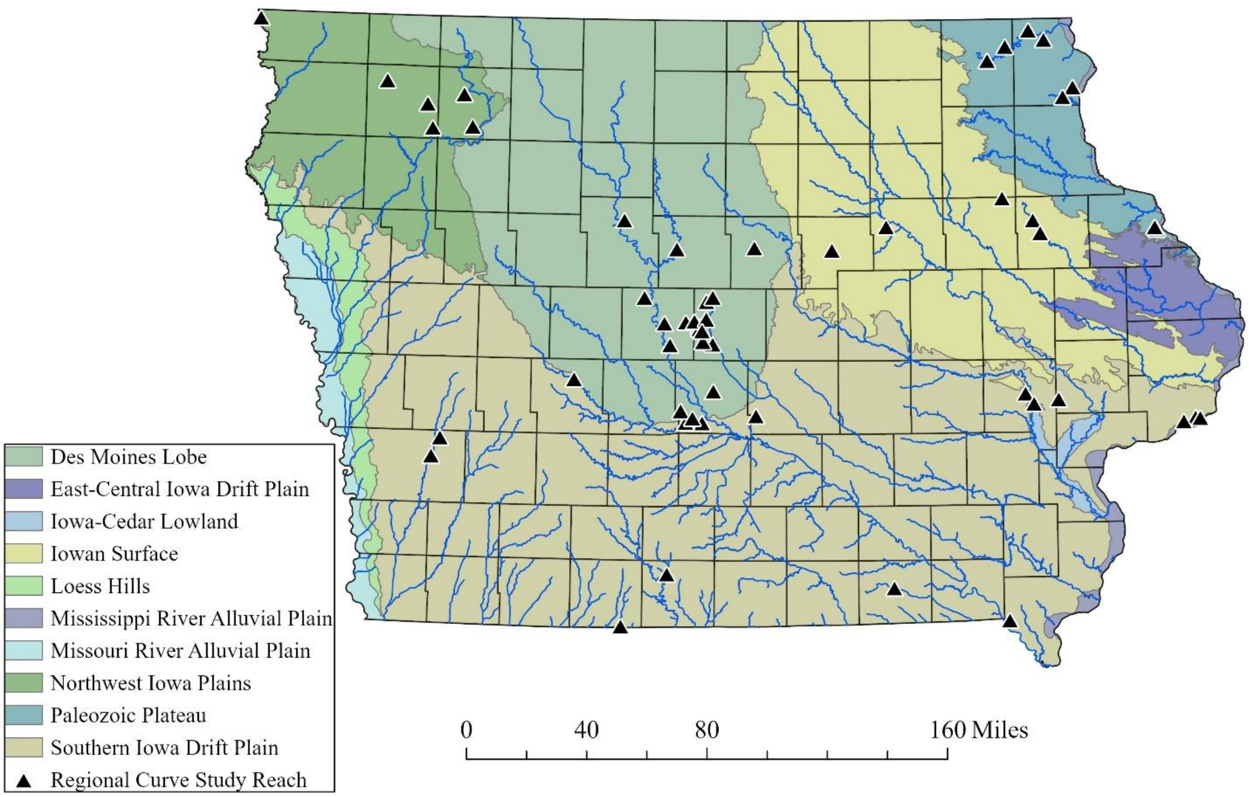

Figure 1. Locations of regional curve study sites and landform regions in the Central Lowland Physiographic Province.

Geological Context

The Des Moines Lobe region was glaciated from 12,000 to 16,000 years before the present and still exhibits many features of a young, glaciated landscape (Prior, 1991). The most prominent feature of glacial activity is the signature of terminal glacial moraines spread out along former glacial ice margins and thick deposits of compact heterogeneous glacial till. The upland landscape is generally comprised of a low-relief plateau with poor surface water drainage and abundant lakes and wetlands. Streams on the Des Moines Lobe typically have poorly developed drainage networks. These drainage networks have been extensively modified to facilitate large-scale agriculture in the past 150 years. Evidence of glacial till and glacial lag is typically observed in channels on the Des Moines Lobe as they erode the recently glaciated landscape.

The Northwest Iowa Plains has gently rolling hills with relatively low and uniform relief. In most areas of the region, there is evidence of a moderate to thick layer of loess over glacial till. The last glacial advance of this landform was about 20,000 to 30,000 years ago or 6,000 to 16,000 years earlier than the Des Moines Lobe advance (Prior, 1991). Stream networks are well defined in this region. The result is a landscape with more effective surface water drainage and uniform features. Soils are thus more erodible and affect turbidity, channel morphology, and floodplain development.

The Southern Iowa Drift Plain is the largest landform in Iowa and covers much of the state's southern half. Gently rolling hills dominate the landscape's topography with well-defined drainage networks throughout the region. Subsurface materials in this region are similar to the Des Moines Lobe because they are dominated by glacial till. However, glacial deposition in this region is older by hundreds of thousands of years, and the till is covered in most places by one or more blankets of wind-blown loess (Prior, 1991). The result is a landscape where most of the landforms of glaciation have been stripped away. Channels in this region have cut through much of the glacial till, and in some places, bedrock is visible. Well-defined dendritic drainage networks are common in this region, where channel networks have effectively reshaped the old glacial plains. The region is evidence of a post-glacial landscape where the channel networks have reworked the glacial plains over time.

The Iowan Surface contains gently rolling hills and occupies about one-quarter of the state's northeastern area. The low relief region has subtle landscape features that exhibit multi-level surfaces with thin, discontinuous loess over glacial drift. The region was part of the Southern Iowa Drift Plain and experienced largescale erosion before and during the Wisconsinan glacial events. Between 16,500 and 21,000 years ago, as part of the Wisconsinan, the landscape experienced cold-climate weathering and erosion that overwhelmed the earlier landscape features (Prior, 1991). One of the most notable landscape features is the elongated ridges known as paha, occupying the southern third of the region. Stream networks are well defined in this region with bedrock exposure, and local karst conditions exist in some areas.

The Paleozoic Plateau is unlike any other landform in Iowa due to its deeply carved terrain, abundant bedrock outcroppings, and lack of glacial deposits. Thin layers of loess cover and isolated patches of glacial drift can be found in the region, but bedrock outcroppings dominate the landscape. The Paleozoic-age sedimentary bedrock occurs throughout the region, originating as sediments accumulating on the seafloor and along coastal margins of tropical marine environments between 300 and 550 million years ago (Prior, 1991). This is expressed by a well-developed drainage network through which many deeply entrenched valleys and plateau-like uplands have been formed. Karst topography can be found with sinkholes, caves, and springs in this region.

Field Methods

Site Selection

Locations for this study were chosen based on several different filtering criteria to provide the most representative additions to the existing hydraulic geometry dataset for the state of Iowa. Iowa Department of Natural Resources (IDNR), Iowa State University's Applied Geomorphology Lab (AGL), and other partners collected preliminary data with the intention of developing a regional curve dataset for Iowa. Following quality assurance and quality control procedures that ensure alignment with the protocols described in this study, data collected by these groups were included in the regional dataset. Filtering criteria include site-specific characteristics and statewide spatial distribution. Previously collected data were analyzed to identify the underrepresented drainage areas in the dataset. This study primarily focused on wadeable streams, typically with watersheds less than 500 mi^2 in area. The previously-collected data was further analyzed to identify gaps in the spatial distribution of survey points throughout the state. Locations were filtered to represent regions of Iowa where the dataset lacks hydraulic geometry measurements. Only locations with a single-threaded channel were surveyed and included in the dataset. Sites were then filtered through the IDNR BioNet and USGS gage sites servers for Iowa. Locations that met the IDNR criteria of a "reference site" were selected because of their physically stable condition and high aquatic biota indices. A BioNet "reference site" regarding aquatic health is defined as a reach representing a stream condition least disturbed by human activities (IDNR, 2021).

Gaged reaches were selected to provide readily-available streamflow data. Gage stations with at least ten years of record were considered for this study to allow for flood frequency analysis. Streamflow data at gage stations further aided in estimating bankfull stage, bankfull discharge, and roughness coefficients. Many cross-sections were surveyed a distance from the gage to avoid channel alterations due to structures and bridges. The most suitable location was often chosen upstream or downstream and rarely exceeding a five percent deviation from the gage site's drainage area. The five percent change in drainage area is a commonly-used constraint to ensure channel geometry measurements represent discharges at the gaged sites (Eash, 1993).

Before visiting the proposed location, each site was evaluated using aerial imagery, comparing changes in the channel pattern over 70 years. Channel profiles were evaluated using the 2010 LiDAR Hillshade. Channel assessments were conducted using the Iowa Geographic Map Server (https://ortho.gis.iastate.edu/). Upon arriving in the field, each site was evaluated for bankfull indicators to further assess its suitability, with the presence of one or more bankfull indicators needed to qualify for inclusion. Sites were further assessed for riffle/pool bed features by identifying riffle-pool sequences along the reach and their orientation relative to channel bends. Reaches without identifiable riffles or runs between bends or straight segments were omitted.

Design and Data Collection

This study was designed to develop regional curves for Iowa by using gaged and ungaged reaches in rural and urban environments in unregulated settings. Channel geometry data collected previously by the IDNR, AGL, and other partners were combined with 32 additional Iowa locations surveyed for this study. Together, 54 locations represent the geologic, hydrologic, and meteorological settings within the state's landform regions. Methods for field data collection to determine the bankfull channel geometry were outlined by Rosgen (1996) and Leopold (1994).

Before conducting the survey, the planned reach was assessed to identify suitable cross-sections and bankfull indicators. Colored pin flags were placed to identify the bankfull stage along the reach and surveyed along with the longitudinal profile. Each site had one or more of the following bankfull indicators:

- A significant break in slope along the channel banks
- Flat depositional feature on a horizontal plane
- Top of point bars
- Change in the size distribution of deposited material
- Changes in vegetation

The most common bankfull indicators in Iowa streams are the significant breaks in slope within the channel and depositional features. At some sites, vegetation was used as a bankfull indicator when there was a clear trend in established perennial vegetation throughout the reach. However, vegetation was never used as the sole bankfull indicator, and when it was used, other bankfull indicators were used for supporting evidence.

Longitudinal surveys were conducted at each site over a reach length of at least 20 bankfull widths or two full meander wavelengths (Leopold, 1994; Rosgen, 1996). Longitudinal stations were established at observed bed features along the reach. At each station, the thalweg and water surface were recorded using a Topcon RL-H5A Horizontal Self-Leveling Rotary Laser and Receiver or a Trimble R12 GNSS Receiver. When bankfull indicators were available, the bankfull stage was surveyed. A best-fit line of the bankfull stage was compared to that of the water surface to compute channel slopes and verify bankfull features along the longitudinal profile (Leopold, 1994).

Up to three cross-sections were surveyed at stable riffles. A stable run was selected if a riffle was absent throughout the planned reach. Fewer cross-sections were surveyed when neither a combination of three riffles or runs were present. At each cross-section, the top of banks, terraces, bankfull stage, breaks in slope, water surface, and thalweg was surveyed using a Johnson 32X Automatic Level or a Trimble R12 GNSS Receiver. Cross-sections near features that could affect the channel geometry were avoided. Data were then entered into RIVERMorph to compare bankfull parameters between the cross-sections and the longitudinal profile. After evaluating the cross-section parameters, values were averaged to construct mean bankfull values for the reach. Due to the unique channel morphology of Iowa streams, this was determined as the best practice to reduce error and bias when estimating reach-scale bankfull parameters.

Riffle pebble counts were conducted at each surveyed reach using the method presented by Wolman (1954). The method required that a minimum of 100 particles be collected to determine the D_{50} and D_{84} particle sizes. Pebble counts allowed for estimating Manning's n values to calculate the bankfull discharge at ungaged streams. Manning's n values were back-calculated using Manning's equation along with the cross-section channel geometry, channel slope, and bankfull discharge for gaged reaches.

$$Q = \frac{1.49}{n} A R^{2/3} S^{1/2} \qquad \text{(Equation 6)}$$

Manning's equation is in English units where Q is bankfull discharge in $ft^3\ s^{-1}$, A is bankfull area in ft^2, R is the hydraulic radius in ft, S is the slope in $ft\ ft^{-1}$, and n is Manning's roughness coefficient. For ungaged reaches, the roughness was estimated using the method presented by

Arcement & Schneider (1989). A base roughness coefficient was selected for this method according to the bed material particle size and adjusted according to five factors. These factors included the degree of channel irregularity, variation in channel cross-section, effects of obstruction, amount of vegetation, and degree of meandering.

Bankfull discharge at gaged reaches was estimated using the method presented by Williams (1978), where the difference between the water surface and bankfull elevation was correlated to real-time data from a USGS or United States Department of Agriculture (USDA) gage station. The difference between the water surface and bankfull stage at the cross-section was used to estimate the bankfull stage at the gage station. Bankfull discharge was then determined by using the gages current stage-discharge rating curve. When a rating curve was unavailable for the gage, a stage-discharge curve was created using annual peak flow data to estimate bankfull discharge. At some stations, bankfull discharge could not be determined because of significant changes in channel elevations, backwater pools, or significant scour around the gage. In these situations, discharge was estimated using the same methodology as ungaged reaches. For ungaged reaches, bankfull discharge was calculated using Manning's equation (Equation 6).

Flood frequency analysis was conducted on all gaged reaches to analyze annual peak discharge data. The Log Pearson Type III distribution method presented in the USGS Bulletin 17B was used to determine the recurrence interval of bankfull discharges and compare them to the 1.5-year discharge (USGS, 1982). A statewide generalized skew coefficient of -0.4 and a standard error of 0.16 was used (Eash et al., 2013).

Sinuosity was computed for each reach by measuring the stream length of the longitudinal profile in ArcGIS Pro and dividing it by the valley length. All drainage basins were delineated using the USGS StreamStats Web-based Geographic Information System tool (https://streamstats.usgs.gov/ss/), which was used to delineate each basin to the endpoint of the longitudinal profile. The StreamStats tool utilizes the ArcHydro toolbox to delineate basins by integrating the National Hydrography Dataset (NHD), Watershed Boundary Dataset (WBD), and National Elevation Dataset (NED). The 10-meter Digital Elevation Model from NED is forced to agree with the NHD and WBD by burning the stream network and walling the drainage boundaries. Accompanying land cover and precipitation statistics were produced for the delineated drainage basins and included in Appendix C. Each surveyed cross-section was photographed in the upstream and downstream directions as well as the left and right banks. Additional photographs were frequently taken along the longitudinal profile to identify individual site-specific characteristics. Additional photographs included but were not limited to bankfull stage, bed material, deposition, log jams, beaver dams, riparian vegetation, and wildlife.

Stratification Schemes

Stratification by Non-Urban and Urban Cover Types

The impacts of total impervious surfaces on channel morphology were analyzed for all locations. An analysis of urban landcover for all watersheds (Figure 2) was conducted by using the National Land Cover Database (NLCD) 2019 Impervious Surface Conterminous United States (NLCD, 2019). All streams with greater than 10% total impervious cover within their upstream basin were categorized as urban reaches. All streams with less than or equal to 10% total impervious cover within their upstream basin were categorized as a non-urban reach. Analysis of the regional dataset, when stratified by non-urban and urban reaches, was conducted to examine the influence of total impervious cover on all bankfull parameters.

The regional curves presented in this section were developed from 54 locations throughout Iowa. Of the 54 locations, 20 were developed using USGS and USDA gage data, with the other 34 being ungaged reaches. Data was collected from five of Iowa's major landform regions with drainage areas ranging from 0.54 mi^2 to 852 mi^2. Twenty-two of the locations used to develop the regional curves presented herein were collected by the IDNR, AGL, and other partners. An additional 32 locations were added to the regional dataset from 2020 to 2021. A summary of these locations and bankfull channel information can be found in Appendix A and Appendix B. To evaluate the performance of Iowa's regional curve regression equations, data from the regional curve dataset was stratified by urban and non-urban cover types to evaluate if further regionalization improved the model's predictive capability. Of the 54 locations, 35 were used to develop curves for non-urban streams, and 19 were used for urban streams.

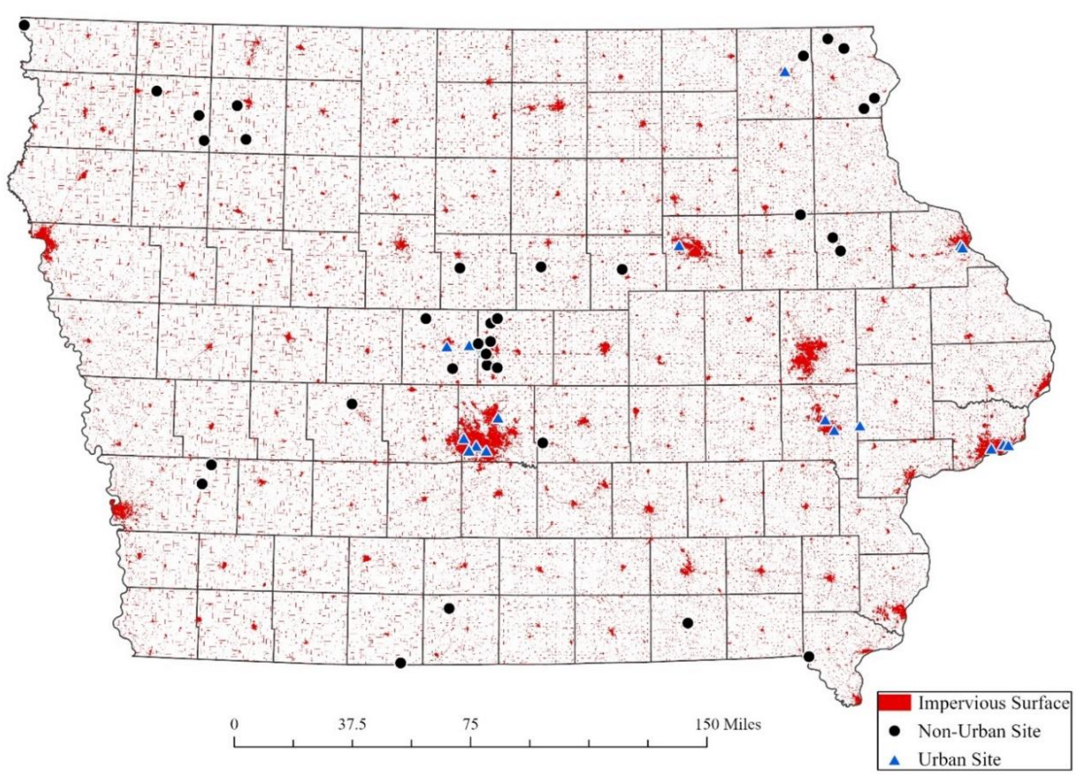

Figure 2. Iowa's NLCD 2019 impervious surfaces and surveyed non-urban and urban reaches.

Stratification by Flood Region

An analysis of flood regions (Figure 3) was conducted using three regions delineated by Eash et al. (2013). Sites were categorized by the flood region in which their basin resides. When stratified by flood region, the non-urban dataset was analyzed to examine its influence on all bankfull channel parameters. The urban dataset lacked the appropriate sample size to populate data for Flood Region 1 (n = 6), Flood Region 2 (n = 10), and Flood Region 3 (n = 3) to make meaningful comparisons and was therefore excluded from this analysis. The regional curves presented were developed from 35 non-urban locations throughout Iowa. Of the 35 locations, 13 were developed using USGS and USDA gage data, with the other 22 being ungaged reaches. This analysis includes five of Iowa's major landform regions with drainage areas ranging from 4.18 mi^2 to 852 mi^2. Seventeen of the locations used to develop the regional curves presented herein were collected by the IDNR, AGL, and other partners. An additional 18 locations were added to the regional dataset from 2020 to 2021. A summary of these locations and bankfull channel information can be found in Appendix A and Appendix B.

To evaluate the performance of Iowa's regional curve regression equations, data from the regional curve dataset was separated by flood region to evaluate if further regionalization improved the model's predictive capability. Of the 35 locations, 15 were used to develop curves for Flood Region 1, 10 locations for Flood Region 2, and 10 locations for Flood Region 3. Streams with greater than 10% total impervious cover within their watershed were omitted from this analysis.

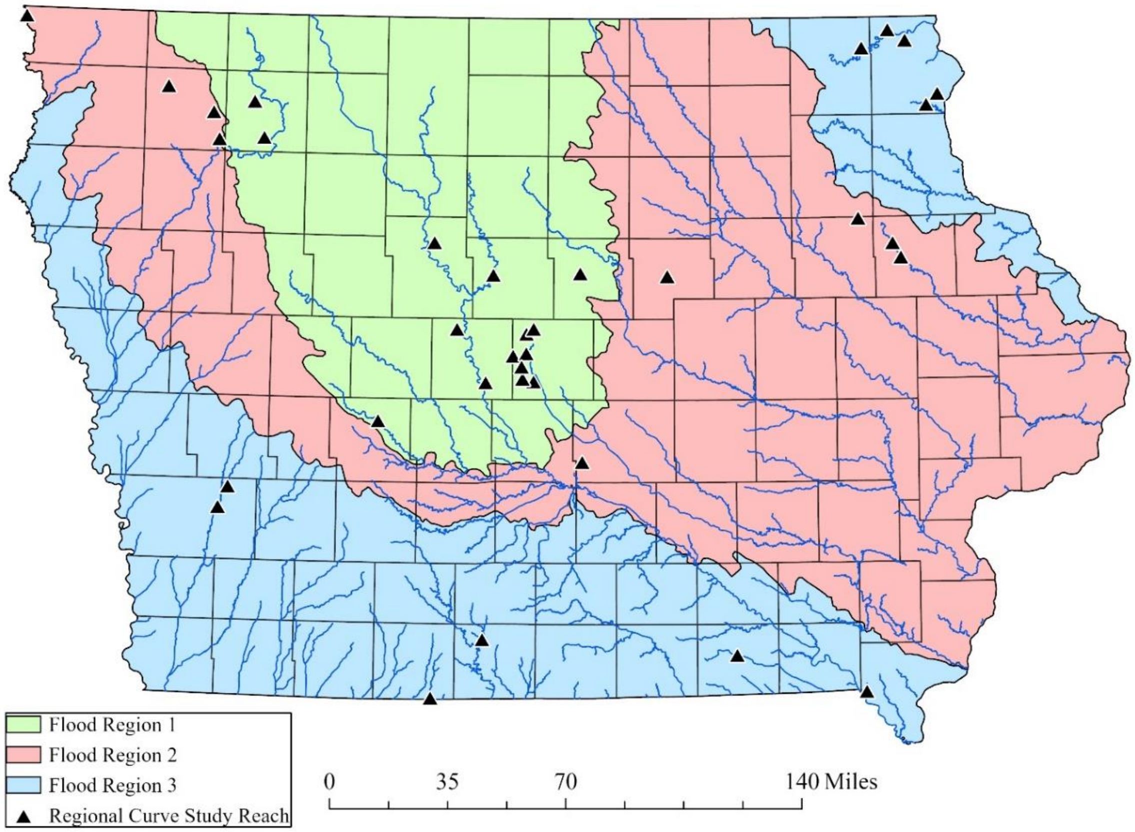

Figure 3. Locations of Iowa's three flood regions and associated non-urban regional curve study reaches.

Statistical Methods

Statistical models that test for significant interaction terms were utilized to evaluate if more refined stratification techniques could improve regional curves. Tests for differences between regional curves when separated by either flood regions or cover type (non-urban and urban) were utilized to determine if stratification is justified—comparing their slopes and intercepts tests for significant differences between regional curves. If the stratified dataset provides more powerful statistical relationships, it can be concluded that stratification does improve model performance and is a more appropriate model.

Multiple linear regression of log-transformed variables was used to develop regional curves and test significant interaction terms (Equation 7). Flood regions and cover types were included in the model as indicator variables to test for significant differences between groups. The multiple linear regression equations follow the general form:

$$log_{10}(Y_{bkf}) = \beta_0 + \beta_1 log_{10}(A_w) + \beta_2 x_2 + \beta_3 log_{10}(A_w) x_2 + \ldots. + \beta_i x_i + \varepsilon_{bkf} \quad \text{(Equation 7)}$$

Where Y_{bkf} is the log-transformed bankfull response parameter (area, width, mean depth, or discharge), A_w is the log-transformed watershed drainage area, x_2 is the indicator interaction variable for flood region or cover type, β values are the fitting parameters for the regression equation, and ε_{bkf} is the residual error term describing the difference between the predicted and observed values. By fitting a linear model to $log_{10}(Y_{bkf})$ predicted by $log_{10}(A_w)$, we are equivalently saying $Y_{bkf} = \beta_0 {A_w}^{\beta_1}$ following the same power-law form as Equation 5.

The tests for flood regions were structured to compare the slopes and intercepts of Flood Region 2 and Flood Region 3 to the corresponding Flood Region 1. The tests for cover type were structured to compare the slopes and intercepts of urban streams to the corresponding non-urban streams. Therefore, Flood Region 1 and non-urban streams represent a control condition in their respective statistical models. For both models, the null hypothesis is no difference between the slope or intercept of the regression equations. A p-value ≤ 0.05 indicates a significantly nonzero difference between the slopes or intercepts of specific stratification schemes, which justifies separate regional curves. It is important to note that a statistically significant difference in regression slopes almost always produces a statistically significant difference in intercepts. Thus, when there is evidence of a difference in regression slopes, differences in intercepts provide little additional value for the analysis. However, evidence that the regression intercepts differ while the slopes do not provide important implications. The regression lines of distinct groups would be parallel in such a model given a pooled slope with different intercepts.

Following initial tests for interactions involving flood region and cover type in the linear model, tests were conducted on other continuous explanatory variables in a multiple linear regression model. The purpose of adding additional explanatory variables into a multiple linear regression model is to determine if their inclusion improves the model by providing better estimates of bankfull channel response variables. For this statistical model, the null hypothesis is that each contrast's slope and intercept is zero. A p-value ≤ 0.05 indicates a significant difference between the slopes or intercepts, which justifies the inclusion of additional variables in the model. The multiple linear regression equations follow the same general form as Equation 7, including additional explanatory variables if significant. Percent total impervious cover, mean annual precipitation, maximum10-year 24-hour precipitation, saturated hydraulic conductivity, mean basin slope, constant of channel maintenance, and basin shape factor were evaluated as potential explanatory variables in the multiple linear regression models. All statistical analysis was performed using R. Version 1.3.1093 (RStudio Team, 2020).

CHAPTER 3. RESULTS

Regional Curves in Non-Urban and Urban Cover Types

Bankfull Cross-Sectional Area

Bankfull cross-sectional area was determined from survey data for all 54 locations. Regional curve equations, R^2, and coefficient of variation (CV) values are presented in Table 1 for non-urban and urban streams. Regional curves for data separated by cover type are presented in Figure 4. Bankfull area vs. drainage area showed a very strong relationship for both cover types. Watershed drainage area can explain 83% of the variability in cross-sectional area for the combined regional dataset. Stratifying the data by cover type improved the explanatory power of the regression equations for non-urban and urban cover types shown by an increase in R^2 to 0.94 and 0.92, respectively. The most significant difference between the Non-Urban and Urban regional curves is seen in smaller drainage areas. A 0.2011 difference in exponent values between these curves, which affect the regression slopes, has the most significant influence on bankfull cross-sectional area in smaller drainage areas. The difference between bankfull cross-sectional area estimates decreases as the drainage area increases. The 95% confidence intervals may overlap; however, there is no data from urban basins >76 mi^2 to make any inferences about the possible convergence of these curves.

Table 1. Bankfull cross-sectional area regression relationships for the combined dataset and non-urban and urban cover types. A_{bkf} is the bankfull cross-sectional area in ft^2 and A_w is the watershed drainage area in mi^2.

Cover Type	Regression Equation	R^2	CV
Combined Regional	$A_{bkf}=18.6196A_w^{0.5650}$	0.83	0.5343
Non-Urban	$A_{bkf}=7.7275A_w^{0.7497}$	0.94	0.3318
Urban	$A_{bkf}=27.0717A_w^{0.5486}$	0.92	0.2583

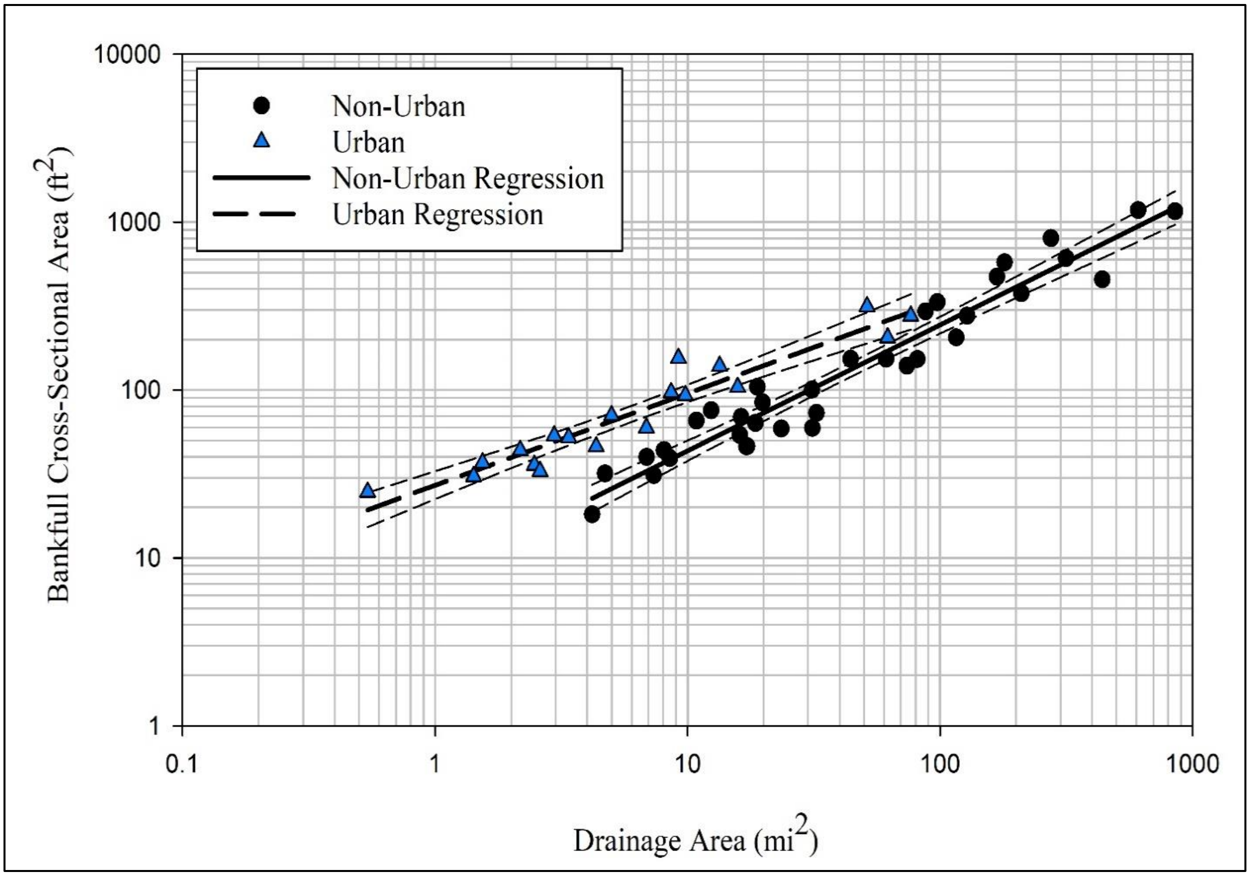

Figure 4. Bankfull cross-sectional area as a function of the drainage area for non-urban and urban streams with 95% confidence intervals.

Bankfull Width

Regional curve equations, R^2, and CV values are presented in Table 2 for non-urban and urban streams. Regional curves for data separated by cover type are presented in Figure 5. Bankfull width vs. drainage area showed a very strong relationship for both cover types. Watershed drainage area can explain 83% of the variability in width for the combined regional dataset. Stratifying the data by cover type improved the explanatory power of the regression equations for non-urban and urban cover types shown by an increase in R^2 to 0.91 and 0.86, respectively. The most significant difference between the Non-Urban and Urban regional curves is once again seen in lower drainage areas. A 0.1129 difference in exponent values between these curves has the most significant influence on bankfull width in smaller drainage areas. As the drainage area increases, the difference between bankfull width estimates decreases. The regression lines begin to converge at drainage areas between 68 mi^2 and 76 mi^2 as the 95% confidence intervals overlap. 76 mi^2 is the dataset's largest urban drainage area, and no comparative statements can be made for larger drainage areas.

Table 2. Bankfull width regression relationships for the combined dataset and non-urban and urban cover types. W_{bkf} is the bankfull width in ft, and A_w is the watershed drainage area in mi^2.

Cover Type	Regression Equation	R^2	CV
Combined Regional	$W_{bkf}=13.0459A_w^{0.3535}$	0.83	0.3118
Non-Urban	$W_{bkf}=8.0857A_w^{0.4543}$	0.91	0.2364
Urban	$W_{bkf}=16.0496A_w^{0.3414}$	0.86	0.2083

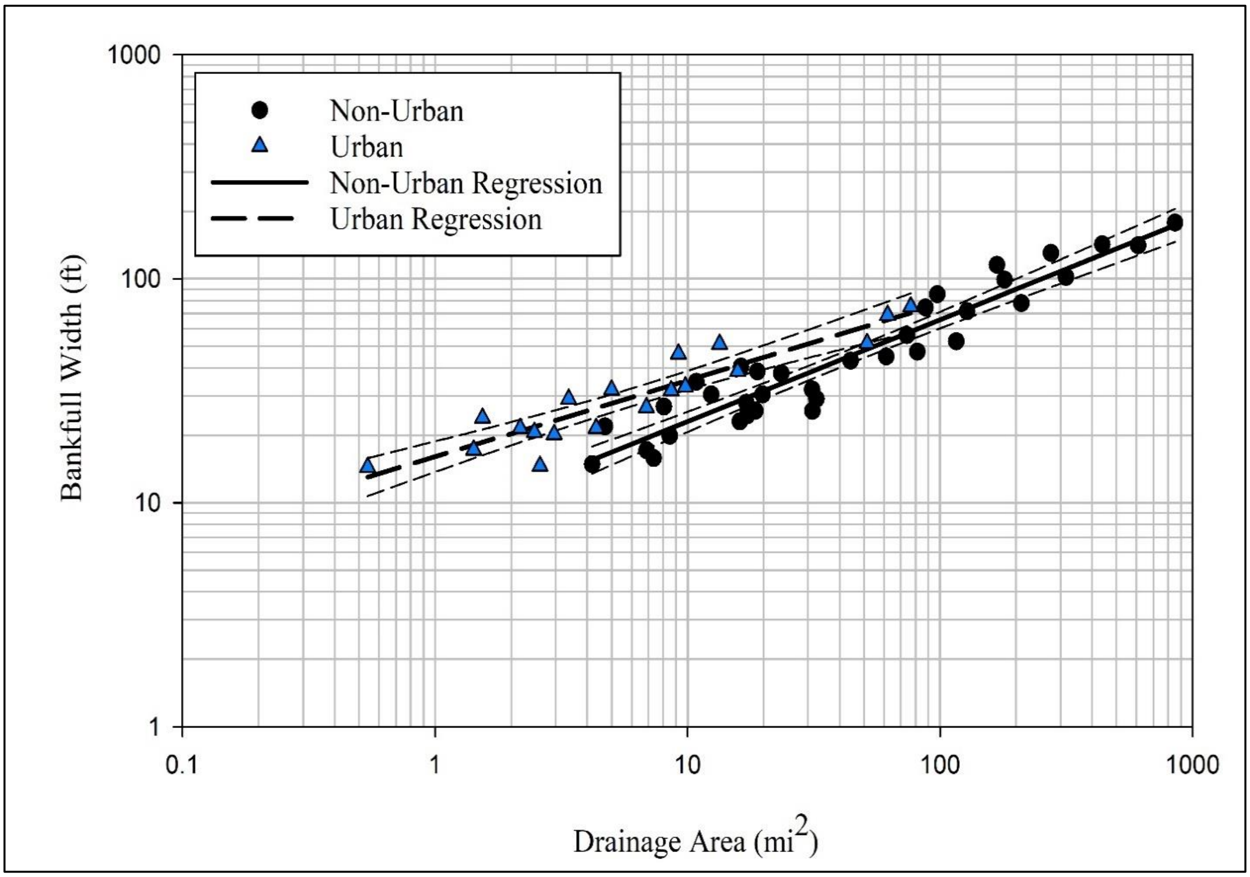

Figure 5. Bankfull width as a function of the drainage area for non-urban and urban streams with 95% confidence intervals.

Bankfull Mean Depth

Regional curve equations, R^2, and CV values are presented in Table 3 for non-urban and urban streams. Regional curves for data separated by cover type are presented in Figure 6. Bankfull mean depth vs. drainage area showed a very strong relationship for both cover types. Watershed drainage area can explain 67% of the variability in bankfull mean depth for the combined regional dataset. Stratifying the data by cover type improved the explanatory power of the regression equations for non-urban and urban cover types shown by an increase in R^2 to 0.82 and 0.69, respectively. The most significant difference between the Non-Urban and Urban regional curves is seen in smaller drainage areas. It is likely due to the 0.0951 difference in exponent values affecting regression slopes. As the drainage area increases, the difference between bankfull mean depth estimates decreases. The regression lines begin to converge at drainage areas between 58 mi^2 and 76 mi^2 as the 95% confidence intervals overlap.

Table 3. Bankfull mean depth regression relationships for the combined dataset and non-urban and urban cover types. D_{bkf} is the bankfull mean depth in ft, and A_w is the watershed drainage area in mi^2.

Cover Type	Regression Equation	R^2	CV
Combined Regional	$D_{bkf}=1.4212A_w^{0.2155}$	0.67	0.2889
Non-Urban	$D_{bkf}= 0.9428A_w^{0.3018}$	0.82	0.2343
Urban	$D_{bkf}=1.6946A_w^{0.2067}$	0.69	0.2070

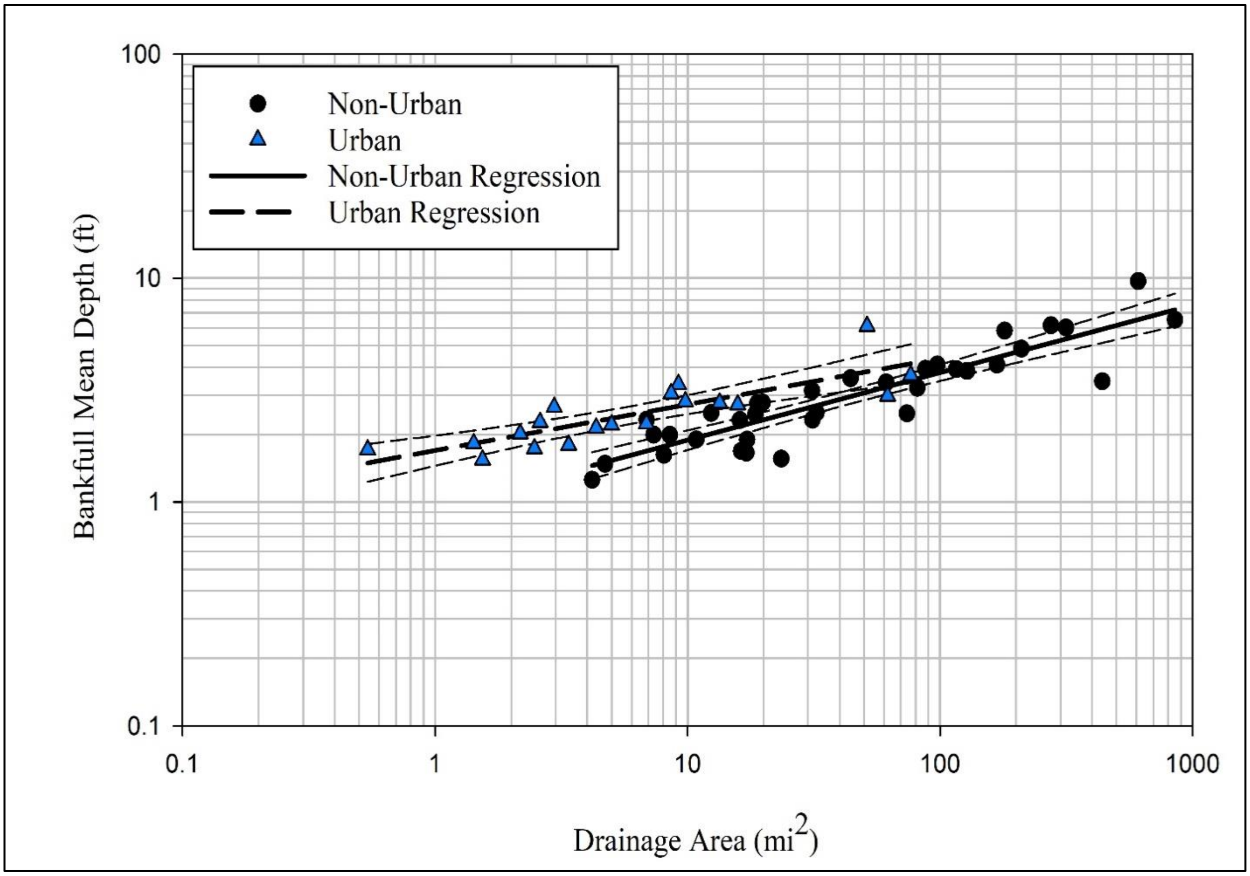

Figure 6. Bankfull mean depth as a function of the drainage area for non-urban and urban streams with 95% confidence intervals.

Bankfull Discharge

Bankfull discharge was determined for all 54 locations using survey data and Manning's equation (Equation 6). Regional curve equations, R^2, and CV values are presented in Table 4 for non-urban and urban streams. Regional curves for data stratified by cover type are presented in Figure 7. Bankfull discharge vs. drainage area showed a very strong relationship for both cover types. The watershed drainage area can explain 78% of the variability in discharge for the combined regional dataset. Stratifying the data by cover type improved the explanatory power of the regression equations for non-urban and urban cover types shown by an increase in R^2 to 0.92 and 0.88, respectively. The most significant difference between the Non-Urban and Urban regional curves is seen in lower drainage areas. Compared to the other bankfull channel parameters, bankfull discharge shows the greatest difference in exponent values between these curves, 0.1914. As the drainage area increases, the difference between bankfull discharge estimates decreases. Unlike bankfull width and mean depth, the 95% confidence intervals do not overlap at larger drainage areas.

Table 4. Bankfull discharge regression relationships for the combined dataset and non-urban and urban cover types. Q_{bkf} is the bankfull discharge in $ft^3\ s^{-1}$ and A_w is the watershed drainage area in mi^2.

Cover Type	Regression Equation	R^2	CV
Combined Regional	$Q_{bkf}=58.3105A_w^{0.6202}$	0.78	0.7510
Non-Urban	$Q_{bkf}= 19.3464A_w^{0.8465}$	0.92	0.4311
Urban	$Q_{bkf}=87.5537A_w^{0.6551}$	0.88	0.3989

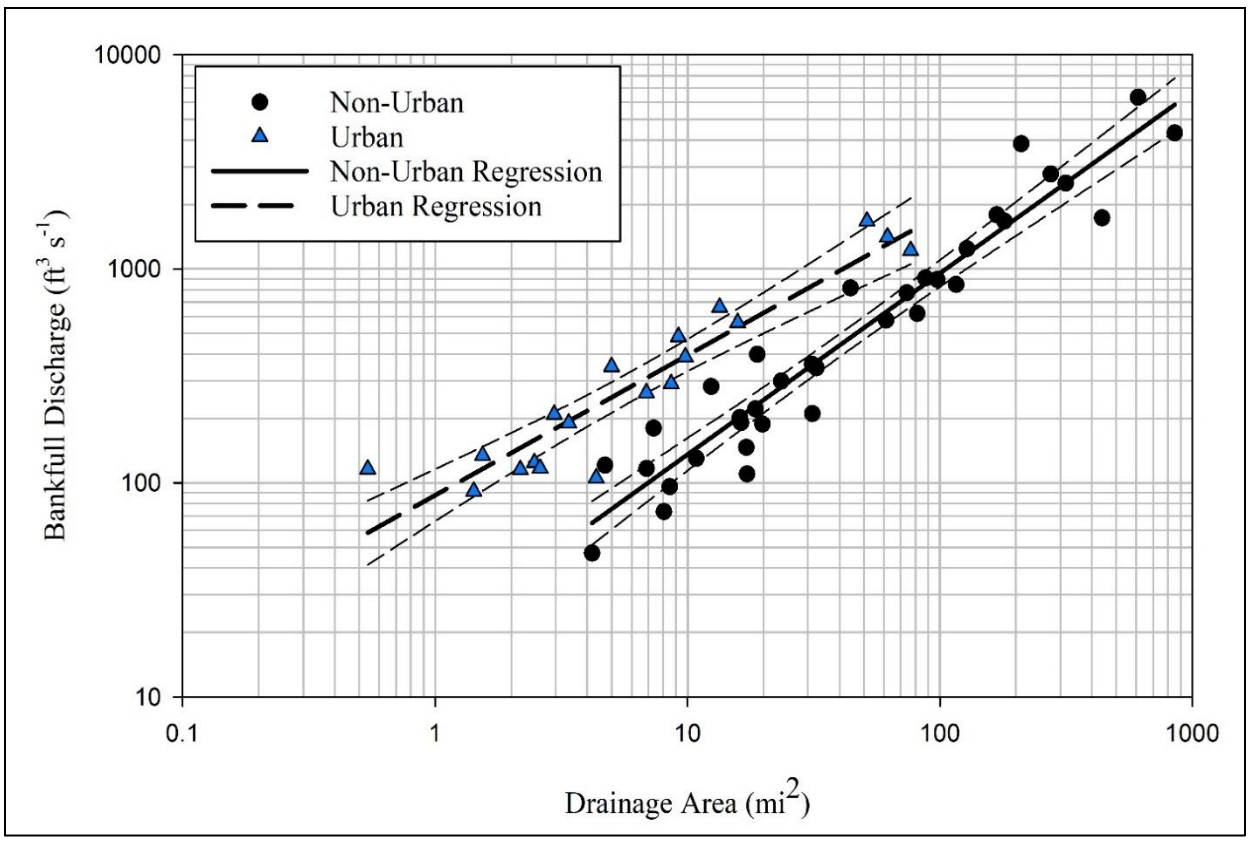

Figure 7. Bankfull discharge as a function of the drainage area for non-urban and urban streams with 95% confidence intervals.

Statistical Analysis

Results from the statistical model testing for cover type as a significant interaction term are presented in Table 5. The model provides evidence that urban regressions have significantly different slopes (p-value ≤ 0.05) and intercepts (p-value ≤ 0.05) from the non-urban control condition for all bankfull parameters.

Table 5. Bankfull channel parameters with associated p-values for non-urban and urban cover types.

Bankfull Parameter	Cover Type	Intercept p-value	Slope p-value
Cross-Sectional Area	Non-Urban	-	-
	Urban	<0.001	<0.001
Width	Non-Urban	-	-
	Urban	<0.001	0.0126
Mean Depth	Non-Urban	-	-
	Urban	<0.001	0.0327
Discharge	Non-Urban	-	-
	Urban	<0.001	0.0135

Cover type interactions were significant, and additional explanatory variables were analyzed for non-urban and urban cover types. Results of the multiple linear regression model are presented in Table 6. The model provides evidence that the inclusion of percent total impervious cover had a significant effect (p-value ≤ 0.05) on the urban regression equations for bankfull cross-sectional area, width, and discharge. Thus, including percent total impervious cover as an explanatory variable in the multiple linear regression model improves the model's ability to predict these bankfull channel parameters. There is insufficient evidence that the inclusion of percent total impervious cover has a significant effect (p-value = 0.3358) on the bankfull mean depth regression equations.

Table 6. Urban bankfull channel regression equations and diagnostic statistics for the multiple linear regression model, including percent total impervious cover as an explanatory variable.

Regression Equation	p-value	R^2	F-statistic
$\log(A_{bkf})= 1.227553+ 0.6609987 \log(A_w) + 0.003068(\% \text{ Impervious})$	<0.001	0.96	213.7
$\log(W_{bkf})= 1.0543785+ 0.3866629 \log(A_w) + 0.0022617(\% \text{ Impervious})$	0.019	0.92	97.87
$\log(D_{bkf})= 0.1758904+ 0.2226511 \log(A_w) + 0.0007959(\% \text{ Impervious})$	0.3358	0.68	19.75
$\log(Q_{bkf})= 1.702952+ 0.726752 \log(A_w) + 0.003583(\% \text{ Impervious})$	0.00751	0.91	95.29

Mean annual precipitation was found to be a significant explanatory variable in non-urban cover types, and the results of the multiple linear regression model are presented in Table 7. The model provides evidence that the inclusion of mean annual precipitation had a significant effect (p-value ≤ 0.05) on non-urban regression equations for bankfull cross-sectional area, width, and discharge. Thus, including mean annual precipitation as an explanatory variable in the multiple linear regression model improves the model's ability to predict these bankfull channel parameters. There is insufficient evidence that the inclusion of mean annual precipitation has a significant effect (p-value = 0.0766) on the bankfull mean depth regression equations. As explanatory variables, mean annual precipitation and drainage area resulted in negative intercept terms for the cross-sectional area and mean depth. As a result, the regression equations for these parameters are only meaningful for drainage areas > 0.6 mi^2.

Table 7. Non-urban bankfull channel regression equations and diagnostic statistics for the multiple linear regression model, including mean annual precipitation as an explanatory variable.

Regression Equation	p-value	R^2	F-statistic
$\log(A_{bkf})= -0.052646+ 0.761251 \log(A_w) + 0.027455(\text{Precipitation})$	<0.001	0.95	342.5
$\log(W_{bkf})= 0.383876+ 0.460740 \log(A_w) + 0.015289(\text{Precipitation})$	0.0164	0.92	193.4
$\log(D_{bkf})= -0.41677+ 0.30659 \log(A_w) + 0.01142(\text{Precipitation})$	0.0766	0.82	80.12
$\log(Q_{bkf})= 0.44778+ 0.85679 \log(A_w) + 0.02448(\text{Precipitation})$	0.0235	0.93	229.6

Hydraulic Geometry Curves in Non-Urban and Urban Cover Types

Bankfull Cross-Sectional Area

Bankfull cross-sectional area was determined from survey data for all 54 locations and plotted as a function of bankfull discharge. Hydraulic geometry equations of the form of Equations 2, 3, and 4, corresponding R^2, and CV values are presented in Table 8 for non-urban and urban streams. Hydraulic geometry for data stratified by cover type is presented in Figure 8. Bankfull cross-sectional area vs. bankfull discharge showed a very strong relationship for both cover types. Bankfull discharge can explain 93% of the variability in cross-sectional area for the combined regional dataset. There was very little change in R^2 between both cover types. Stratifying the data by cover type improved the explanatory power of the regression equations slightly for non-urban and urban streams, shown by an increase in R^2 to 0.94 for both cover types. Furthermore, there is little difference in exponents between the regression equations, ranging from 0.7927 to 0.8506.

Table 8. Bankfull cross-sectional area hydraulic geometry relationships for the combined dataset and non-urban and urban cover types. A_{bkf} is the bankfull cross-sectional area in ft^2 and Q_{bkf} is the bankfull discharge in ft^3 s^1.

Cover Type	Regression Equation	R^2	CV
Combined Regional	A_{bkf}=0.6577$Q_{bkf}^{0.8506}$	0.93	0.3103
Non-Urban	A_{bkf}=0.6957$Q_{bkf}^{0.0.8504}$	0.94	0.3359
Urban	A_{bkf}=0.8244$Q_{bkf}^{0.7927}$	0.94	0.2206

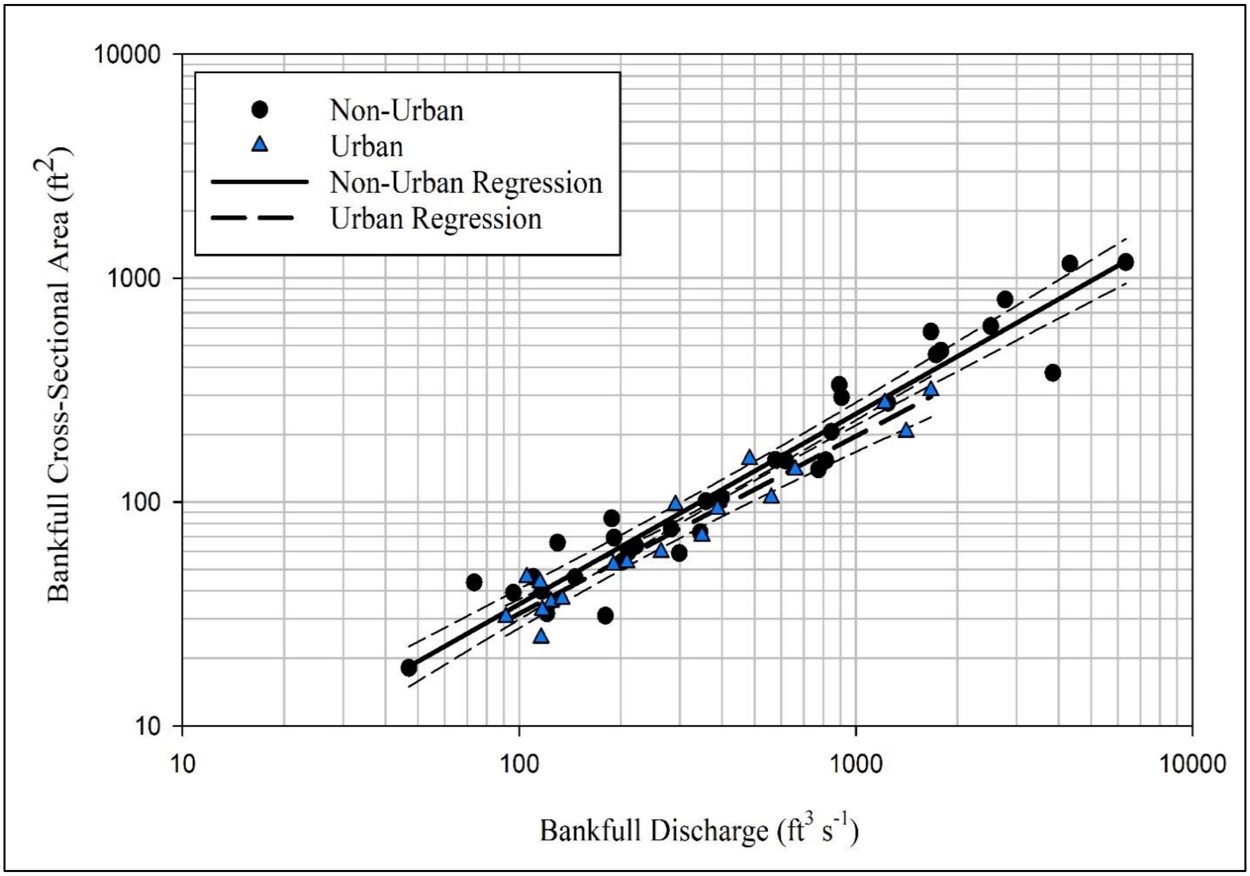

Figure 8. Bankfull cross-sectional area as a function of the bankfull discharge for non-urban and urban streams with 95% confidence intervals.

Bankfull Width

Hydraulic geometry equations, R^2, and CV values are presented in Table 9 for non-urban and urban streams. Hydraulic geometry for data stratified by cover type is presented in Figure 9. Bankfull width vs. bankfull discharge showed a very strong relationship for both cover types. Bankfull discharge can explain 87% of the variability in bankfull width for the combined regional dataset. There was very little change in R^2 between both cover types. Stratifying the data by cover type improved the explanatory power of the regression equations for urban streams, shown by an increase in R^2 to 0.88. For non-urban streams, the explanatory power of the regression equation was the same as the combined dataset. Furthermore, there is little difference in exponents between the regression equations, ranging from 0.4932 to 0.5145.

Table 9. Bankfull width hydraulic geometry relationships for the combined dataset and non-urban and urban cover types. W_{bkf} is the bankfull width in ft, and Q_{bkf} is the bankfull discharge in $ft^3\ s^1$.

Cover Type	Regression Equation	R^2	CV
Combined Regional	$W_{bkf}=1.7904Q_{bkf}^{0.5145}$	0.87	0.2693
Non-Urban	$W_{bkf}=2.0111Q_{bkf}^{0.5043}$	0.87	0.2891
Urban	$W_{bkf}=1.8283Q_{bkf}^{0.4932}$	0.88	0.1921

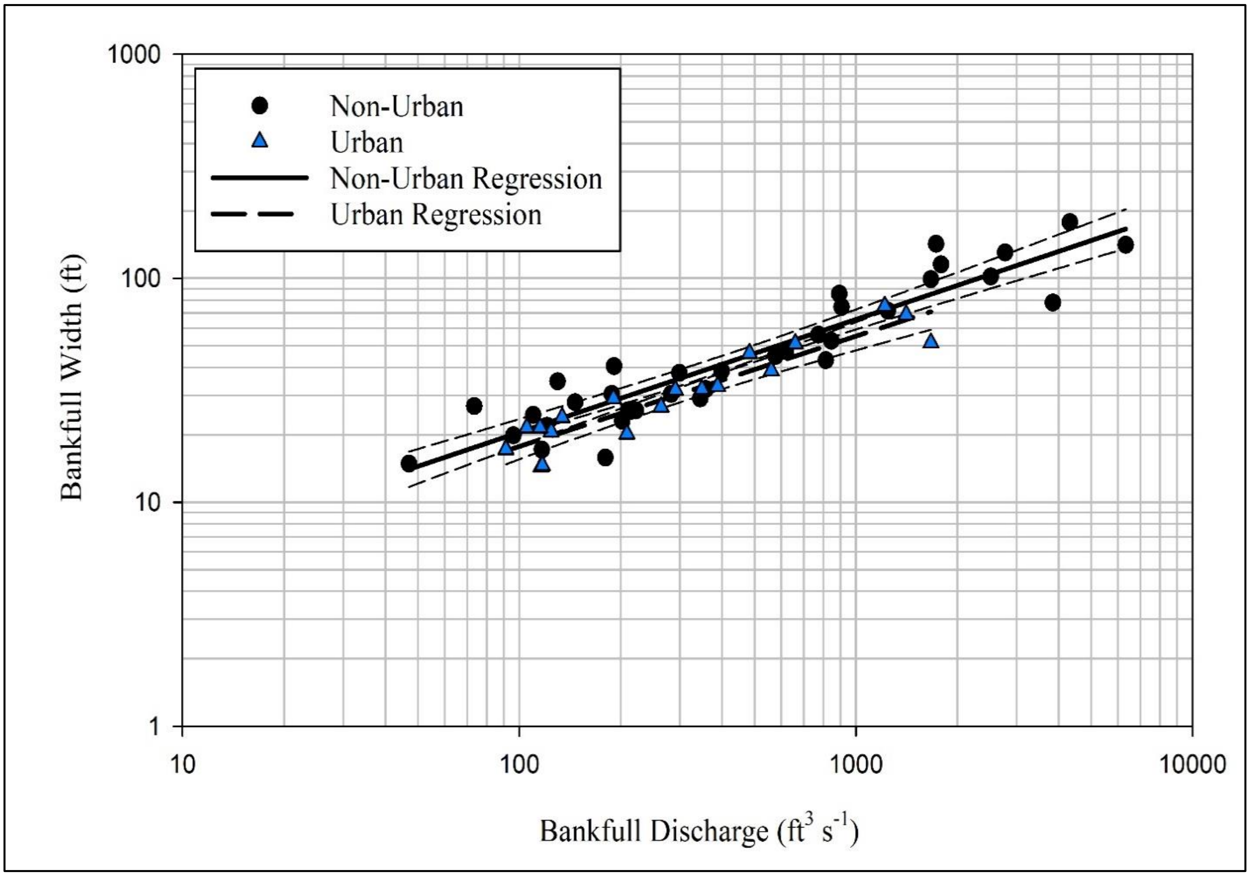

Figure 9. Bankfull width as a function of the bankfull discharge for non-urban and urban streams with 95% confidence intervals.

Bankfull Mean Depth

Hydraulic geometry equations, R^2, and CV values are presented in Table 10 for non-urban and urban streams. Hydraulic geometry for data stratified by cover type is presented in Figure 10. Bankfull width vs. bankfull discharge showed a very strong relationship for both cover types. Bankfull discharge can explain 84% of the variability in bankfull mean depth for the combined regional dataset. Stratification had divergent effects on R^2 for urban and non-urban cover types. Stratifying the data by cover type improved the explanatory power of the regression equations for non-urban streams, shown by an increase in R^2 to 0.87; however, a decrease in R^2 to 0.71 was seen for urban streams. Urban streams also had a significantly lower R^2 when compared to non-urban streams. This would suggest that bankfull discharge is less effective at predicting bankfull mean depth for urban streams within the dataset. There is little difference in exponents between the regression equations, ranging from 0.2987 to 0.3533.

Table 10. Bankfull mean depth hydraulic geometry relationships for the combined dataset and non-urban and urban cover types. D_{bkf} is the mean bankfull mean depth in ft, and Q_{bkf} is the bankfull discharge in $ft^3 s^1$.

Cover Type	**Regression Equation**	**R^2**	**CV**
Combined Regional	$D_{bkf}=0.3578Q_{bkf}^{0.3418}$	0.84	0.1955
Non-Urban	$D_{bkf}= 0.3345Q_{bkf}^{0.3533}$	0.87	0.1953
Urban	$D_{bkf}=0.4548Q_{bkf}^{0.2987}$	0.71	0.2010

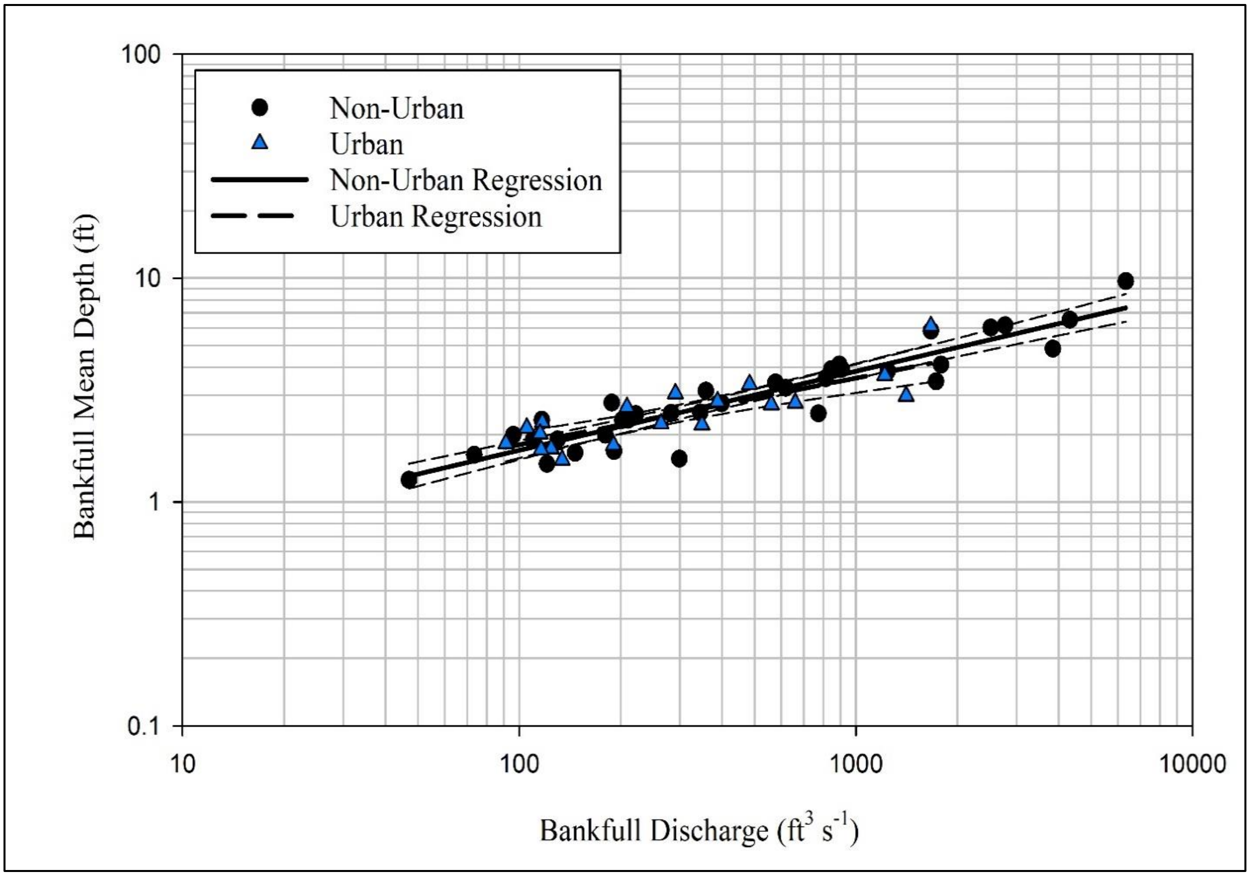

Figure 10. Bankfull mean depth as a function of the bankfull discharge for non-urban and urban streams with 95% confidence intervals.

Bankfull Velocity

Hydraulic geometry equations, R^2, and CV values are presented in Table 11 for non-urban and urban streams. Hydraulic geometry for data stratified by cover type is presented in Figure 11. Bankfull velocity vs. bankfull discharge showed a moderate relationship for both cover types. Bankfull discharge can explain 29% of the variability in bankfull velocity for the combined regional dataset. Stratifying the data by cover type improved the explanatory power of the regression equations for urban streams, shown by an increase in R^2 to 0.57. For non-urban streams, the explanatory power of the regression equation was the same as the combined dataset. There is a significant difference in R^2 between both cover types, which may result from some influential channel characteristics such as slope, bed material, large woody debris, and vegetation. The exponent values of the regression equations range from 0.1368 to 0.2376. The urban regression equation has a significantly steeper slope than the combined regional and non-urban dataset, and as the drainage area increases, the difference between bankfull velocity estimates increases.

Table 11. Bankfull velocity hydraulic geometry relationships for the combined dataset and non-urban and urban cover types. V_{bkf} is the bankfull velocity in ft $s^{-1,}$ and Q_{bkf} is the bankfull discharge in ft^3 s^1.

Cover Type	Regression Equation	R^2	CV
Combined Regional	$V_{bkf}=1.5314Q_{bkf}^{0.1441}$	0.29	0.3050
Non-Urban	$V_{bkf}= 1.4846Q_{bkf}^{0.1368}$	0.29	0.3151
Urban	$V_{bkf}=1.0029Q_{bkf}^{0.2376}$	0.57	0.2231

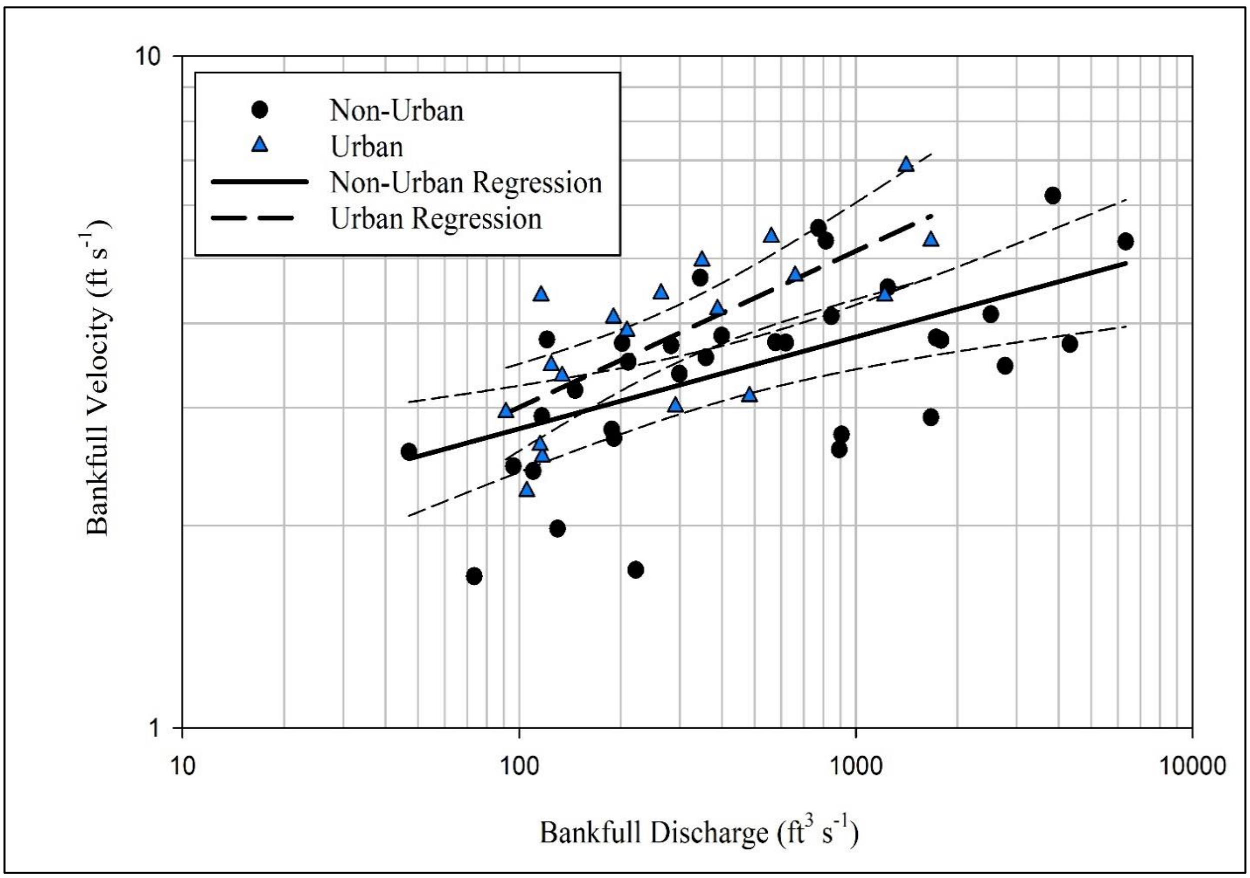

Figure 11. Bankfull velocity as a function of the bankfull discharge for non-urban and urban streams with 95% confidence intervals.

Bankfull Slope

Hydraulic geometry equations, R^2, and CV values are presented in Table 12 for non-urban and urban streams. Hydraulic geometry for data stratified by cover type is presented in Figure 12. Bankfull slope vs. bankfull discharge showed a poor relationship for both cover types. Bankfull discharge can explain 14% of the variability in bankfull slope for the combined regional dataset. There is a significant difference in R^2 between both cover types. Stratifying the data by cover type improved the explanatory power of the regression equations for non-urban streams shown by an increase in R^2 to 0.15. A decrease in R^2 to 0.02 was observed for urban streams. Urban streams also had a significantly lower R^2 when compared to non-urban streams. This would suggest that bankfull discharge is not as effective at predicting bankfull slope for urban streams within the dataset. Furthermore, bankfull discharge is a poor predictor of bankfull slope, and care should be exercised when analyzing this relationship. The exponent values of the regression equations range from -0.2790 to -0.1110. The urban regression equation has a gentler slope than the combined regional and non-urban datasets, and as drainage area increases, the difference between bankfull slope estimates increases.

Table 12. Bankfull slope hydraulic geometry relationships for the combined dataset and non-urban and urban cover types. S_{bkf} is the bankfull slope in ft $ft^{-1,}$ and Q_{bkf} is the bankfull discharge in ft^3 s^1.

Cover Type	Regression Equation	R^2	CV
All	S_{bkf}=0.0105Q_{bkf} $^{-0.2790}$	0.14	1.2806
Non-Urban	S_{bkf}= 0.0074Q_{bkf} $^{-0.2600}$	0.15	1.2151
Urban	S_{bkf}=0.0061Q_{bkf} $^{-0.1110}$	0.02	1.0687

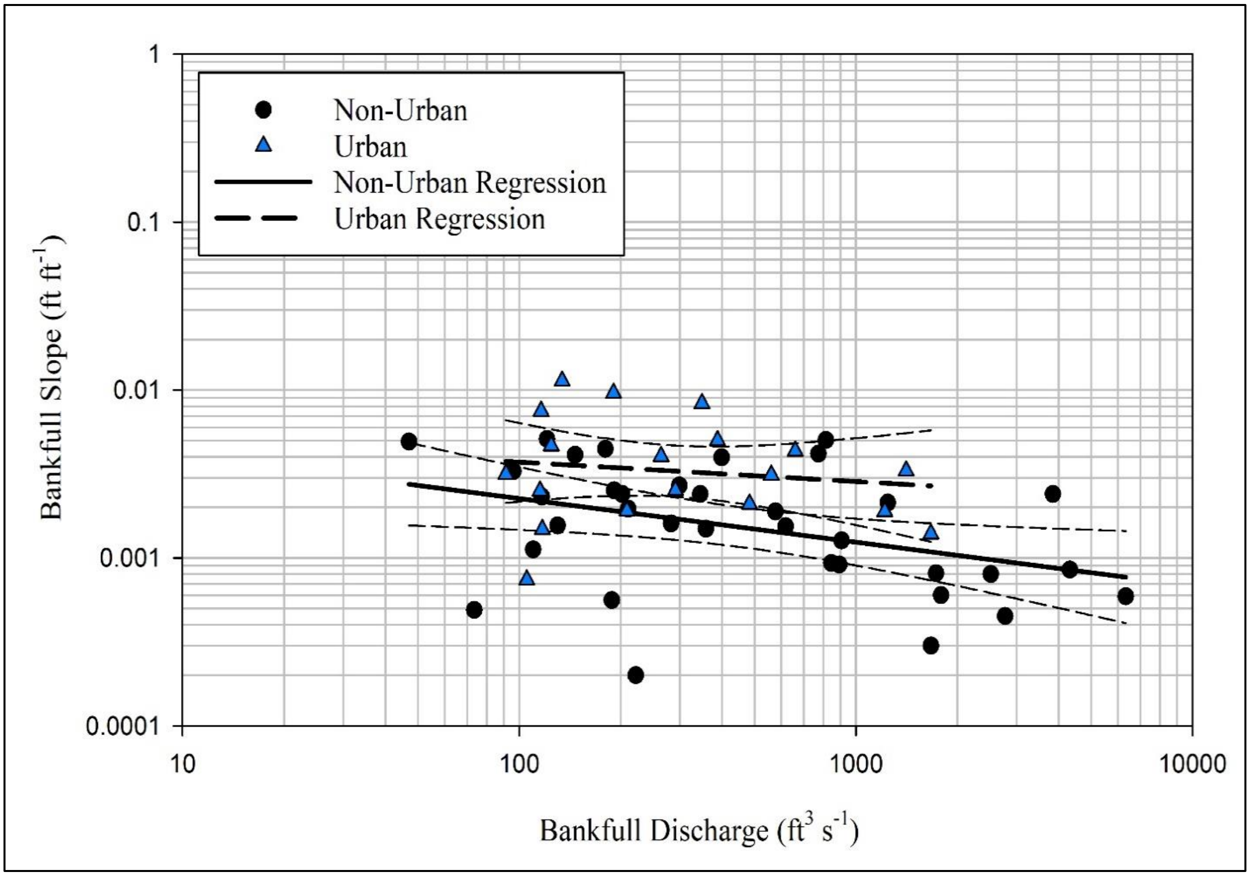

Figure 12. Bankfull slope as a function of the bankfull discharge for non-urban and urban streams with the combined regional regression with 95% confidence intervals.

Statistical Analysis

Results from the statistical model testing for cover type as a significant interaction term are presented in Table 13. The model does not provide sufficient evidence that urban regressions have significantly different slopes (p-value > 0.05) or intercepts (p-value > 0.05) from the non-urban control condition for all bankfull parameters.

Table 13. Bankfull channel hydraulic geometry relationships with associated p-values for non-urban and urban cover types.

Bankfull Parameter	Cover Type	Intercept p-value	Slope p-value
Cross-Sectional Area	Non-Urban	-	-
	Urban	0.7090	0.4520
Width	Non-Urban	-	-
	Urban	0.8011	0.9720
Mean Depth	Non-Urban	-	-
	Urban	0.3170	0.2970
Slope	Non-Urban	-	-
	Urban	0.8968	0.5170
Velocity	Non-Urban	-	-
	Urban	0.3866	0.1886

Flood Region Regional Curves in Non-Urban Cover Types

Bankfull Cross-Sectional Area

Bankfull cross-sectional area was determined from survey data for all 35 non-urban locations. Regional curve equations, R^2, and CV values are presented in Table 14 for each of Iowa's flood regions and the non-urban dataset. Regional curves for data stratified by flood region are presented in Figure 13. Bankfull cross-sectional area vs. drainage area showed a very strong relationship for all regions. Watershed drainage area can explain 94% of the variability in cross-sectional area for the non-urban dataset. Stratifying the data by flood region provided mixed results. Flood Region 2 showed an increase in R^2 to 0.96, Flood Region 3 a decrease in R^2 to 0.93, and Flood Region 1 neither increased nor decreased. The range of exponents for the regression equations is from 0.6951 to 0.8291. Minor differences are seen between flood regions, with Flood Region 1 having the smallest exponent of 0.6951 and Flood Region 2 having the largest, 0.8291. The most significant difference between flood region curves is for drainage areas greater than 100 mi^2.

Table 14. Bankfull cross-sectional area regression relationships for the non-urban combined dataset and three of Iowa's flood regions. A_{bkf} is the bankfull cross-sectional area in ft^2 and A_w is the watershed drainage area in mi^2.

Region	Regression Equation	R^2	CV
Non-Urban	$A_{bkf}=7.7275A_w^{0.7497}$	0.94	0.3318
Flood Region 1	$A_{bkf}=9.0960A_w^{0.6951}$	0.94	0.3548
Flood Region 2	$A_{bkf}= 5.8609A_w^{0.8291}$	0.96	0.3284
Flood Region 3	$A_{bkf}=7.2357A_w^{0.7774}$	0.93	0.3032

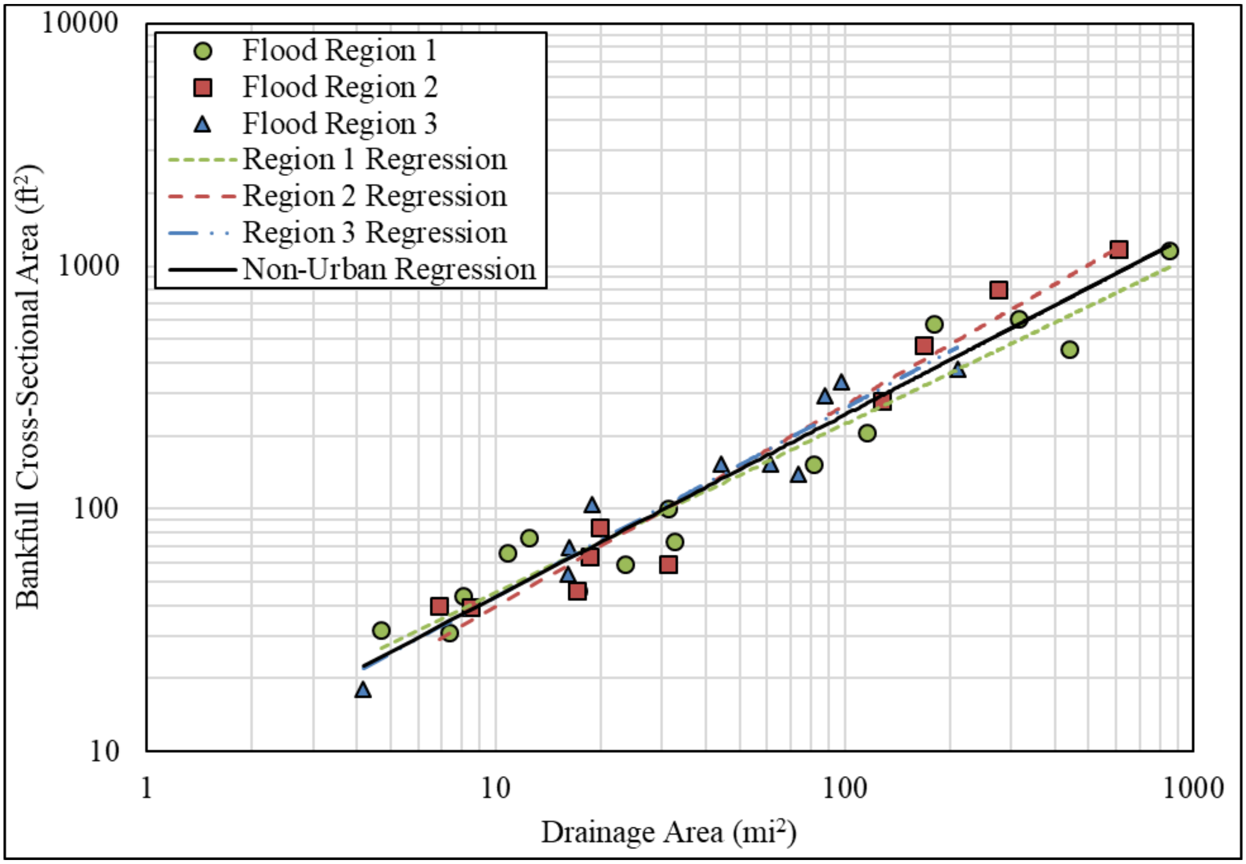

Figure 13. Bankfull cross-sectional area as a function of the drainage area for Iowa's three flood regions and the non-urban regression of the combined dataset.

Bankfull Width

Bankfull width was determined from survey data for all 35 locations. Regional curve equations, R^2, and CV values are presented in Table 15. Regional curves for data stratified by flood regions are presented in Figure 14. Bankfull width vs. drainage area showed a very strong relationship for all regions. Watershed drainage area can explain 91% of the variability in bankfull width for the non-urban dataset. Stratifying the data by flood region provided mixed results. Flood Region 2 showed an increase in R^2 to 0.96, Flood region 3 a decrease in R^2 to 0.87, and Flood Region 1 neither increased nor decreased. The range of exponents for the regression equations is from 0.4218 to 0.5196. Minor differences are seen between flood regions, with Flood Region 1 having the smallest exponents of 0.4218 and Flood Region 2 having the largest, 0.5196. The most significant difference between flood region curves is when drainage areas are greater than 100 mi^2 and less than 10 mi^2.

Table 15. Bankfull width regression relationships for the non-urban combined dataset and three of Iowa's flood regions. W_{bkf} is the bankfull width in ft, and A_w is the watershed drainage area in mi^2.

Region	Regression Equation	R^2	CV
Non-Urban	$W_{bkf}=8.0857A_w^{0.4543}$	0.91	0.2364
Flood Region 1	$W_{bkf}=9.1264A_w^{0.4218}$	0.91	0.2578
Flood Region 2	$W_{bkf}=6.0670A_w^{0.5196}$	0.96	0.2037
Flood Region 3	$W_{bkf}=8.7653A_w^{0.4429}$	0.87	0.2377

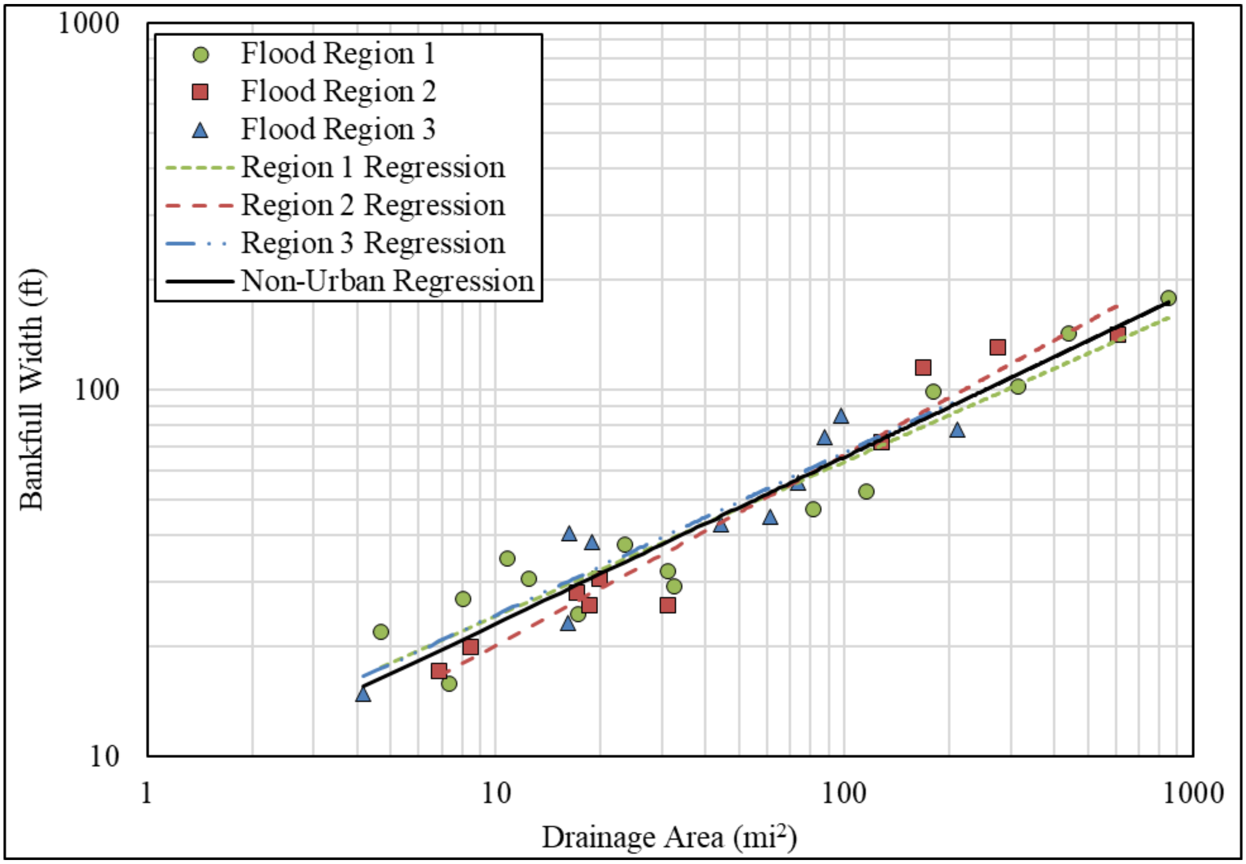

Figure 14. Bankfull width as a function of the drainage area for Iowa's three flood regions and non-urban regression of the combined dataset.

Bankfull Mean Depth

Bankfull mean depth was determined from survey data for all 35 locations. Regional curve equations, R^2, and CV values are presented in Table 16 for Iowa's flood regions and the non-urban regional data set. Regional curves for data stratified by flood region is presented in Figure 15. Bankfull mean depth vs. drainage area showed a very strong relationship for all regions. Watershed drainage area can explain 82% of the variability in bankfull width for the non-urban dataset. Stratifying the data by flood region provided mixed results. Flood Region 2 and Flood Region 3 showed an increase in R^2 to 0.86 and 0.83, respectively, while Flood Region 1 showed a decrease in R^2 to 0.81. Minor differences are seen between flood regions, with Flood

Region 1 having the smallest exponent of 0.2761 and Flood Region 3 having the largest, 0.3336. The most significant difference between flood region curves is seen as drainage areas increase above 10 mi^2.

Table 16. Bankfull mean depth regression relationships for the non-urban combined dataset and three of Iowa's flood regions. D_{bkf} is the bankfull mean depth in ft, and A_w is the watershed drainage area in mi^2.

Region	**Regression Equation**	R^2	**CV**
Non-Urban	$D_{bkf}= 0.9428A_w^{0.3018}$	0.82	0.2343
Flood Region 1	$D_{bkf}=0.9946A_w^{0.2761}$	0.81	0.2546
Flood Region 2	$D_{bkf}=0.9224A_w^{0.3260}$	0.86	0.2475
Flood Region 3	$D_{bkf}=0.8343A_w^{0.3336}$	0.83	0.2035

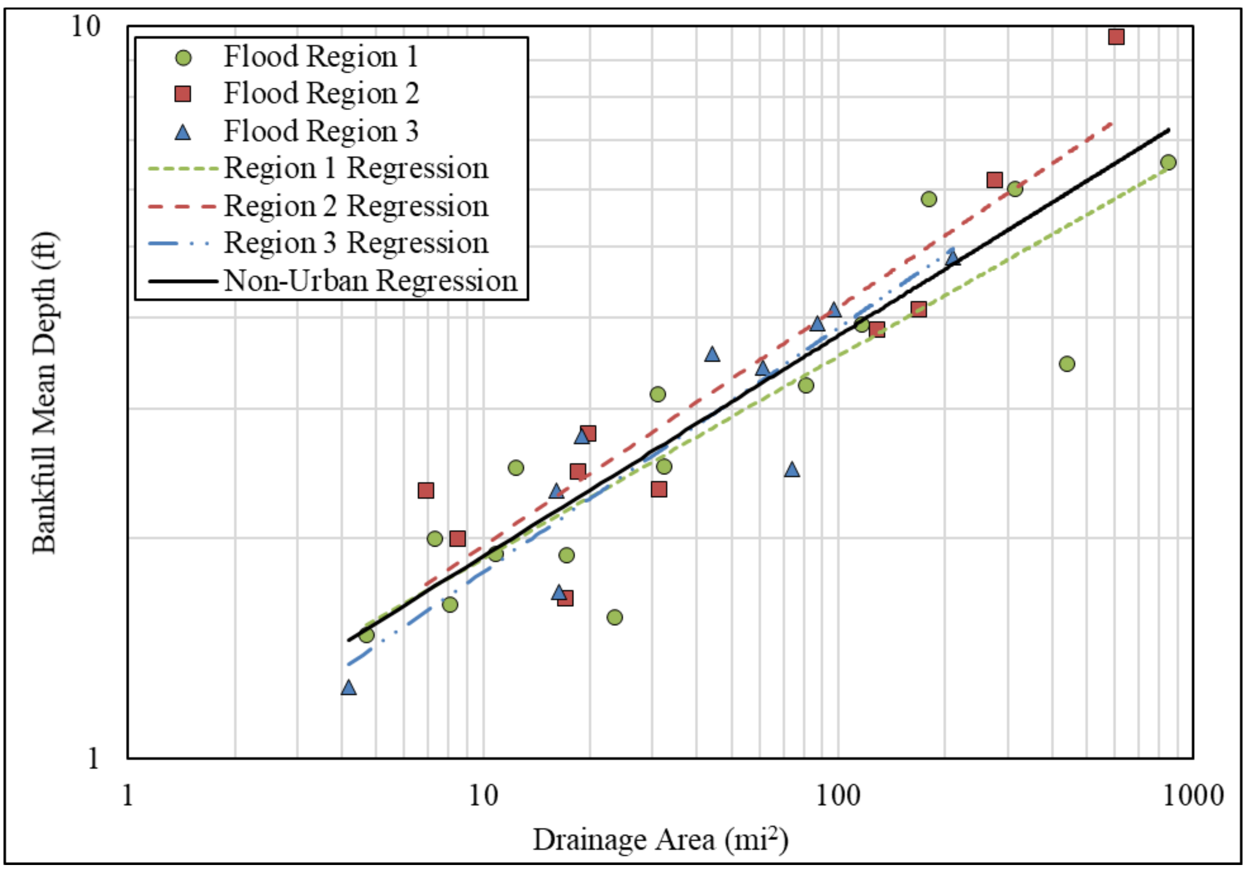

Figure 15. Bankfull mean depth as a function of the drainage area for Iowa's three flood regions and non-urban regression of the combined dataset.

Bankfull Discharge

Bankfull discharge was determined from survey data for all 35 locations. Regional curve equations, R^2, and CV values are presented in Table 17 for Iowa's flood regions and the non-urban regional data set. Regional curves for data stratified by flood region is presented in Figure 16. Bankfull discharge vs. drainage area showed a very strong relationship for all regions. Watershed drainage area can explain 92% of the variability in bankfull discharge for the non-urban dataset. Stratifying the data by flood region provided mixed results. Flood Region 2 and Flood Region 3 showed an increase in R^2 to 0.98 and 0.93, respectively, while Flood Region 1 neither increased nor decreased. Significant differences are seen between flood regions, with Flood Region 1 having the smallest exponent of 0.7374 and Flood Region 3 having the largest, 0.9940. The most significant difference between flood region curves is seen as drainage areas increase above 50 mi^2.

Table 17. Bankfull discharge regression relationships for the non-urban combined dataset and three of Iowa's flood regions. Q_{bkf} is the bankfull discharge in $ft^3\ s^{-1}$ and A_w is the watershed drainage area in mi^2.

Region	Regression Equation	R^2	CV
Non-Urban	$Q_{bkf}= 19.3464A_w^{0.8465}$	0.92	0.4311
Flood Region 1	$Q_{bkf}=27.2830A_w^{0.7374}$	0.92	0.4313
Flood Region 2	$Q_{bkf}=11.9842A_w^{0.9608}$	0.98	0.2740
Flood Region 3	$Q_{bkf}=12.9952A_w^{0.9940}$	0.93	0.3789

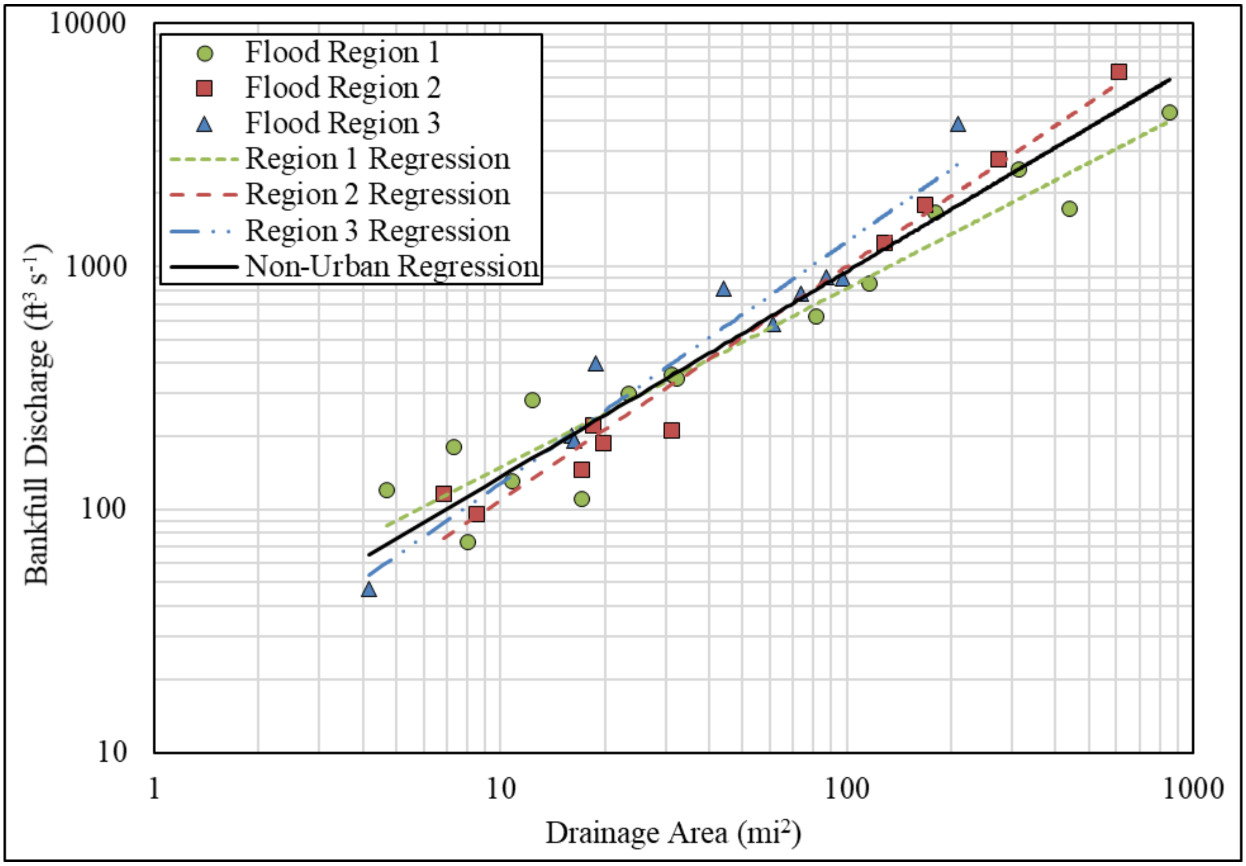

Figure 16. Bankfull discharge as a function of the drainage area for Iowa's three flood regions and non-urban regression of the combined dataset.

Statistical Analysis

Results from the statistical model testing for flood regions as a significant interaction term are presented in Table 18. The model does not provide sufficient evidence that Flood Region 2 and Flood Region 3 regressions have significantly different slopes (p-value > 0.05) or intercepts (p-value > 0.05) from the Flood Region 1 control condition for bankfull cross-sectional area, width and mean depth. There is evidence that bankfull discharge has significantly different slopes for Flood Region 2 (p-value = 0.0149) and Flood Region 3 (p-value = 0.0221) when compared to the Flood Region 1 control condition.

Table 18. Bankfull channel parameters with associated p-values for Iowa's three flood regions.

Bankfull Parameter	Region	Intercept p-value	Slope p-value
Cross-Sectional Area	Flood Region 1	-	-
	Flood Region 2	0.1773	0.0952
	Flood Region 3	0.5418	0.3958
Width	Flood Region 1	-	-
	Flood Region 2	0.0939	0.1002
	Flood Region 3	0.8843	0.7673
Mean Depth	Flood Region 1	-	-
	Flood Region 2	0.752	0.396
	Flood Region 3	0.53	0.425
Discharge	Flood Region 1	-	-
	Flood Region 2	0.0270	0.0149
	Flood Region 3	0.0820	0.0221

Analysis of Return Periods

Bankfull return periods were calculated for all gaged locations and presented in Table 19. Comparing the estimated bankfull discharge to the 1.5-year discharge provides a valuable comparison and quality control metric in estimated discharge values. The Log Pearson Type III recurrence interval range for the combined regional dataset is 1.1078 – 1.6990 with an average of 1.3966 years. The Log Pearson Type III recurrence interval range for the non-urban data set is 1.1661 – 1.6990 with an average of 1.4499 years. For the urban dataset, the recurrence interval range is 1.1078 – 1.5184, with an average of 1.2975. There is an 11% reduction in recurrence interval for urban streams compared to non-urban streams.

Table 19. Estimated bankfull discharge and 1.5-year discharge used to calculate recurrence intervals for all surveyed gaged reaches.

Site Name	Gage ID	Latitude	Longitude	Estimated Discharge $ft^3 s^{-1}$	1.5-year Discharge $ft^3 s^{-1}$	Recurrence Interval (years)	Percent Impervious
Waterloo Creek near Dorchester, IA	05388310	43.44800	-91.50584	814	885	1.4335	5.3
Yellow River near Ion, IA	05389000	43.12412	-91.28636	2454	3846	1.1878	5.0
Maquoketa River at Manchester, IA	05416900	42.47173	-91.44988	2773	3396	1.3673	5.9
Crow Creek at Bettendorf, IA	05422470	41.56701	-90.47404	561	580	1.4723	36.5
Duck Creek at Davenport, IA	05422600	41.54956	-90.54994	1670	2358	1.1921	37.8
Muddy Creek at Coralville, IA	05454090	41.70028	-91.56256	291	671	1.1078	61.9
South Branch Ralston Creek at Iowa City, IA	05455010	41.65076	-91.50853	209	291	1.2218	77.6
Hoover Creek at Hoover National Historic Site	05464942	41.66966	-91.35029	117	142	1.3812	19.6
Keigley Branch near Story City, IA	05469990	42.14829	-93.61908	345	355	1.4717	4.7
South Skunk River near Ames, IA	05470000	42.06406	-93.61956	2516	2198	1.6577	6.5
Bluff Creek at Pilot Mound, IA	05481510	42.16637	-94.01995	299	287	1.5446	4.0
Walnut Creek at Des Moines, IA	05484800	41.58703	-93.70360	1219	1919	1.1888	45.5
Fourmile Creek near Ankeny, IA DS1	05485605	41.71710	-93.57044	1410	1388	1.5184	18.7
Fox River at Bloomfield, IA	05494300	40.76918	-92.41379	907	2109	1.1661	5.3
Little Floyd River near Sanborn, IA	06600030	43.18534	-95.72794	96	100	1.4577	9.2
Ocheyedan River near Spencer, IA	06605000	43.12898	-95.22049	1730	1809	1.4591	5.4
Willow Creek near Cornell, IA	06605750	42.97492	-95.15986	619	569	1.5828	4.1
West Nishnabotna River at Hancock, IA	06807410	41.38612	-95.37448	6331	5130	1.6990	5.3
Walnut Creek in Jasper County	WQS0047	41.59923	-93.29535	117	150	1.4088	5.4
Walnut Creek in Story County	WQS0053	41.95517	-93.64005	180	202	1.4132	4.9
Combined Dataset Mean	-	-	-	1233	1419	1.3966	18.4
Non-Urban Dataset Mean	-	-	-	1475	1618	1.4499	5.5
Urban Dataset Mean	-	-	-	782	1050	1.2975	42.5

CHAPTER 4. DISCUSSION

Comparison with Regional Curves Developed by Bieger et al. (2015)

Many regional curves have been developed across the United States. While many of these curves were developed in the country's eastern regions, Bieger et al. (2015) gathered data published by almost 50 different authors filling in many spatial gaps in regional curve studies. Their analysis developed regression equations for the Central Lowland physiographic province and the Interior Plains physiographic division, within which the entire Iowa state boundary resides. Nationwide regression equations were also developed. A significant amount of the data used to construct the bankfull regression equations for the Interior Plains physiographic division and Central Lowland physiographic province was retrieved from data collected in Iowa by Eash (1993). Data collected by Eash (1993) accounted for bankfull channel width and depth data from 111 gaged sites across Iowa. A comparison between the regression equations presented here and those developed by Bieger et al. (2015) and Eash (1993) is presented in Table 20. Graphical representations of these regional curves are presented in Figures 17-19.

A comparison of bankfull cross-sectional area regressions from the multiple studies are presented in Figure 17. Exponents for the regional curves presented in Table 20 have a possible range of values between 0.460 and 0.750. The Iowa Non-Urban exponent is larger than the others, with an exponent value of 0.750. This difference is seen in Figure 17, where the Iowa Non-Urban curve has a markedly steeper slope than the others. The Iowa Non-Urban, Iowa Urban, and Eash (1993) regional curves have significantly different intercept terms than the others. For the Iowa Urban and Eash (1993) regional curves, this provides valuable information since it appears that a difference in slope is not the reason for this, as is the case for the Iowa Non-Urban curve. The regional curves developed in this study and by Eash (1993) explain more of the variability in bankfull cross-sectional area as seen by significantly higher R^2 values. This suggests that more refined stratification from the province level improves the model's capability of predicting bankfull cross-sectional area.

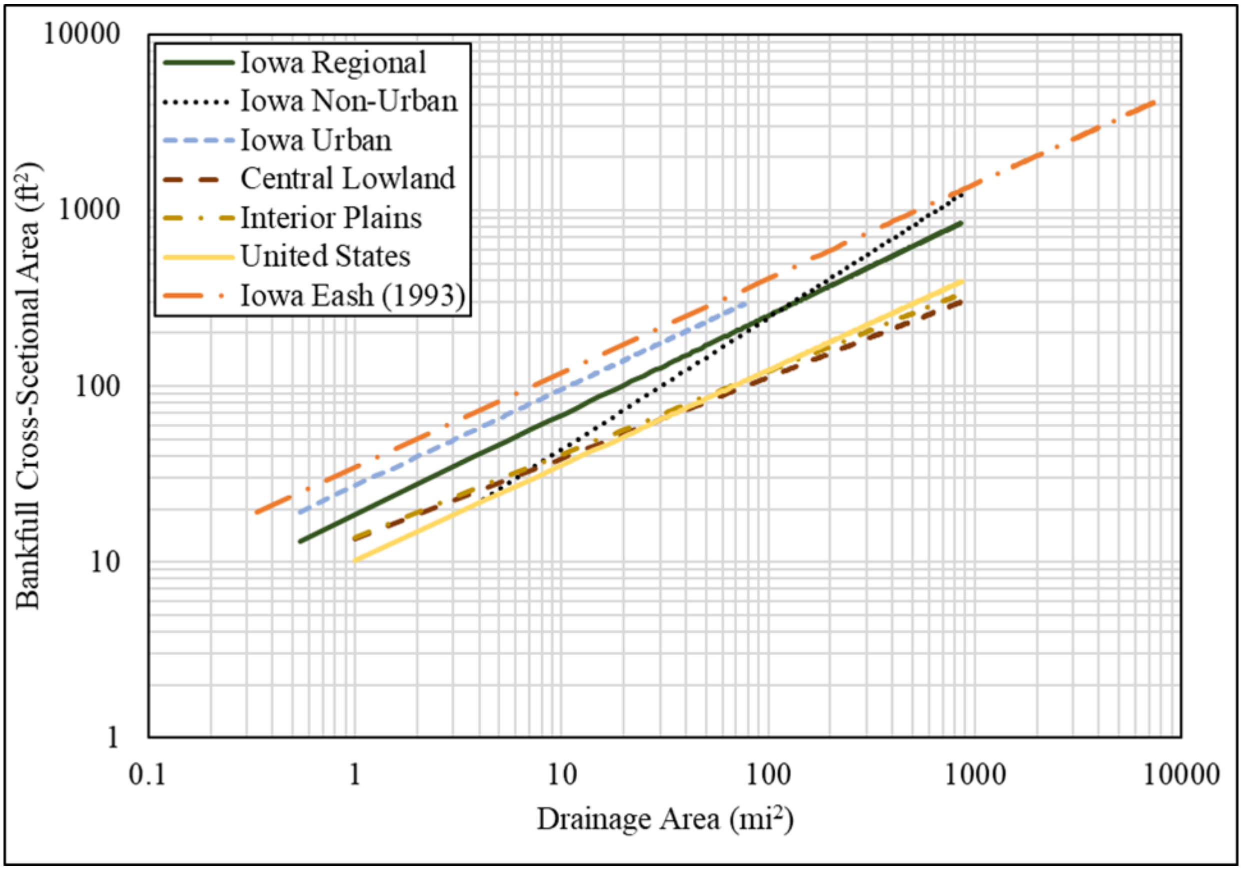

Figure 17. Comparison of bankfull cross-sectional area regional curves relevant for Iowa streams

Bankfull width regressions are presented in Figure 18. The exponents for the regional curves presented in Table 20 are similar, with the possible range of exponent values from 0.340 to 0.454. The Iowa Non-Urban has the highest exponents at 0.454. The Iowa Non-Urban and the Eash (1993) regional curves can explain more of the variability in bankfull width and have the highest R^2 values of 0.91. This suggests that more refined stratification from the province level improves the model's capability of predicting bankfull width. Like the bankfull cross-sectional regional curves, the Iowa Urban curve has a slope similar to many of the other regional curves with a stark increase in its intercept. This is similar to the pattern observed by Doll et al. (2002) and Hammer (1972), where urban streams share similar slopes to non-urban streams with significantly larger intercepts.

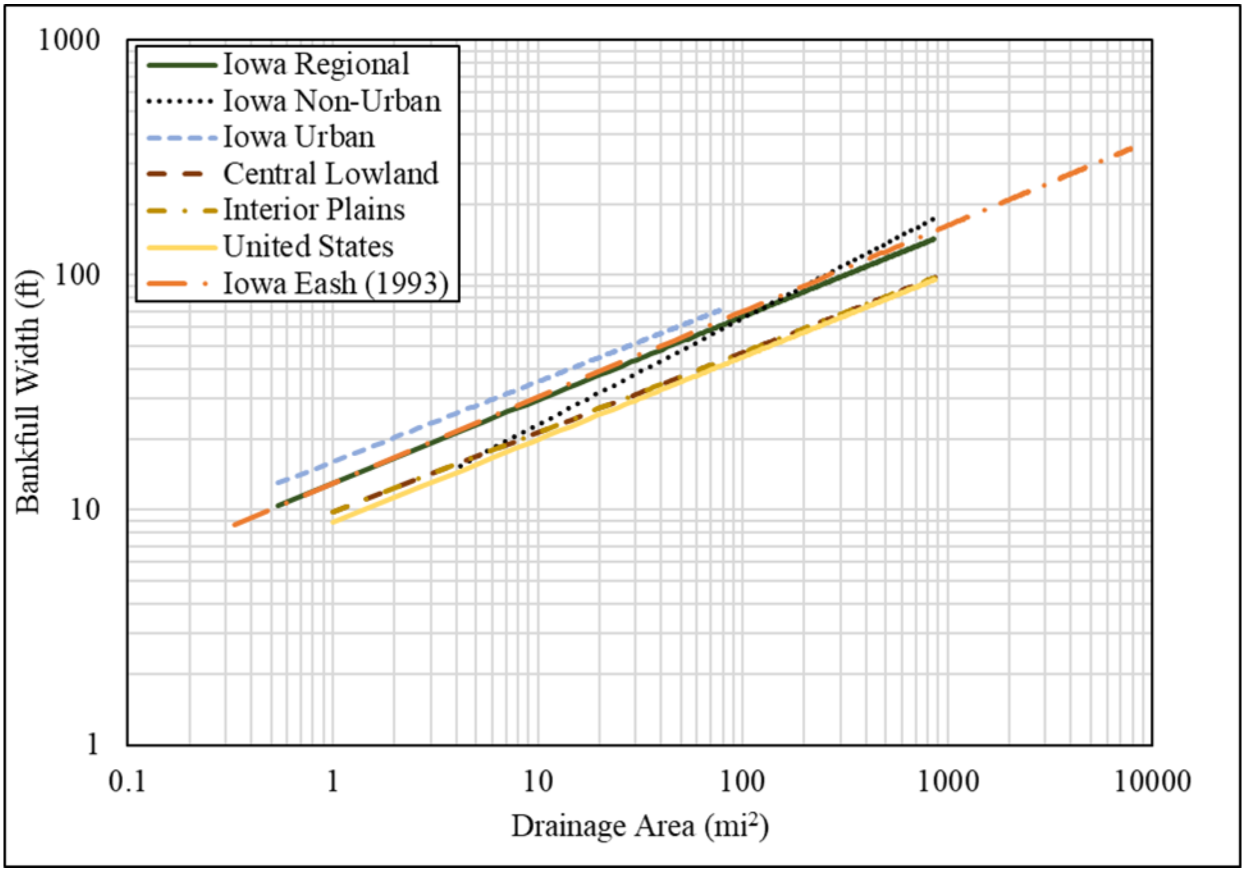

Figure 18. Comparison of bankfull width regional curves relevant for Iowa streams

Bankfull depth regressions are presented in Figure 19. The exponents for the regional curves presented in Table 20 have a possible range of exponent values between 0.170 to 0.302. The Iowa Non-Urban exponent is larger than the others, with an exponent of 0.302. This is seen in Figure 19, where the Iowa Non-Urban curve has a markedly steeper slope than the others. There is a greater separation between the regional curves, which is likely a cause of the weaker relationship between bankfull depth and drainage area compared to the other bankfull parameters. The Eash (1993) regional curve shows the greatest separation from the other curves with an intercept value that is noticeably larger than the others. The regional curves developed in this study can explain more of the variability in bankfull depth as seen by significantly higher R^2 values. This suggests that more refined stratification from the province level improves the model's capability of predicting bankfull depth.

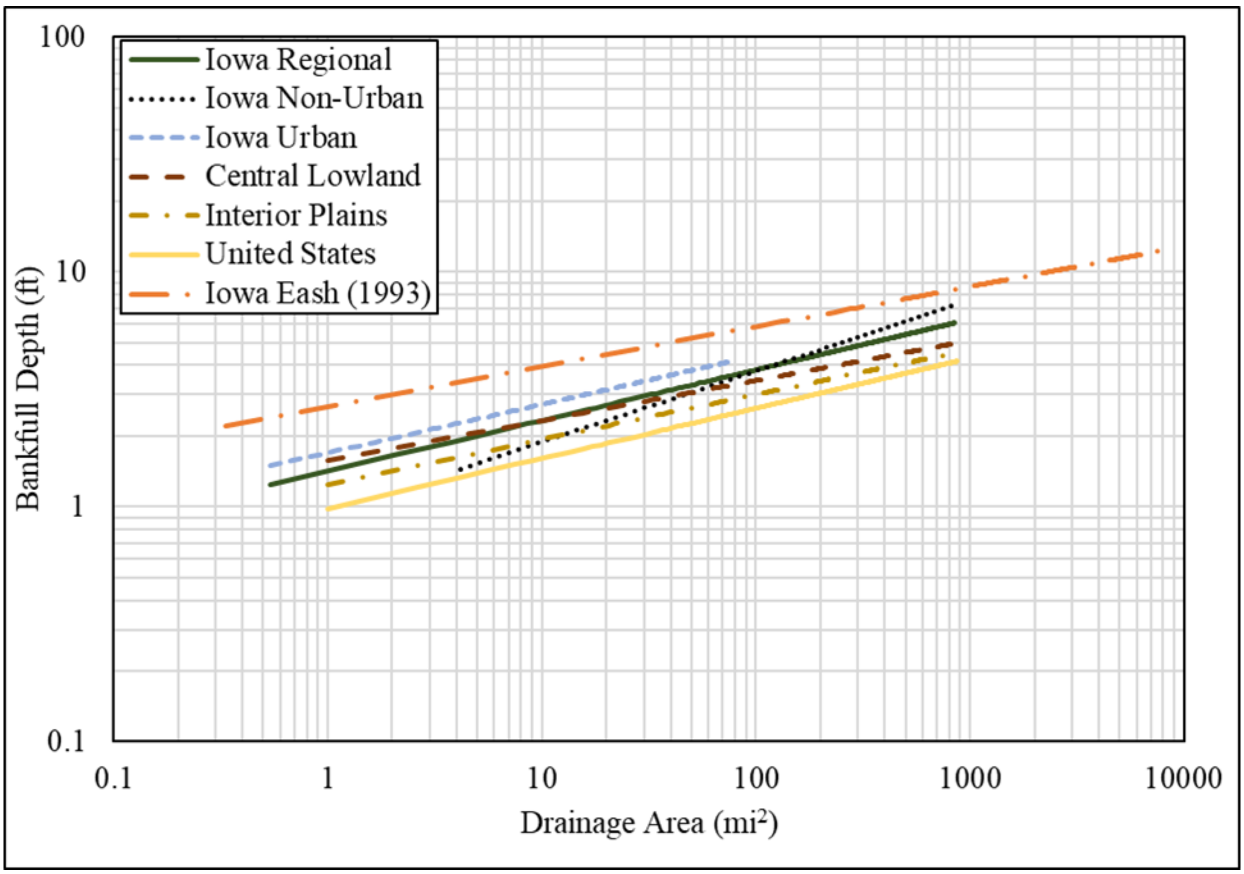

Figure 19. Comparison of bankfull depth regional curves relevant for Iowa streams

Table 20. Comparison of regional curves relevant for Iowa streams, where m is the regression intercept in standard units, and b is the regression slope for bankfull cross-sectional area, width, and depth.

Regional Curves	Cross-Sectional Area			Width			Depth		
	m	b	R^2	m	B	R^2	m	b	R^2
Iowa Regional	18.62	0.565	0.83	13.05	0.354	0.83	1.42	0.216	0.67
Iowa Non-Urban	7.73	0.750	0.94	8.09	0.454	0.91	0.94	0.302	0.82
Iowa Urban	27.07	0.549	0.92	16.05	0.341	0.86	1.69	0.207	0.69
Beiger et al. (2015) Central Lowland Province	13.45	0.460	0.66	9.78	0.340	0.79	1.57	0.170	0.34
Beiger et al. (2015) Interior Plains Division	13.78	0.472	0.65	8.40	0.351	0.75	1.25	0.191	0.38
Beiger et al. (2015) United States	10.23	0.540	0.58	8.86	0.352	0.66	0.98	0.213	0.43
Eash (1993)	34.69	0.536	0.87	13.01	0.366	0.91	2.67	0.170	0.57

Statistical Comparison to Eash (1993) Bankfull Regional Curves

Bankfull regional curves presented in this study were compared to the data collected by Eash (1993). Seven of the gaged reaches presented herein were surveyed by Eash (1993), accounting for 35% of the gaged sites included in this study. Eash's (1993) data was used to develop a bankfull cross-sectional area, width, and depth regression equations (Table 20) to compare against the combined Iowa Regional regression. Data points and regression lines are presented in Figures 20-22. Statistical analysis testing for a difference between the regional curves is presented in Table 21. The statistical methods used in this study were employed to test for significant differences between these regional curves. The analysis suggests that bankfull cross-sectional area and depth regression equations developed in this study have significantly similar slopes with different intercepts to that of the Eash (1993) regressions. However, the bankfull width regression equations developed in this study have similar intercepts and slopes with p-values of 0.973 and 0.591, respectively. There are discrepancies in statistically significant differences in the bankfull parameter intercepts between the regressions developed in this study to that of Eash (1993). A difference in survey methods and site selection procedures from those presented in this study could explain the larger intercept values of the bankfull depth and subsequent bankfull cross-sectional area regressions. Still, they all show significant similarities in their regression slopes. It follows that we may fail to reject the null hypothesis and conclude that the regression equations developed in this study are statistically similar to those developed by Eash (1993). Supporting evidence of their similarities and differences is presented in Figures 20-22.

Table 21. Bankfull parameter results for comparing the combined Iowa Regional curve to the data collected by Eash (1993) with associated p-values for the regression slopes and intercepts.

Bankfull Parameter	Regional Curve	Intercept p-value	Slope p-value
Cross-Sectional Area	Eash (1993)	-	-
	Iowa Regional	<0.001	0.468
Width	Eash (1993)	-	-
	Iowa Regional	0.973	0.591
Depth	Eash (1993)	-	-
	Iowa Regional	<0.001	0.097

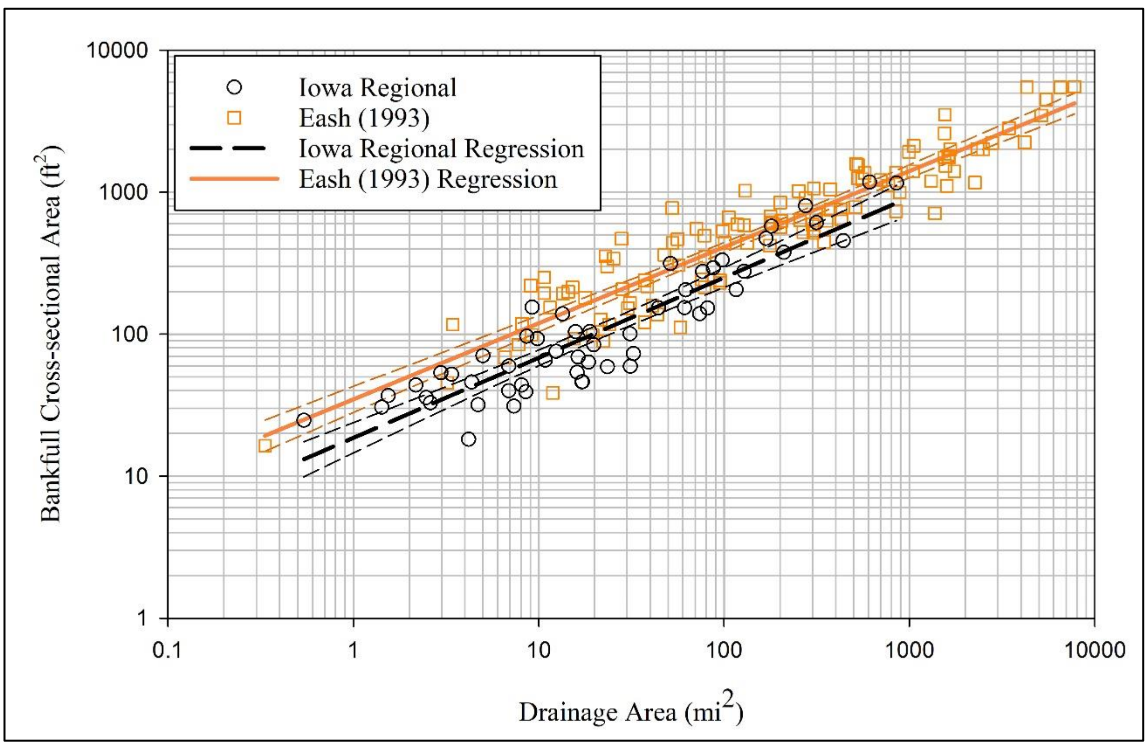

Figure 20. Comparison of the combined Iowa bankfull cross-sectional area regional curve to data collected by Eash (1993) with 95% confidence intervals.

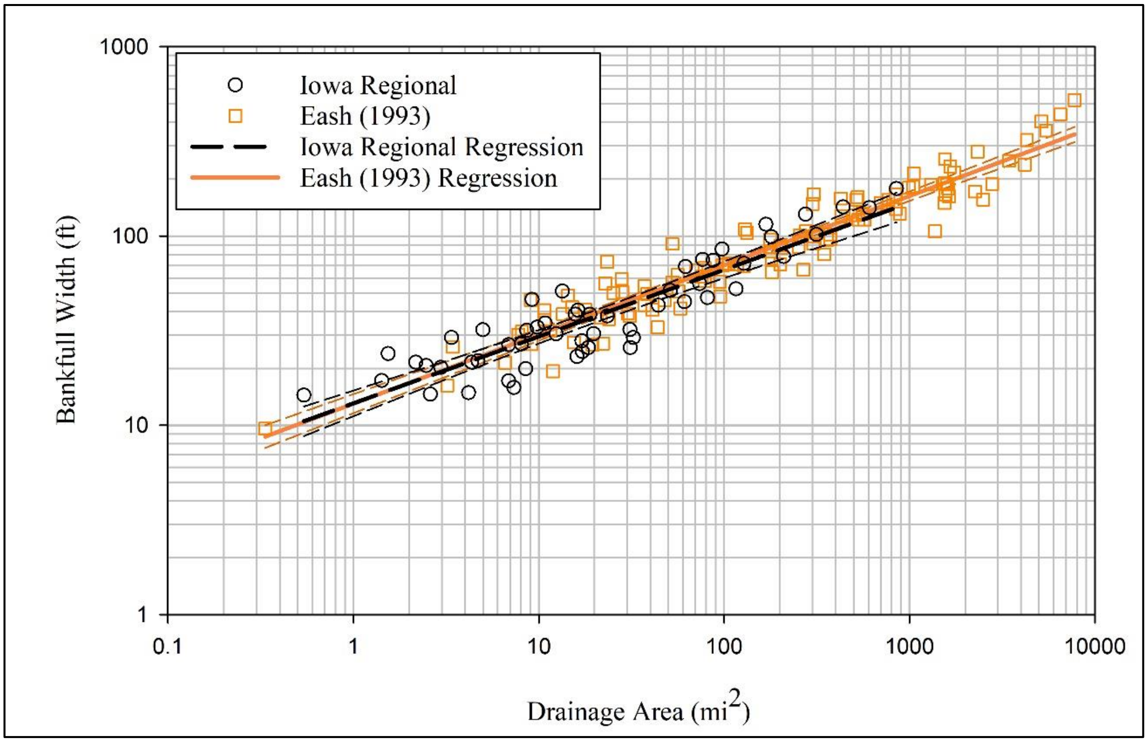

Figure 21. Comparison of the combined Iowa bankfull width regional curve to data collected by Eash (1993) with 95% confidence intervals.

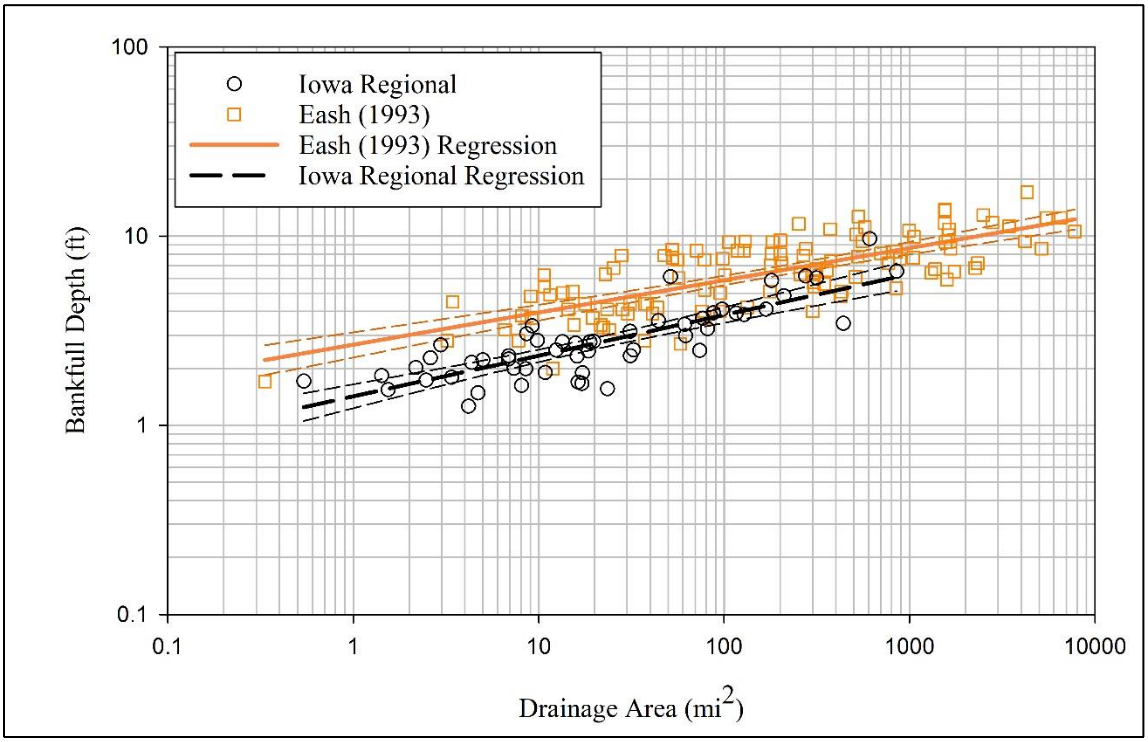

Figure 22. Comparison of the combined Iowa bankfull depth regional curve to data collected by Eash (1993) with 95% confidence intervals.

Regional Curve Stratification

The study found a strong relationship between all bankfull channel parameters and drainage area. For the combined regional dataset, bankfull cross-sectional area and width produced the strongest relationship to drainage area with an R^2 of 0.83, followed by discharge and mean depth with R^2 values of 0.78 and 0.67, respectively. This is consistent with other studies that have found bankfull cross-sectional area and width to have a stronger relationship to drainage area than other bankfull parameters (Cinotto, 2003; Doll et al., 2002, 2003; Metcalf et al., 2009). Overall, regional curves from the combined regional dataset outperform those from Bieger et al. (2015) developed for the Central Lowland Province, Interior Plains Division, and the United States. This suggests that finer stratification methods via the state boundary of Iowa improve regional curve performance. Such results are not surprising when analyzing the spatial distribution of data used to populate the Central Lowland physiographic province, which spans over ten states within the central U.S. with substantial variability in precipitation, landform regions, cover types, and climates.

Further stratification of the combined regional dataset by cover type increased the R^2 for all bankfull parameters. The R^2 for non-urban and urban bankfull cross-sectional area, width, and discharge were similar. Bankfull mean depth for urban streams had a lower R^2 of 0.69 than non-urban streams of 0.82, suggesting that the drainage area for non-urban cover types is better at predicting bankfull mean depth than urban cover types. Overall, the stratification of the combined regional dataset improved the explanatory power of the regression equations to predict bankfull parameters. Not only was there an increase in the predictive capability of the bankfull channel parameters when grouped by cover types, but the results of the statistical analysis found that non-urban and urban regressions have significantly different slopes and intercepts for all bankfull parameters (Table 5). Hession et al. (2003) found similar results where the slopes and intercepts were significantly different for channel widths and cross-sectional areas but not depths. A study by Doll et al. (2002) found regression lines of urban and rural streams to have the same slope but different intercepts. While there is no apparent cause for these discrepancies, different physiographic provinces in which the studies were conducted or differences in basin parameters may cause these inconsistencies.

Separating the non-urban dataset by flood region proved to be an ineffective stratification scheme. Flood Region 1 saw an increase or no change in R^2 for bankfull cross-sectional area, width, and discharge and a decrease for bankfull mean depth. Flood Region 2 saw an increase in R^2 for all bankfull parameters. Flood Region 3 saw an increase in bankfull mean depth and discharge and a decrease in bankfull cross-sectional area and width. All flood regions show similar slopes and intercepts for all bankfull parameters, with the most significant difference between the flood regions being seen in drainage areas > 100 mi^2. This is possibly due to the dominant land use within the basin or the limited number of data points in non-urban basins above 100 mi^2. Results from the statistical analysis found that flood region regressions do not have significantly different slopes or intercepts for bankfull cross-sectional area, width, and mean depth (Table 18). Flood region regressions for bankfull discharge proved statistically significant and provided the sole justification for stratification. This is seen by a significant difference in regression slopes for Flood Region 2 (p-value = 0.0149) and Flood Region 3 (p-value = 0.0221) compared to the Flood Region 1 control condition. Furthermore, there was a significant difference in intercepts for Flood Region 2 (p-value = 0.0270) and a non-significant intercept for Flood Region 3 (p-value = 0.0820) compared to the Flood Region 1 control condition. Even though the intercept for Flood Region 3 does not meet the significance criteria (p-value ≤ 0.05), it is close with a p-value = 0.0820. Furthermore, since the slope of the regression line for Flood Region 3 is significantly different, its separation from the non-urban regional dataset is justified. Stratification of the non-urban regional dataset by flood regions increased the R^2 for many bankfull parameters. Still, it did not meet the necessary conditions (p-value ≤ 0.05) to justify this stratification method for bankfull cross-sectional area, width, and mean depth. Bankfull discharge for all flood regions did meet the necessary condition (p-value ≤ 0.05), and there is justification for its stratification via flood region boundaries. Differences in bankfull discharge regressions between flood regions provide supportive evidence for delineating three flood regions for Iowa by Eash et al. (2013), who used annual exceedance probability as a response variable in their model. It is unclear why there was no significant difference between the other flood region bankfull channel parameters since bankfull discharge is the driving force in creating the geometry of the channel (FISRWG, 1988). It should be mentioned that Flood Region 2 yielded bankfull cross-sectional area and width p-values of 0.0952 and 0.1002 for regression slopes, respectively, which are close to the 0.05 threshold.

Multiple Linear Regression

The addition of percent impervious and mean annual precipitation as explanatory variables in the non-urban and urban multiple linear regression model was significant for bankfull cross-sectional area, width, and discharge. Adding percent impervious and mean annual precipitation into multiple linear regression models for bankfull mean depth was insignificant (p-value > 0.05). Adding percent impervious into urban regressions improved the R^2 and is better at predicting bankfull cross-sectional area, width, and discharge than the reduced urban regional curve. These results are consistent with a study conducted by Hession et al. (2003), who found urbanization to have a significant effect (different slopes and intercepts) on bankfull channel widths and cross-sectional areas, but not depths. Adding mean annual precipitation into non-urban regressions slightly improved the R^2 and is better at predicting bankfull cross-sectional area, width, and discharge than the reduced non-urban regional curve. The R^2 increased by 0.01 for bankfull cross-sectional area, width, and discharge, indicating that adding mean annual precipitation can only explain an additional 1% of the variability in the different bankfull parameter models. While mean annual precipitation proved significant for bankfull cross-sectional area, the model produced a negative intercept estimate, -0.052646. Chaplin (2005) observed a similar issue and found that the inclusion of percent carbonate into a multiple linear regression model for bankfull discharge yielded negative estimates. Even though it proved to be a significant explanatory variable (p-value < 0.0001), he did not include it in the model because it estimated impossible discharge values for small watersheds. When using mean annual precipitation and drainage area as explanatory variables, the model can estimate negative bankfull cross-sectional areas. However, the regression equations only estimate a negative bankfull cross-sectional area for drainage areas < 0.6 mi^2, significantly lower than the smallest non-urban basin surveyed in this study. Smaller non-urban basins may not have well-defined channels, so regressions truncated at a low threshold basin area are not unreasonable. Therefore, adding mean annual precipitation into a multiple linear regression model for non-urban cover types increases the model's predictive capability for bankfull cross-sectional area, width, and discharge.

Hydraulic Geometry for Non-Urban and Urban Cover Types

For hydraulic geometry relationships, separation of the combined regional data set improved or caused no change in the R^2 for all non-urban bankfull parameters. Urban streams saw an increase in R^2 for bankfull cross-sectional area, width, and velocity and a decrease in bankfull mean depth and slope. R^2 values for non-urban and urban cover types are similar for bankfull cross-sectional area and width, with a more significant difference for depth, velocity, and slope. Poor relationships between bankfull velocity and slope to bankfull discharge are expected since the same trends are typically seen with drainage area as the explanatory variable. Hydraulic geometry curves developed for non-urban and urban streams provided power-law coefficients that multiply to approximately one (0.98) and exponents that sum to one (1.00), satisfying the check for continuity. Additionally, the hydraulic geometry exponents presented in Tables 8-12 are consistent with widely-cited ranges for bankfull width, mean depth, and velocity of 0.50 to 0.53, 0.37 to 0.40, and 0.10, respectively (Leopold, 1994). Comparing regional and hydraulic geometry curves provides some value in understanding the effect of impervious cover on regression equations. First, hydraulic geometry yielded the same or higher R^2 values for non-urban bankfull cross-sectional area and mean depth and lower values for width. While there was a lower R^2 for bankfull width for the hydraulic geometry curve, 0.87, it was close to the non-urban regional curve, 0.91. Hydraulic geometry relationships for urban cover types had higher R^2 values for bankfull cross-sectional area, width, and mean depth. The higher R^2 values in the hydraulic geometry curves for most bankfull parameters are consistent with claims that bankfull discharge is a more reliable independent variable than drainage area because discharge is the driving force in creating the geometry of the channel (FISRWG, 1988). Second, statistical methods used to test for differences between non-urban and urban cover types showed no significant difference between cover types for hydraulic geometry curves. This analysis shows that stratification of hydraulic geometry curves by cover type is not warranted. Insufficient statistical evidence indicates that stratification by cover type improves the model’s ability to predict bankfull cross-sectional area, width, and mean depth. Impervious cover has been shown to increase bankfull discharges for streams in urban cover types (Figure 7), with drainage area as an independent variable. While urbanization has been shown to influence stormwater runoff, flood frequency, peak discharges, and sediment transport (Booth, 1991; Schueler, 1995; Wolman, 1967), the capability of bankfull discharge to control the hydraulic geometry of the stream is not affected by cover type in this study.

Comparison Between Methods of Estimating Bankfull Discharges

Two methods of estimating bankfull discharges at gaged reaches were used to assess each method's capability to provide consistent results. The method using Manning's equation, used to estimate bankfull discharges at ungaged sites in this study, was compared against the method presented by Williams (1978) used for gaged sites. Many sites included in the hydraulic geometry analysis estimated discharges using Manning's equation (Equation 6), where channel geometry parameters were used to derive bankfull discharges. Since channel geometry was used to derive bankfull discharges and bankfull discharges were used as explanatory variables in the hydraulic geometry regressions, an analysis was performed to test the validity of the results presented in Table 13. Both methods were conducted and evaluated at 12 gaged reaches to test for significant differences between groups. A comparison between both methods is presented in Table 22. A visual representation of the differences between both methods is presented in Figure 21. Statistical methods employed in this study were used to test for statistically significant differences between the slopes and intercepts between groups. Results from the statistical model testing for the method of estimating discharge as a significant interaction term are presented in Table 23. The model does not provide sufficient evidence that the method presented by Williams (1978) has significantly different slopes (p-value > 0.05) or intercepts (p-value > 0.05) from Manning's equation control condition for all parameters. Therefore, there is insufficient evidence that bankfull discharges differ significantly between both methods of estimation at twelve gaged reaches included in the dataset.

Table 22. Results from two methods of estimating bankfull discharges at gaged reaches.

Site Name	Manning's Equation	Williams (1978)	Cover Type
Crow Creek at Bettendorf, IA	331	561	Urban
Duck Creek at Davenport, IA	1417	1670	Urban
Fox River at Bloomfield, IA	1332	907	Non-Urban
Hoover Creek at Hoover National Historic Site	85	117	Urban
Little Floyd River near Sanborn, IA	108	96	Non-Urban
Maquoketa River at Manchester, IA	2773	1827	Non-Urban
Muddy Creek at Coralville, IA	381	291	Urban
South Branch Ralston Creek at Iowa City, IA	197	209	Urban
South Skunk River near Ames, IA	2516	2668	Non-Urban
Walnut Creek at Des Moines, IA	1246	1219	Urban
Walnut Creek in Story County	134	180	Non-Urban
West Nishnabotna River at Hancock, IA	6331	6864	Non-Urban

By conducting this analysis, we may make general conclusions about estimating bankfull discharges for the hydraulic geometry and regional curves presented in this study. Since the two methods of estimating bankfull discharge are not significantly different, we can: (1) infer that the bankfull discharges estimated from Manning's equation for the other ungaged sites are reasonable; (2) hydraulic geometry relationships that relate channel geometry from discharge computed using Manning's equation are not artifacts of the same geometry parameters figuring into the discharge computation. It follows that the methods of estimating bankfull discharges used in this study are a valid and practical way of describing bankfull channel geometry for the hydraulic geometry curves.

Table 23. Hydraulic geometry results for comparing the two methods of estimating bankfull discharges with associated p-values for the regression slopes and intercepts.

Bankfull Parameter	Method	Intercept p-value	Slope p-value
Cross-Sectional Area	Manning's Equation	-	-
	Williams (1978)	0.671	0.696
Width	Manning's Equation	-	-
	Williams (1978)	0.830	0.850
Mean Depth	Manning's Equation	-	-
	Williams (1978)	0.665	0.678
Slope	Manning's Equation	-	-
	Williams (1978)	0.977	0.985

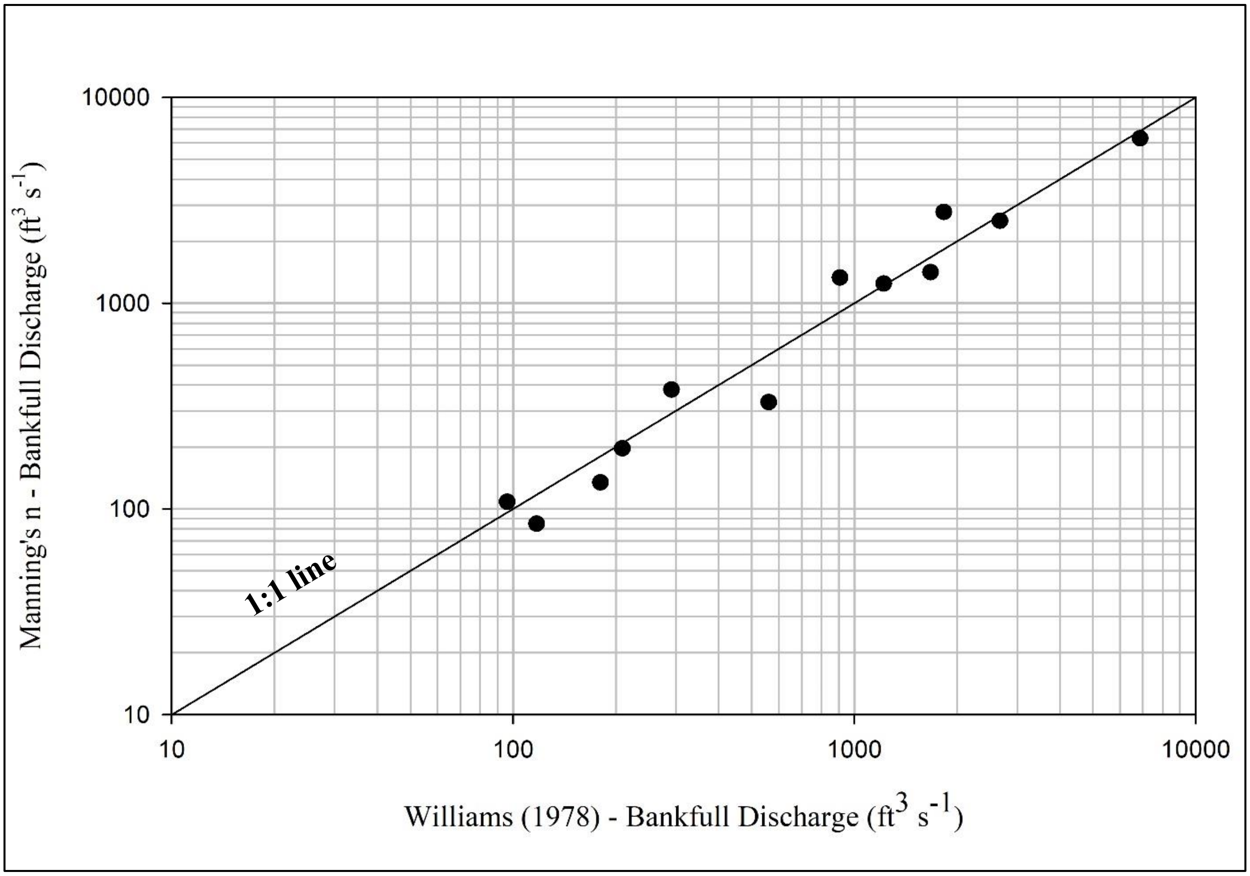

Figure 23. Comparison between two methods used to estimate bankfull discharges at 12 gaged reaches.

Return Periods

The average recurrence interval of bankfull discharge (Table 19) at sites co-located with gage stations is slightly lower than the widely-cited 1.5-year average return period for the U.S. but within the reported range of observed values (Leopold et al., 1995). This study found a slight reduction in recurrence interval for urban streams, despite the differences in bankfull channel parameters between cover types. The average recurrence interval for urban streams is slightly lower than non-urban streams in this study, with an 11% reduction between non-urban and urban streams. Recurrence intervals for both cover types fall within a similar range of possible values of 1.1661 – 1.6990 and 1.1078 – 1.5184, respectively, for non-urban and urban streams. These results are similar to those of Doll et al. (2002), who found a range of possible values for urban and rural streams to be 1.1 – 1.5 and 1.09 – 1.8, respectively. Furthermore, there was only a slight reduction in average bankfull recurrence intervals of 0.1 years between rural and urban streams (Doll et al., 2002) which is close to the 0.1524 year reduction found in this study. Non-urban streams (n = 13) are more geographically dispersed than urban streams (n = 7) within the dataset so other regional basin factors may explain the difference in recurrence intervals. This analysis does not provide strong evidence to support the notion that increased urbanization causes a reduced return interval (Huang et al., 2008; Villarini et al., 2009), and further analysis must be conducted to make any definitive conclusions.

CHAPTER 5. CONCLUSION

Channel morphology data from 32 locations were combined with a preliminary regional dataset to develop hydraulic geometry and regional curves for Iowa streams. We used multiple linear regression models to evaluate stratification schemes and assess whether models could be improved by adding additional basin parameters. Each assessment included a survey of the channel geometry, analysis of bed material, and estimation of bankfull discharge. Linear regression of log-transformed variables was used to develop regional regression equations for bankfull cross-sectional area, width, mean depth, and discharge. By collecting channel morphology measurements from 32 additional locations across the state, the refined regional regression equations have increased the power of predicting bankfull parameters statewide. Statistical methods that test for interactions within the linear model found flood regions to be a nonsignificant variable for bankfull cross-sectional area, width, and mean depth, even when there was an increase in R^2. However, cover type was a significant term affecting the slope and intercept between non-urban and urban streams and improved the R^2 for all bankfull channel parameters. Thus, statistical analysis justifies stratification of the combined regional dataset into non-urban and urban cover types. Including percent total impervious cover into the model as an additional explanatory variable was significant and improved the capability of predicting bankfull cross-sectional area, width, and discharge for streams with > 10% impervious cover. Additionally, adding mean annual precipitation into the model for streams classified as non-urban (≤ 10% impervious cover) was significant and improved the model's capability of predicting bankfull cross-sectional area, width, and discharge.

Comparing the regional curves developed in this study to those developed by Bieger et al. (2015) indicated that more refined stratification improved regional curve performance with an increase in R^2 for all bankfull parameters. The Iowa Non-Urban curve has the highest exponent values for bankfull cross-sectional area, width, and mean depth, resulting in a significantly steeper slope compared to the other curves. Additional comparisons to data collected by Eash (1993) found no significant differences between bankfull parameter slopes (p-value > 0.05). Overall, this study's regional curves outperformed the generalized curves developed by Bieger et al. (2015), supporting the application of finer stratification schemes.

Understanding the effects of various parameters on bankfull geometry is necessary to apply stratification methods that best represents bankfull channel form. Results of this study highlight the importance of percent total impervious cover for the whole upstream basin and its effects on the bankfull channel. Interpreting how urbanization influences channel morphology is paramount as urban area continues to increase and infringe on watershed boundaries. Stream restoration practitioners can use the regional curves developed herein to assist in bankfull identification and construct preliminary bankfull channel designs in non-urban and urban reaches in Iowa. The regional curves developed here can be used to assist practitioners when field identification of the bankfull stage is not possible but should not be used in place of field verified bankfull dimensions when they are present. The regional curves developed in this study provide stream restoration practitioners with a framework detailing the possible range of values for the bankfull channel. While this study provides insight into the effects of urbanization in Iowa streams, additional work is recommended to determine the effects of other contributing factors such as vegetation cover on channel morphology in urban and non-urban settings.

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APPENDIX A. SITE DESCRIPTIONS, LONGITUDINAL PROFILES, AND RIFFLE CROSS SECTIONS OF SURVEYED REACHES

Blood Run
Blood Run Creek at Blood Run National Historic Landmark

View looking upstream at the reach of Blood Run at Blood Run National Historic Landmark

This reach is located approximately 2,000 ft West Apple Ave., in Northwest, IA. The reach is located on Blood Run National Historic Landmark land.

The reach ran along a riparian area consisting of tallgrass prairie on both sides of the channel. The area surrounding the reach is dominated by tallgrass prairie and agriculture. Tile drainage into the stream is possible and could affect discharges. The channel was incised with irregular meanders and had a mild slope. The channel had few riffle-pool sequences and had minor bedform and point bar formation. The bankfull channel was poorly defined throughout the reach. The primary bankfull indicators at the site included the changes in the size distribution of deposited material, breaks in bank slope, and the presence of perennial woody vegetation. The banks were well vegetated and lined with tall grasses. The bank material was primarily comprised of alluvium throughout most of the reach. Cut banks up to 20 ft were present immediately upstream of the reach. The stream could not access the floodplain on both sides throughout most of the reach. The bed material was dominated by coarse sand with occasional cobble and gravel in the riffles. Moderate channel widths, considerable bank heights, slumping bank material, and lack of floodplain access would indicate that this reach is degrading to degrading and widening.

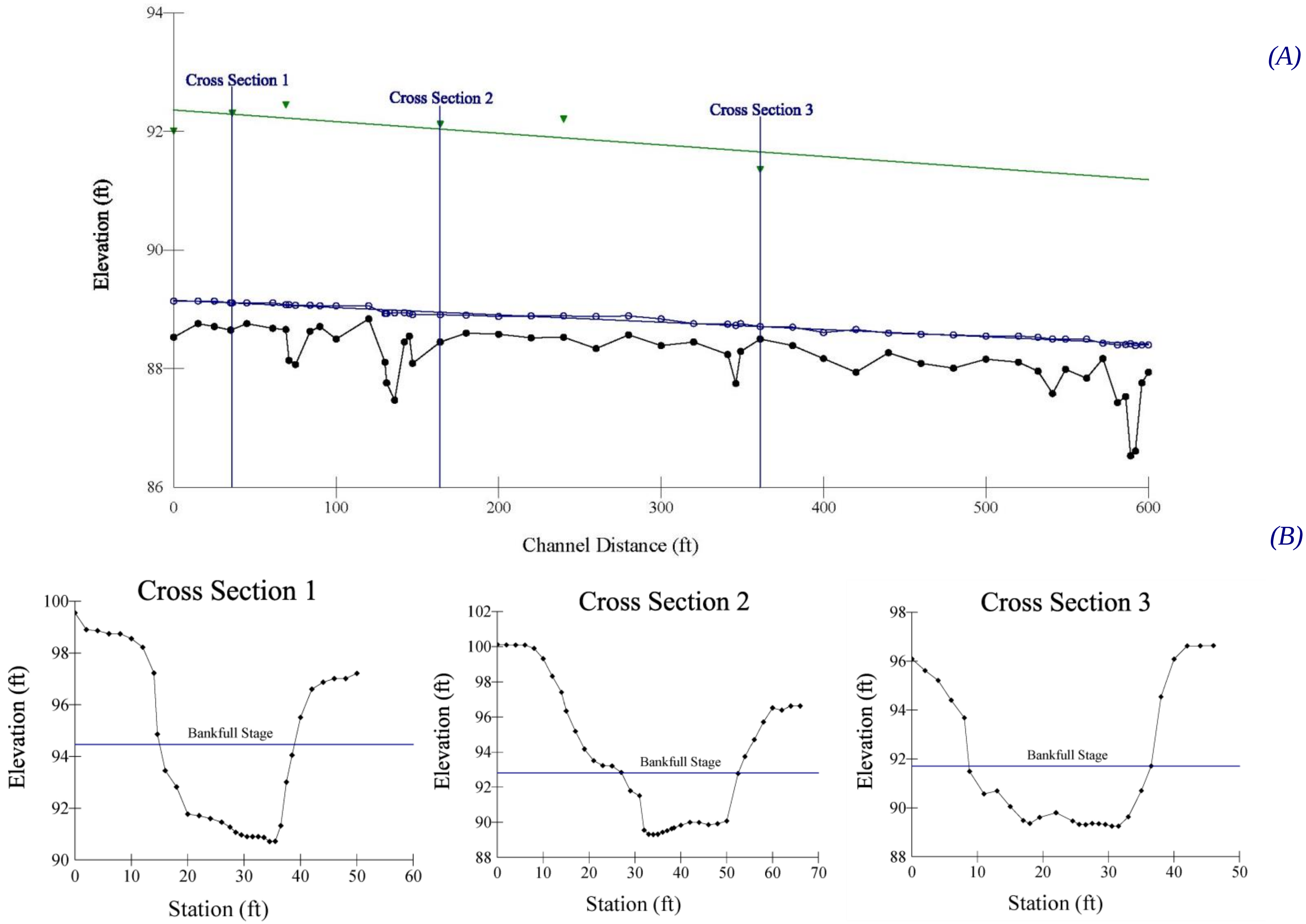

Figure A.1 Longitudinal profile (A), and riffle cross-sections (B), in study reach of Blood Run Creek at Blood Run National Historic Landmark.

College Creek
College Creek below Ames Middle School

View looking upstream at the reach of College Creek below Ames Middle School

This reach is located approximately 0.25 miles downstream from Ames Middle School, where a footbridge runs over the stream with rip rap armoring the banks on both sides. The bridge does not appear to affect bankfull discharge below this point.

The reach ran along a housing development on its left bank and a steep open vegetated meadow on its right bank. The channel was fairly narrow, moderately sinuous with irregular meanders, and had a mild slope. The channel had numerous synchronous riffle-pool sequences. The bankfull channel was moderately defined throughout the reach. The primary bankfull indicators at the site included the back of point bars and breaks in bank slope. The banks were well vegetated and lined with trees in many areas. The right bank exhibited significant bank erosion where soughing of bank material and woody vegetation was apparent. The stream could access the floodplain on its left bank for most of the reach. Floodplain access on the right bank was limited throughout the reach due to its steep banks. The bed was gravel-dominated with some small cobble and sand present. Glacial till was exposed in the bottom of the channel within the upper portion of the reach. Non-native material such as concrete and brick was observed along the reaches stream bed. Steep, eroding banks, lack of floodplain access, and the presence of glacial till would indicate this reach is degrading.

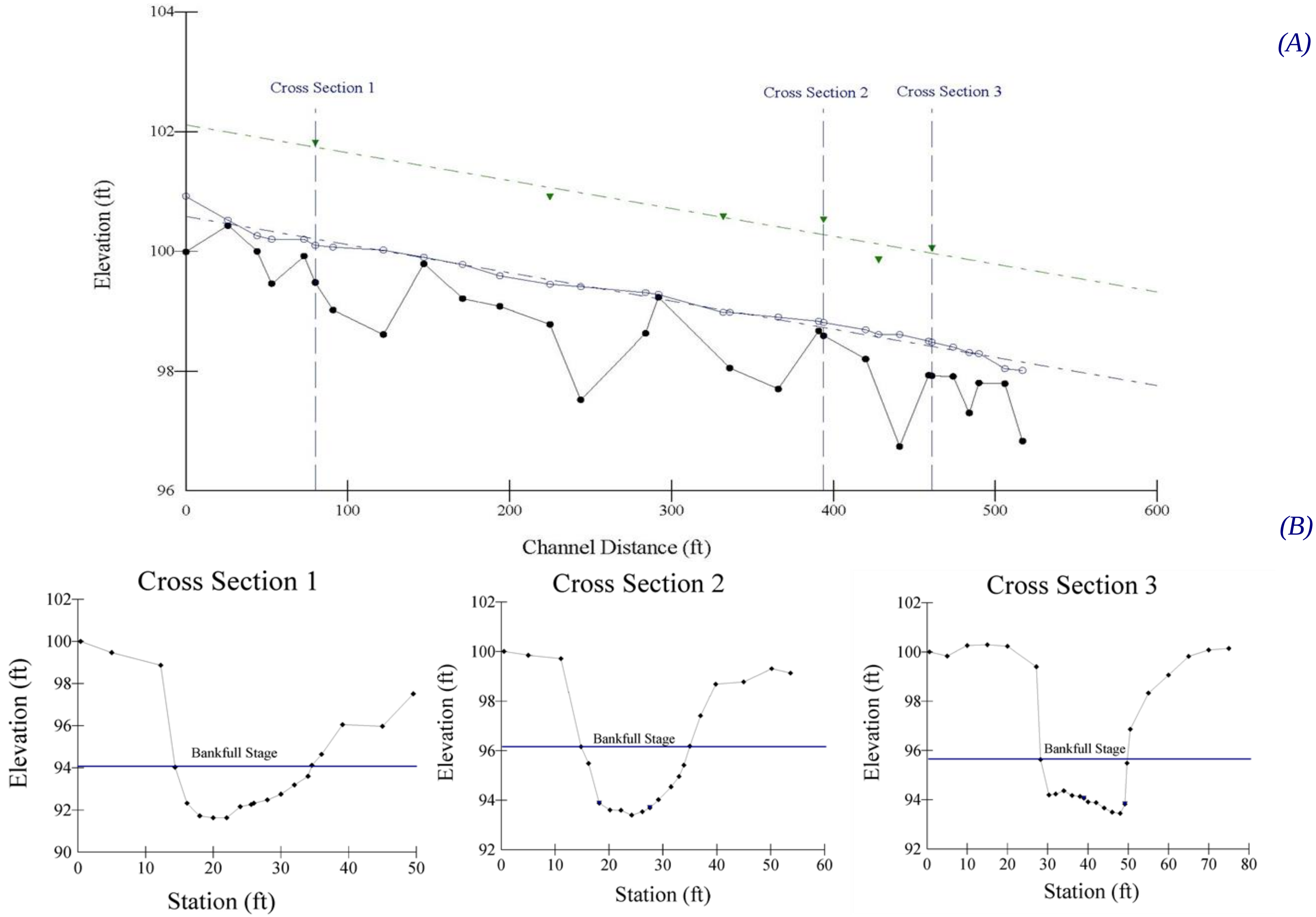

Figure A.2 Longitudinal profile (A), and riffle cross-sections (B), in study reach of College Creek below Ames Middle School.

Station 05422470
Crow Creek at Bettendorf, IA

View looking upstream at the reach of Crow Creek at Bettendorf, IA

The continuous stream-flow gaging station is located approximately 200 ft upstream of a highway bridge. The bridge likely affects bankfull discharge at the stream-flow gaging station. No evidence of a backwater effect was determined above the gage station.

The reach ran along a densely vegetated riparian woodland on both sides of the channel. A walking path is directly adjacent to the stream along some sections of the reach. A dense woodland immediately surrounded the reach, but most of the basin is dominated by urban development. Stormwater drainage systems likely influence discharges; however, no inlets were observed. The channel was incised in some sections, moderately sinuous with irregular meanders, and had a mild slope. The channel had few, irregularly spaced riffle-pool sequences. The bankfull channel was well defined throughout the reach. The primary bankfull indicators at the site included prominent breaks in bank slope, the back of point bars, and woody, perennial vegetation. The majority of the banks were well vegetated and lined with numerous riparian species. Some banks along the reach were steep, eroded, and lacked vegetation. The bank material was primarily comprised of alluvium throughout most of the reach. Cut banks up to 5 ft were present in some areas and usually occurred at outer bends. The stream could access the floodplain on both sides throughout most of the reach. The majority of the floodplain area consisted of grasses and woody vegetation. The bed was sand and gravel-dominated with some cobbles throughout. Large woody debris was mostly absent throughout the reach. Appropriate channel widths, moderate bank heights, and few eroding banks would indicate that this channel is in quasi-equilibrium to degrading.

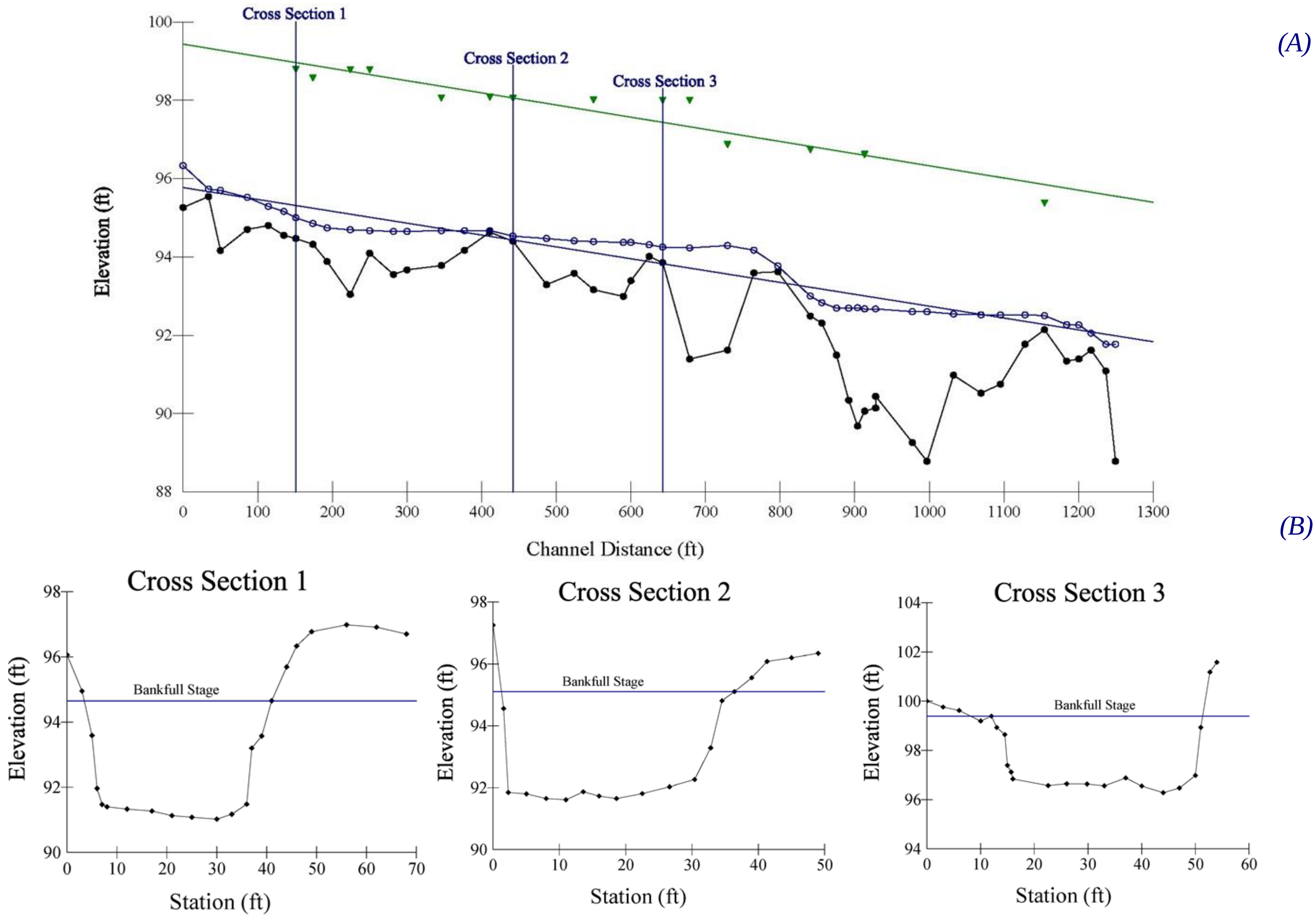

Figure A.3 Longitudinal profile (A), and riffle cross-sections (B), in study reach of Crow Creek at Bettendorf, IA.

Station: 05422600
Duck Creek at Davenport, IA

View looking downstream at the reach of Duck Creek below Eastern Avenue

The continuous stream-flow gaging station is located approximately 500 ft upstream of a roadway bridge. The bridge likely affects bankfull discharge at the stream-flow gaging station. No evidence of a backwater effect was determined above the gage station.

This reach is located approximately 400ft downstream of Eastern Avenue and runs along a vegetated riparian woodland on both sides of the channel. A dense woodland immediately surrounded the reach, but most of the basin is dominated by urban development. Stormwater drainage systems likely influence discharges; however, no inlets were observed. The channel was moderately incised, with irregular meanders, and had a mild slope. The channel had few riffle-pool sequences along with irregularly dispersed sand bedforms. The bankfull channel was well defined throughout the reach. The primary bankfull indicators at the site included prominent breaks in bank slope, flat depositional features on a horizontal plane, large woody perennial vegetation, and changes in particle size deposition. The banks were well vegetated and lined with numerous riparian species. Though the banks were steep in some sections, they were primarily stable and well-vegetated. The bank material was primarily comprised of glacial till and cobble throughout most of the reach. The stream has limited access to the floodplain on both sides throughout most of the reach. Floodplain vegetation consisted of large woody vegetation and dense grasses. The bed was sand and gravel-dominated with some cobbles throughout. Large woody debris was mainly absent throughout the reach. Appropriate channel widths, moderate bank heights, lack of excessive deposition, and few eroding banks would indicate that this channel is in quasi- equilibrium to degrading.

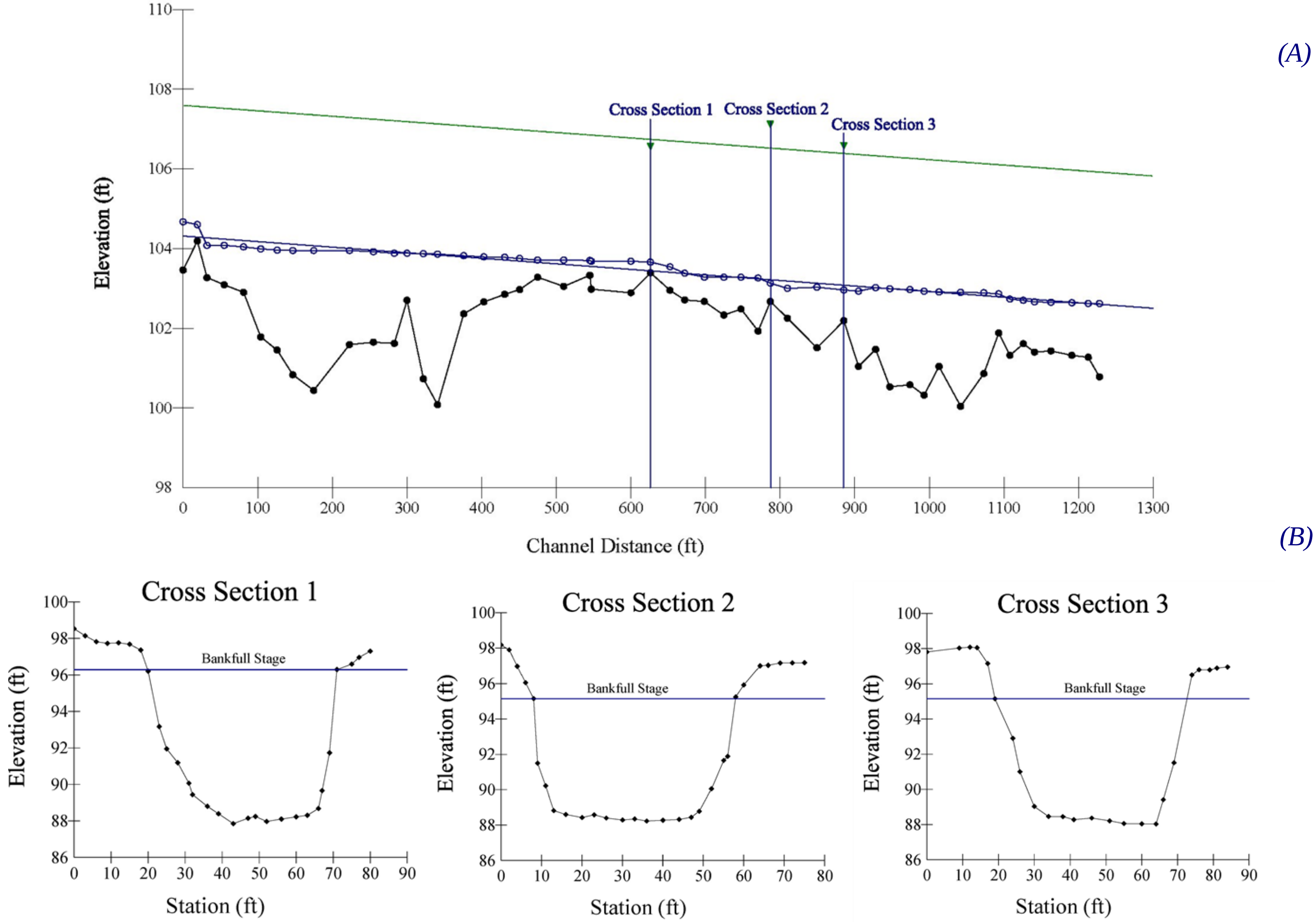

Figure A.4 Longitudinal profile (A), and riffle cross-sections (B), in study reach of Duck Creek at Davenport.

Station 05494300
Fox River at Bloomfield, IA

View looking downstream from bridge at the reach of Fox River at Bloomfield

The continuous stream-flow gaging station is located approximately 10 ft downstream of a highway bridge. The bridge has a pier on both sides of the channel and may affect bankfull discharge at the gaging station. A scour pool and widening of the channel downstream of the bridge are likely due to flow constriction upstream of the bridge.

The reach ran along a densely wooded riparian corridor downstream of the stream-flow gaging station. The land surrounding this reach is dominated by agriculture, where tile drainage systems likely influence discharges. The channel was very wide, deep, and straight with a mild slope. Sand bedforms dominated the channel with Infrequent and irregular riffle-run sequences throughout the reach. The bankfull channel was moderately well defined throughout the reach. The primary bankfull indicators at the site included prominent breaks in bank slope, the back of point bars, change in the size distribution of deposited material, and established woody vegetation. The banks were well vegetated with grasses, forbs, and some woody vegetation. Established willow populations dominated the riparian area adjacent to the channel in the lower portions of the reach. There were cut banks up to 50 ft in isolated areas in the lower portions of the reach. The floodplain could not be accessed on either side of the channel at bankfull flows for most of the reach. The bed was sand-dominated with some gravel along the riffle sections. Aerial photography shows the reach had been channelized in the early 19th century, while the present channel form would indicate it is readjusting through widening and aggregation. The presence of large point bars, steep eroding cut banks, and establishment of large woody vegetation indicate this reach is adjusting to past modifications by aggrading, widening, and increasing its sinuosity.

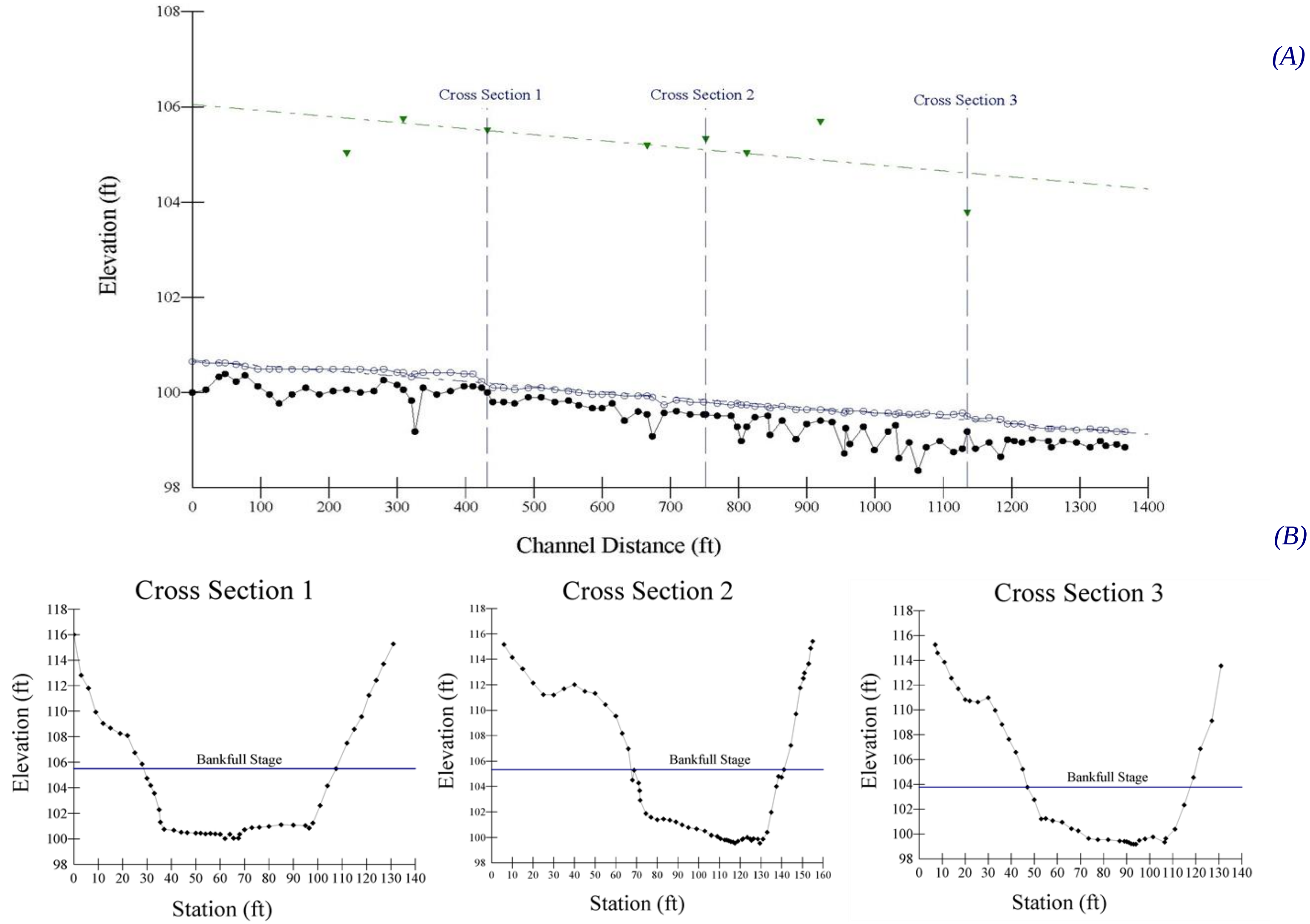

Figure A.5 Longitudinal profile (A), and riffle cross-sections (B), in study reach of Fox River at Bloomfield, IA.

French Creek
French Creek at French Creek Wildlife Management Area

View looking upstream at the reach of French Creek at French Creek Wildlife Management Area

This reach is located approximately 0.45 miles southeast of the French Creek Wildlife Management Area parking area. The reach is located in a remote wooded valley bottom surrounded by steep valley walls.

The reach ran along a densely vegetated riparian woodland within the French Creek Wildlife Management Area. The area surrounding this reach is dominated by agriculture, but discharges are not likely influenced by tile drainage. Discharges are likely influenced by springs and seeps due to the moderate relief of the surrounding area. The channel was narrow, highly sinuous with irregular to tortuous meanders, and had a moderate slope. The channel had numerous riffle-pool sequences with a large compound pool in the lower sections of the reach. The bankfull channel was well defined throughout the reach. The primary bankfull indicators at the site included flat depositional features on a horizontal plane and breaks in bank slope. The banks were densely vegetated and lined with grasses, forbs, and perineal woody vegetation. Small cut banks up to 5 ft were observed where the channel met the valley wall and at outer bends. The stream could access its floodplain throughout most of the reach. The bed was gravel and cobble dominated with some boulders present. Abundant aquatic vegetation lined the channel bottom, along with the presence of numerous historic gabion baskets. There was a large log jam at the upper section of the reach, causing a large scour pool where glacial till was exposed. Inactive floodplain terraces were observed along the reach where the channel met the valley wall. Narrow channel widths, small bank heights, and mature riparian vegetation would indicate that this channel is in quasi-equilibrium to degrading.

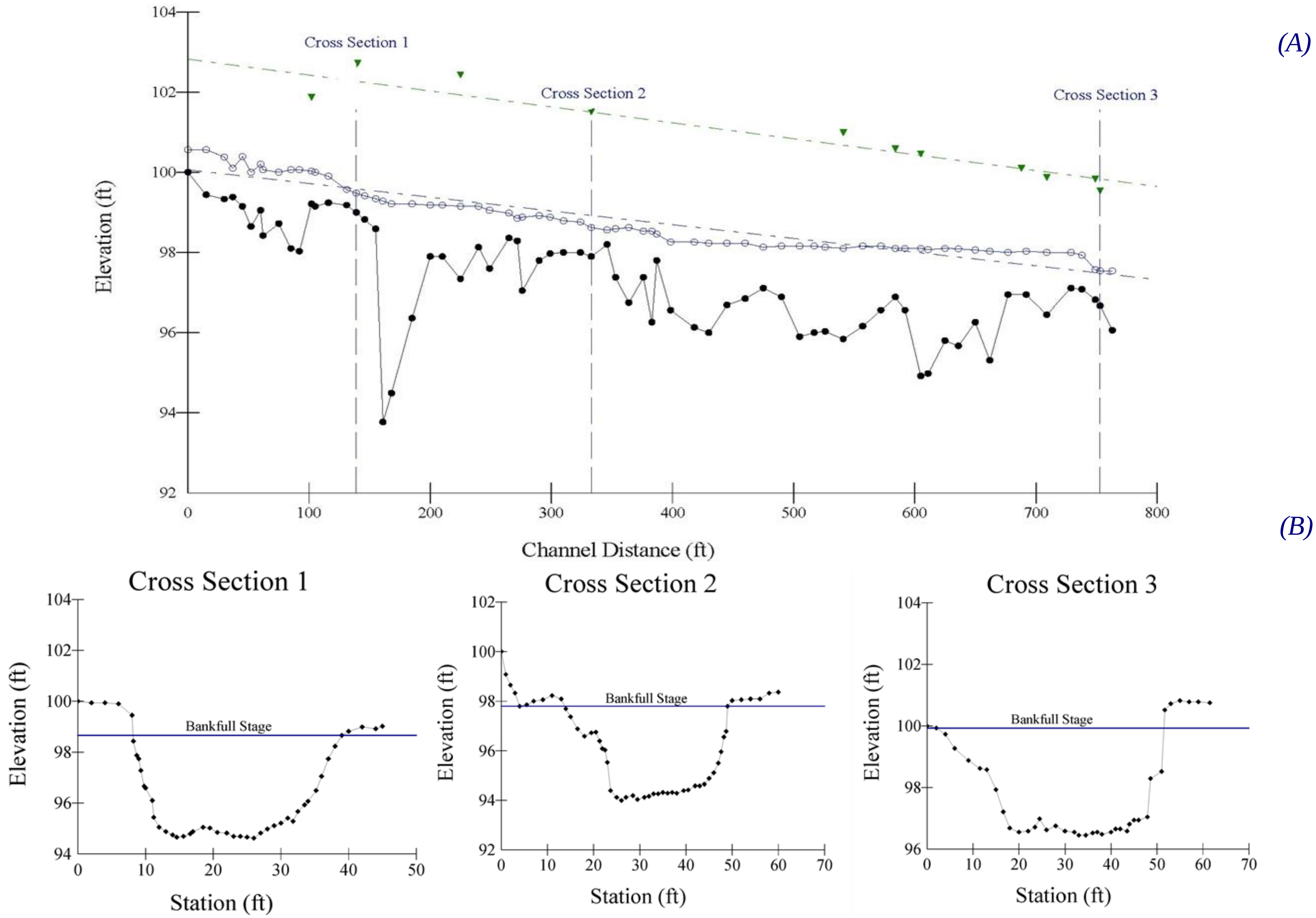

Figure A.6 Longitudinal profile (A), and riffle cross-sections (B), in study reach of French Creek at French Creek Wildlife Management Area.

Honey Creek
Honey Creek at Herman Park

View looking upstream at the reach of Honey Creek in Herman Park

This reach is located approximately 3,000 ft North of U.S. Route 30 in Boone County, IA, in Herman Park. There are no structures within the immediate vicinity of the reach.

The reach ran along a steep-walled, heavily vegetated woodland within Herman Park. A dense woodland immediately surrounded the reach, but most of the basin is dominated by urban development. A small gravel road with minimal traffic was directly adjacent to the left side of the reach. The stream valley was mostly confined with moderately-high eroding banks in several places. Stormwater drainage systems likely influence discharges; however, no inlets were observed. The channel was incised, moderately sinuous with irregular meanders, and had a mild slope. The channel has few riffle-pool sequences and limited point bar depositions. The bankfull channel was moderately defined throughout the reach. The primary bankfull indicators at the site included the back of point bars, changes in the size distribution of deposited material, changes in bank slope, and woody, perennial vegetation. The banks were moderately vegetated and lined with woody shrubs and deciduous trees. The bank material was primarily comprised of glacial till throughout most of the reach. Cut banks up to 8 ft were present in some areas and usually occurred at outer bends. The stream had limited access to the floodplain throughout the reach. The bed material was dominated by moderately embedded cobble in the riffles and coarse sand in the pools. Large woody debris and log jams were commonly found throughout the reach, along with some glacial erratics. Moderate channel widths, considerable bank heights, slumping bank material, and lack of floodplain access would indicate this reach is degrading and widening.

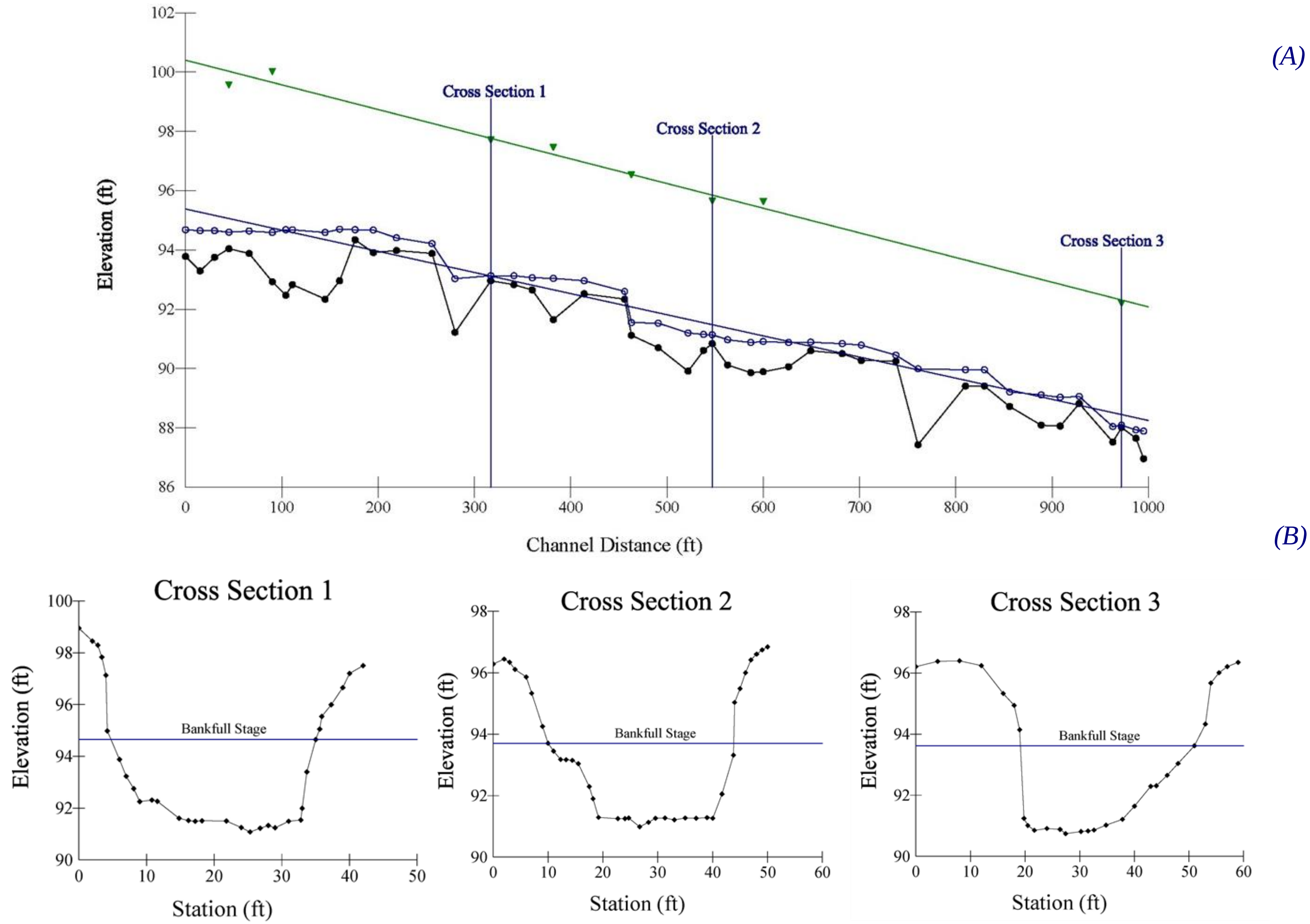

Figure A.7 Longitudinal profile (A), and riffle cross-sections (B), in study reach of Honey Creek at Herman Park.

Station 05464942
Hoover Creek at Hoover National Historic Site, West Branch, IA

View looking downstream at the reach of Hoover Creek at Hoover National Historic Site

The continuous stage-discharge gaging station is located on the right bank below a footbridge approximately 0.25 miles upstream of the Hoover Presentational Library, Hoover National Historic site in West Branch. A scour pool upstream of the footbridge was likely due to a backwater effect and constriction affecting bankfull flows at the gaging station.

The reach ran along the maintained grounds of the Hoover National Historic site. The land surrounding this area is dominated by agriculture and urban development. Discharges are likely influenced by tile drainage and stormwater drainage systems; however, no inlets were observed. The channel was wide, deep, and straight with a mild slope. A mixture of gravel, sand, silt, and clay dominated this channel with irregular and infrequent riffle-run sequences. The channel bottom was comprised of clay material overlain by gravel-sized debris, likely a product of broken-down asphalt. Abundant urban debris was scattered throughout the reach. The bankfull channel was very poorly defined throughout the reach. The primary bankfull indicators at the site included prominent breaks in bank slope and changes in vegetation. The banks were well vegetated along its upper section and bare along the lower sections where clay was exposed. Tree removal was observed throughout the reach, leaving large tree stumps along the banks. The floodplain could not be accessed on either side of the channel at bankfull flows. The shape and size of the channel, steep banks, and the absence of woody debris indicate this reach has been modified to prevent flooding of the Hoover National Historic Site.

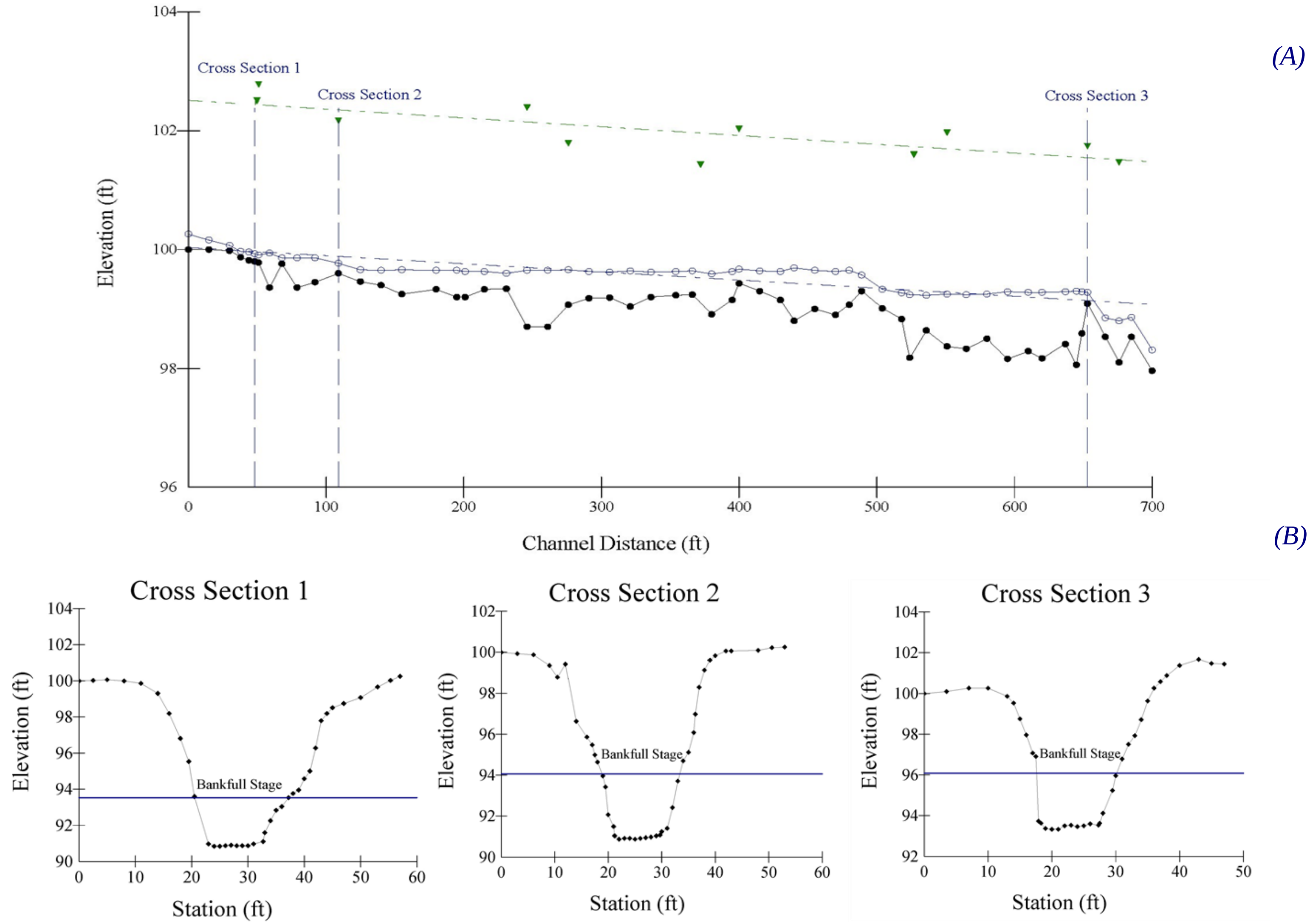

Figure A.8 Longitudinal profile (A), and riffle cross-sections (B), in study reach of Hoover Creek at Hoover National Historic Site.

Jordan Creek
Jordan Creek at Des Moines, IA

View looking downstream at the reach of Jordan Creek in Southwoods Park

This reach is located approximately 2,000 ft South of EP Parkway in Des Moines, IA, in Southwoods Park. There are no structures within the immediate vicinity of the reach.

The reach ran along a forested area within the boundaries of Southwoods Park. A dense woodland immediately surrounded the reach, but most of the basin is dominated by urban development. The stream occupied a narrow valley that was void of infrastructure. The stream valley was mostly confined with moderately high eroding banks in several places. Stormwater drainage systems likely influence discharges; however, no inlets were observed. The channel was incised, moderately sinuous with irregular meanders, and had a mild slope. The channel had adequate riffle-pool sequences, consistent sand bedform, and point bar deposition. The bankfull channel was moderately defined throughout the reach. The primary bankfull indicators at the site included the back of point bars, changes in the size distribution of deposited material, changes in bank slope, and woody, perennial vegetation. The banks were moderate to poorly vegetated and lined with woody shrubs and deciduous trees. The bank material was primarily comprised of glacial till throughout most of the reach. Cut banks up to 8 ft were present in some areas and usually occurred at outer bends. The stream had limited access to the floodplain throughout the reach. The bed material was dominated by cobble and large glacial erratics in the riffles and coarse sand in the pools. Large woody debris and log jams were commonly found throughout the reach, and large glacial erratics were observed in the riffles. Moderate channel widths, considerable bank heights, slumping bank material, and lack of floodplain access would indicate this reach is degrading and widening.

(A)

(B)

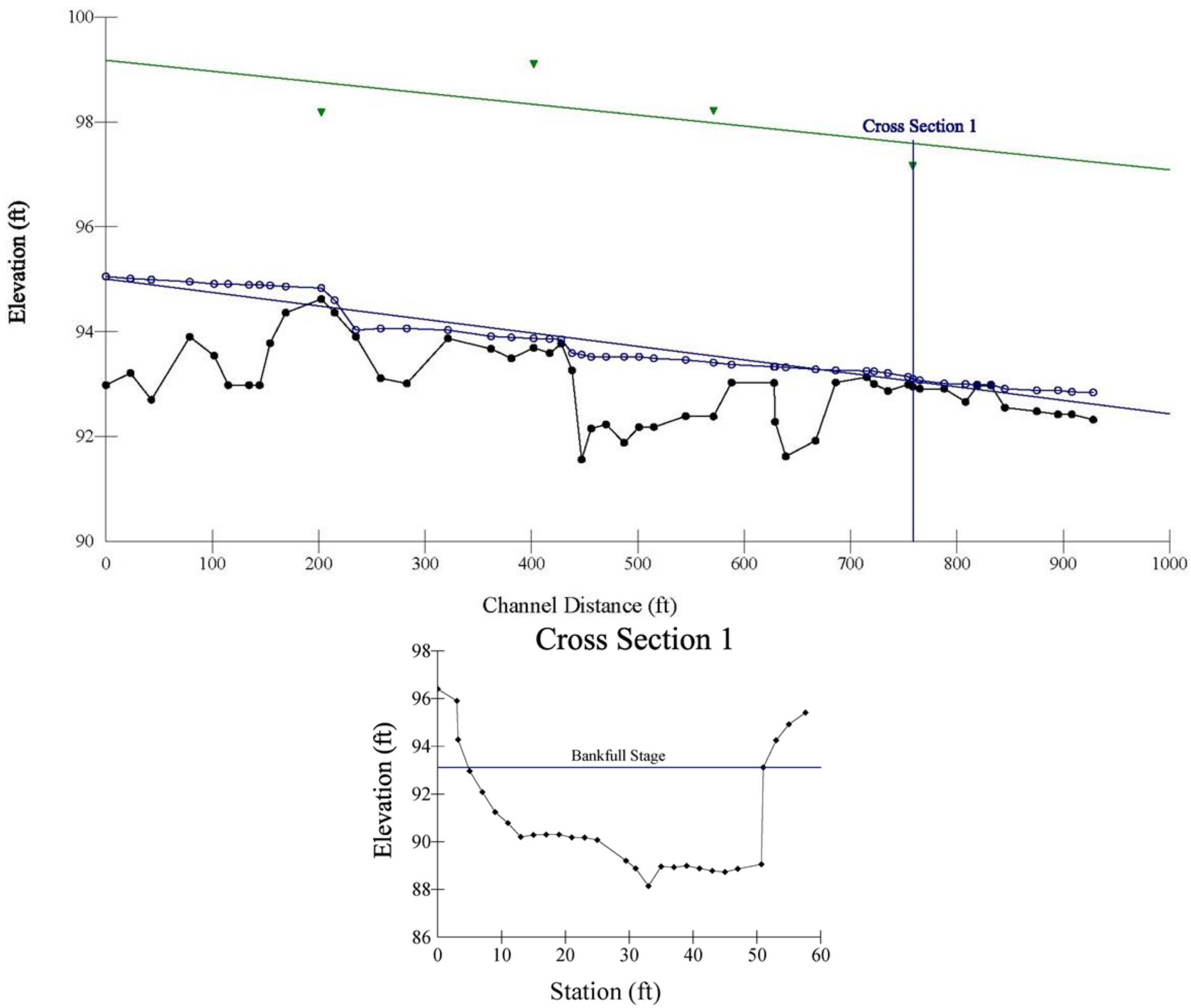

Figure A.9 Longitudinal profile (A), and riffle cross-sections (B), in study reach of Jordan Creek at Des Moines.

Lick Creek
Lick Creek at Shimek State Forest

View looking downstream at the reach of Lick Creek at Shimek State Forest

This reach is located approximately 0.5 miles south of Highway 2 in the Shimek State Forest. The reach is located in a remote wooded valley bottom surrounded by steep valley walls. Bedrock outcrops are common in this area.

The reach ran along a densely vegetated riparian woodland within the Shimek State Forest. Forested woodlands dominate the area surrounding this reach. The channel was fairly wide, moderately sinuous with irregular to tortuous meanders, and had a moderate slope. The channel had numerous riffle-pool sequences. The bankfull channel was well defined throughout the reach. The primary bankfull indicators at the site included flat depositional features on a horizontal plane, the top of point bars when present, and breaks in bank slope. The banks were densely vegetated and lined with grasses, forbs, and perineal woody vegetation. Small cut banks up to 10 ft were observed where the channel met the valley wall and at outer bends. The stream could access its floodplain throughout most of the reach and had well-established riparian willow stands on its bar features. The bed was gravel and cobble dominated with some sand bedforms present in between riffles. Some aquatic vegetation was present on the channel bottom, along with cement debris near the lower section of the reach. The channel met a bedrock outcropping in the middle of the reach and caused a large scour pool at its outer bend. Inactive floodplain terraces were observed throughout some sections of the reach. Moderate channel widths, small bank heights, mature riparian vegetation, and sand bedforms indicate that this channel is in quasi-equilibrium to aggrading.

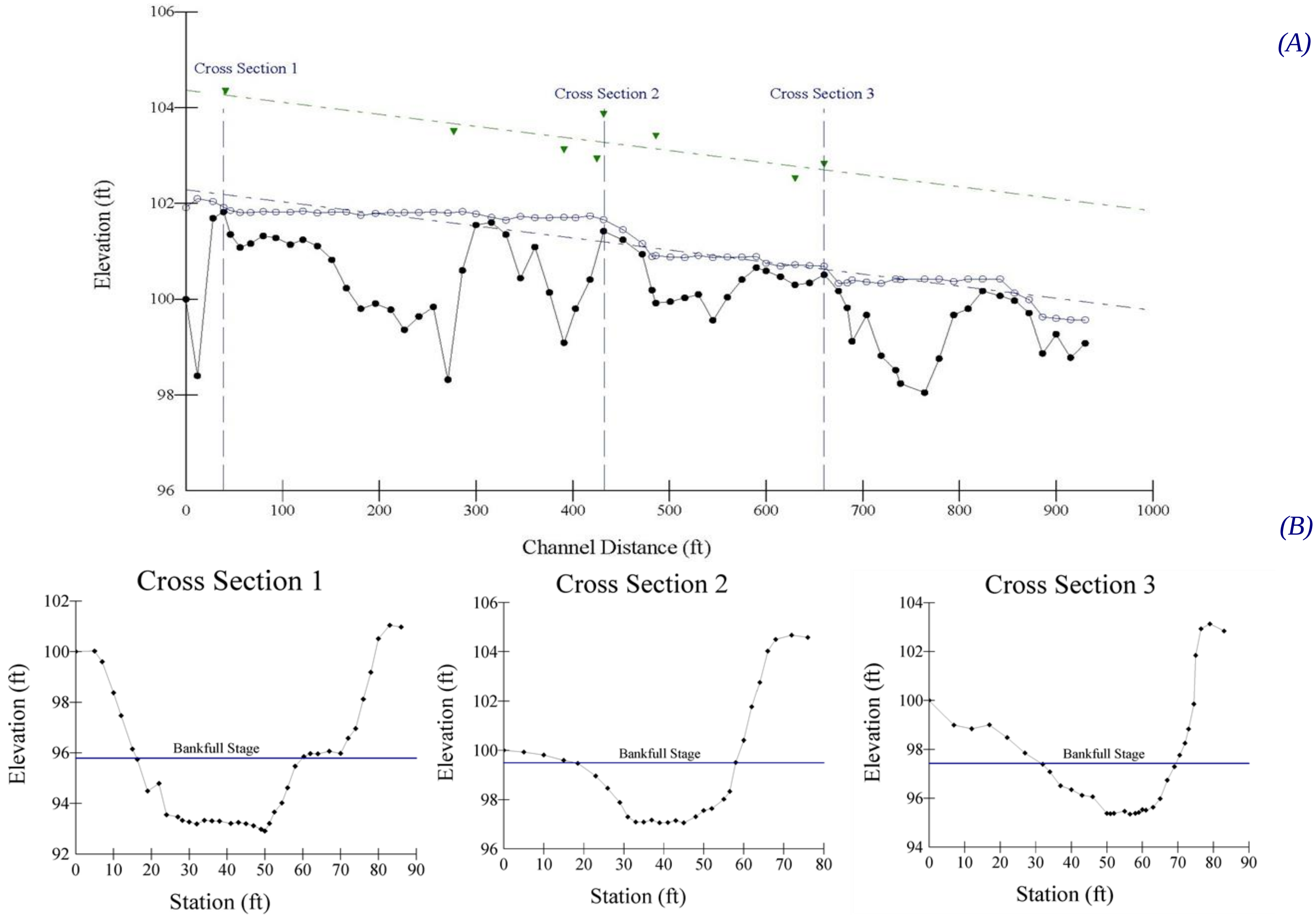

Figure A.10 Longitudinal profile (A), and riffle cross-sections (B), in study reach of Lick Creek at Shimek State Forest.

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Station 06600030
Little Floyd River near Sanborn, IA

View looking downstream from the bridge at the reach of Little Floyd River near Sanborn

The continuous crest-stage gaging station is located just below a highway bridge on the downstream side. The bridge appears to affect bankfull discharge at the gage due to a backwater effect and constriction of flows, causing a large scour pool downstream of the bridge. The surveyed reach began approximately 200 ft downstream of the bridge to avoid any effect on the bankfull stage.

The reach ran along open agricultural land dominated by cornfields. The land surrounding this reach is dominated by agriculture, where tile drainage systems likely influence discharge. The channel was very narrow, deep, and moderately sinuous with a mild slope. Irregular riffle-pool sequences dominated this channel below the gaging station. The bankfull channel was well defined throughout the reach. The primary bankfull indicators at the site included prominent breaks in bank slope where the stream banks met the floodplain. The banks were well vegetated with grasses and forbs. There was isolated bank erosion along some sections of the reach at outer bends. Soughing of bank material was evident, causing grassy terraces with some grass growing along the channel bottom. The floodplain could be accessed on both sides throughout the reach. The bed was gravel-dominated, with some sand and silt collecting in the pools. Clay was exposed at the bottom of some pools within the reach. Narrow channel widths, small bank heights, and a moderate sinuous pattern indicate that this channel takes the form of a premodified channel to slightly degrading.

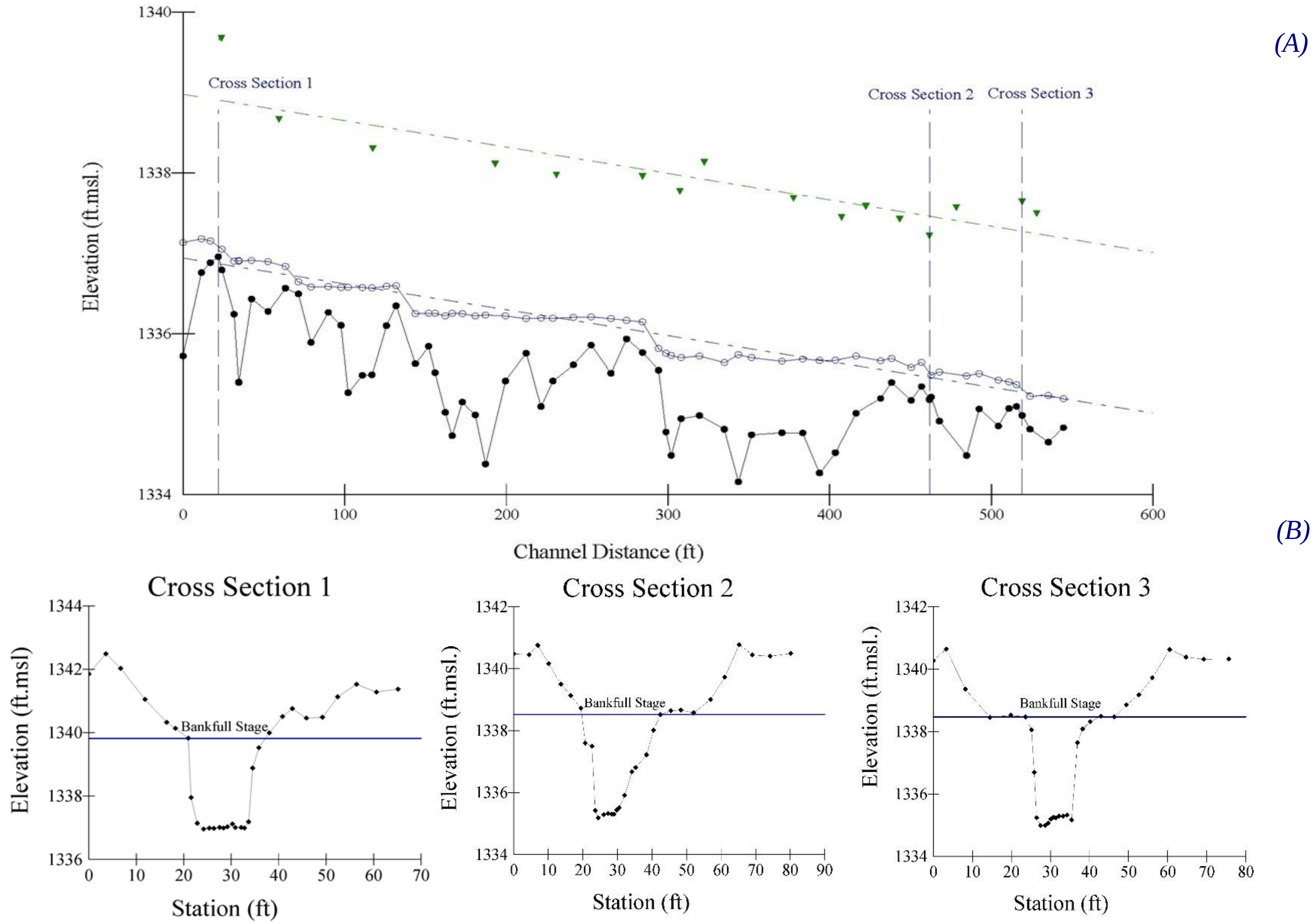

Figure A.11 Longitudinal profile (A), and riffle cross-sections (B), in study reach of Little Floyd River near Sanborn, IA.

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Little Waterman
Little Waterman Creek near Waterman Wildlife Area

View looking down at the reach of Little Waterman Creek near Waterman Wildlife Area

This reach is located approximately 0.35 miles east of the Waterman Wildlife Area parking area. The reach ends at the confluence of Little Waterman Creek and Waterman Creek.

The reach ran along an open vegetated meadow near the Waterman Wildlife Area. The area surrounding this reach is dominated by agriculture, and discharges may be influenced by tile drainage. Historic beaver activity observed through aerial photography may influence the upstream portions of Little Waterman Creek but likely does not affect the channel geometry of this reach. The channel was narrow, highly sinuous with irregular meanders, and had a mild slope. The channel had numerous synchronous riffle-pool sequences. The bankfull channel was well defined throughout the reach. The primary bankfull indicators at the site included flat depositional features on a horizontal plane, back of point bars when present, and breaks in bank slope. The banks were densely vegetated and lined with grasses and forbs. Small cut banks up to 5 ft were observed along some of the reach’s outer banks where the radius of curvature is tight. The stream could access its floodplain throughout the reach. The bed was gravel-dominated with some small cobble and sand present. Clusters of grass were present in some sections, resulting from sloughed bank material or low annual flows. Narrow channel widths, small bank heights, and highly sinuous pattern indicate that this channel is premodified to slightly degrading.

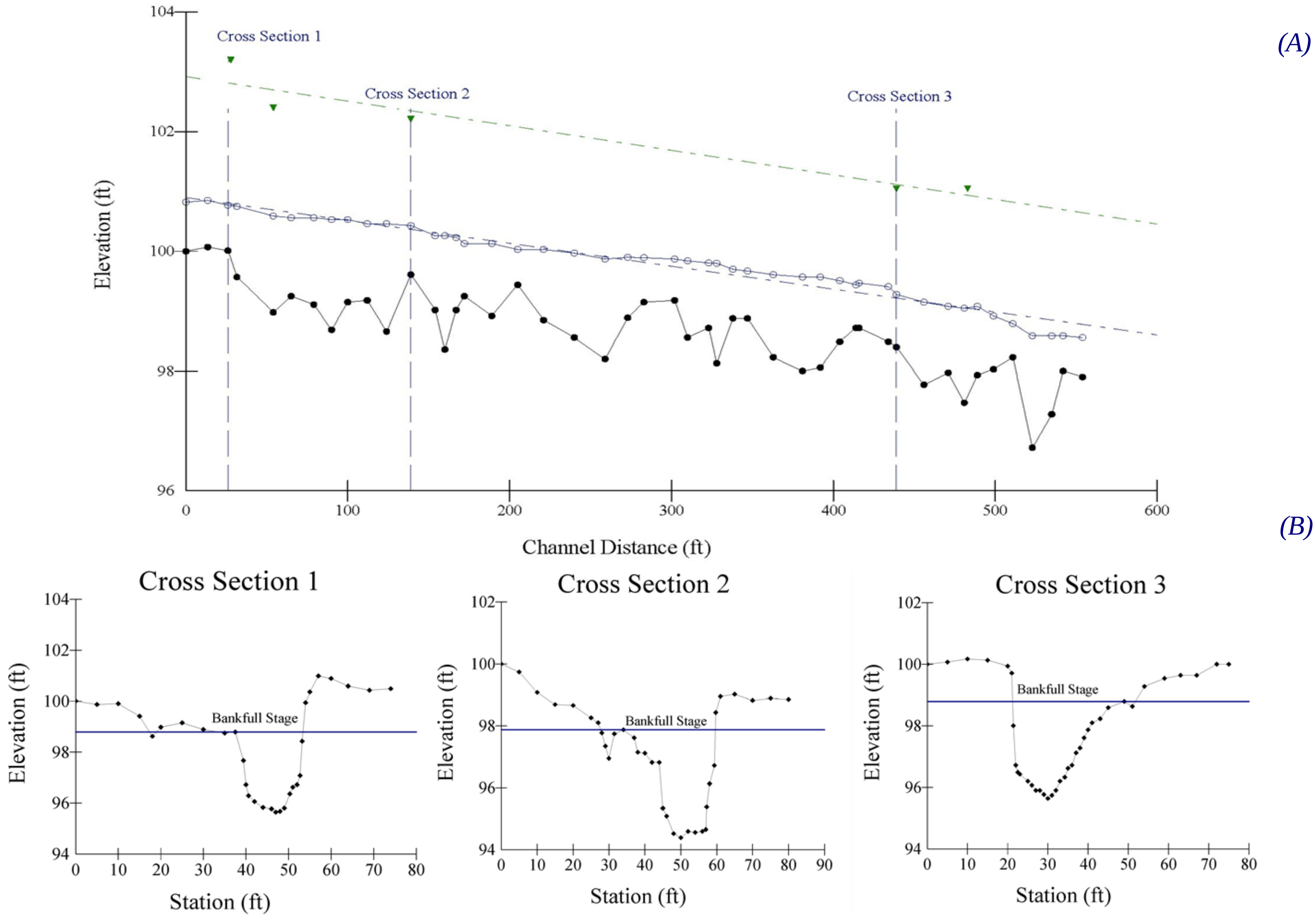

Figure A.12 Longitudinal profile (A), and riffle cross-sections (B), in study reach of Little Waterman Creek near Waterman Wildlife Area.

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Long Creek
Long Creek at Dekalb Wildlife Management Area

View looking upstream at the reach of Long Creek at Dekalb Wildlife Management Area

This reach is located approximately 700 ft east of 185th Avenue in the Dekalb Wildlife Management Area. The reach is approximately 300 ft downstream of a large outer bend where the channel meets to avoid a large scour pool. The reach is in a remote mixed hardwood woodland corridor surrounded by agricultural fields.

The reach ran along a densely vegetated riparian woodland area. The area surrounding this reach is dominated by agriculture, but discharges are not likely influenced by tile drainage. The channel was very wide, highly sinuous with regular meanders, and had a moderate slope. The channel had minor step-pool bedforms at the beginning of the reach before transitioning to sand bedforms with few riffle-run sequences. The bankfull channel was moderately well defined throughout the reach. The primary bankfull indicators at the site included breaks in bank slope and the top of point bars. The banks were densely vegetated and lined with grasses, forbs, and perineal woody vegetation. Large cut banks up to 15 ft were sloughing of the bank material, and large woody vegetation was observed in some places. The stream could not access its floodplain throughout most of the reach. Healthy and mature willow stands were common throughout the reach on point bars and lateral bars. The bed was sand-dominated with gravel and cobbles present at riffle cross-sections. An active beaver dam was in the middle of the reach, causing a large pool. Beaver activity was observed along the reach through the presence of active dams, fresh chews, prints, and scat. Moderate widths, considerable bank heights, the soughing of bank material and vegetation, and stable riffle bedforms indicate that this channel is widening and degrading in the upper section and widening and aggrading in the lower sections the reach.

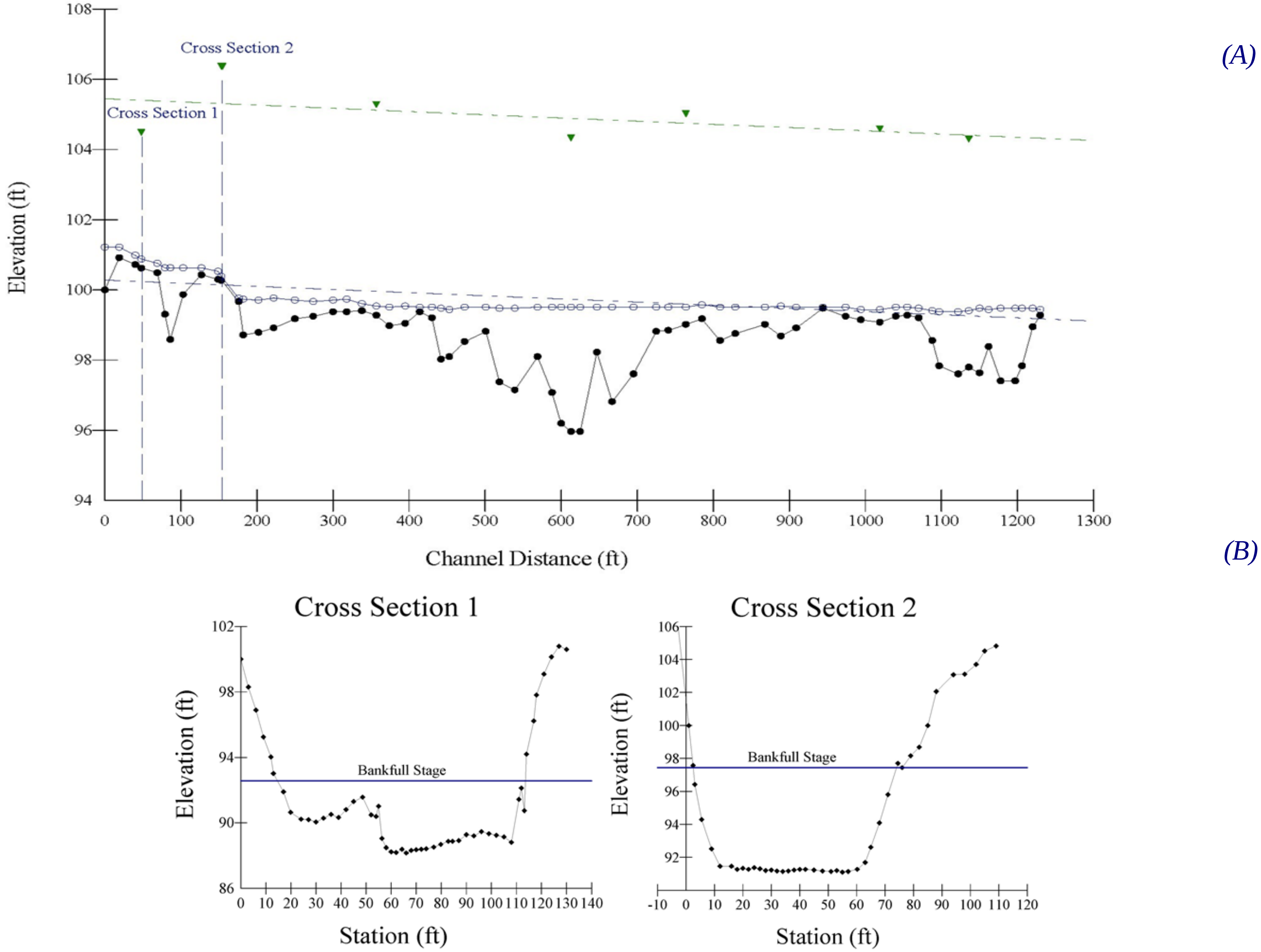

Figure A.13 Longitudinal profile (A), and riffle cross-sections (B), in study reach of Long Creek at Dekalb Wildlife Management Area.

Lotts Creek
Lotts Creek at Ringgold Wildlife Management Area

View looking upstream from the bridge at the reach of Lotts Creek at Ringgold Wildlife Management Area

This reach is located approximately 250 ft north of 320th Street in the Ringgold Wildlife Management Area. The reach is in a remote mixed hardwood woodland near the Missouri border.

The reach ran along a densely vegetated riparian woodland within the Ringgold Wildlife Management Area. Forested woodlands dominate the area surrounding this reach. The channel was fairly wide, moderately sinuous with irregular meanders, and had a mild slope. The channel was dominated by sand bedforms and scour pools around large woody vegetation with few riffle-pool sequences. The bankfull channel was well defined throughout the reach. The primary bankfull indicators at the site included flat depositional features on a horizontal plane, the top of point bars when present, and breaks in bank slope. The banks were densely vegetated and lined with grasses, forbs, and perineal woody vegetation. Cut banks up to 15 ft were observed in places where overhanging roots and sloughing of large woody vegetation were common. The stream could access its floodplain throughout some of the reach, but widespread inundation of the floodplain was infrequent. The bed was sand-dominated with some gravel and cobble at riffle sections. Some aquatic vegetation was present on the channel bottom. Glacial lag and till were common in the upper section of the reach with a clay-lined channel and boulders up to 1.5 ft. Large woody debris and log jams were common throughout the reach. Inactive floodplain terraces were observed throughout some sections of the reach. Moderate channel widths, large bank heights, mature riparian vegetation, and sand bedforms indicate that this channel is widening and degrading.

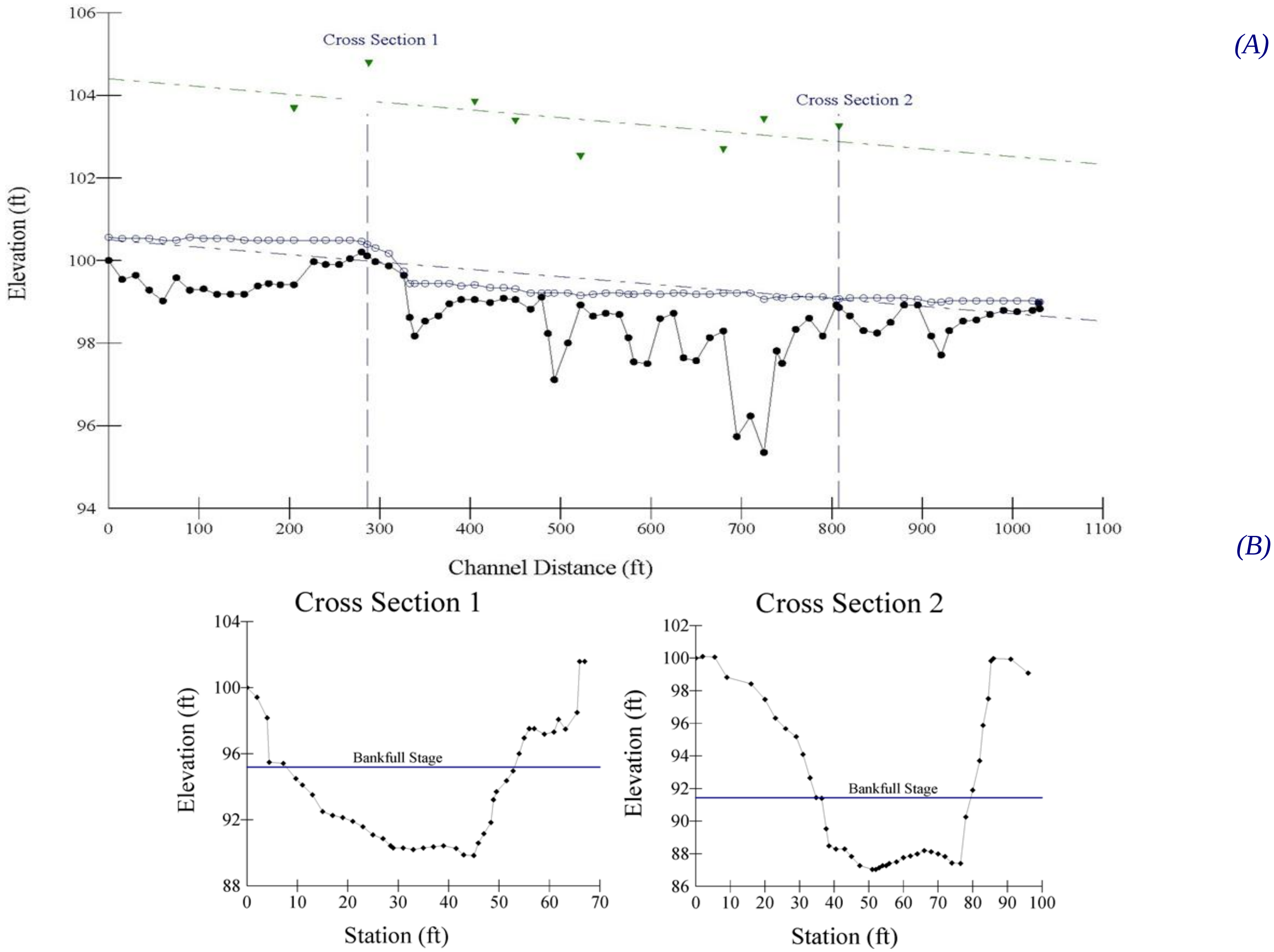

Figure A.14 Longitudinal profile (A), and riffle cross-sections (B), in study reach of Lotts Creek at Ringgold Wildlife Management Area.

Middle Catfish
Middle Catfish Creek at Dubuque, IA

View looking upstream at the reach of Middle Catfish at Dubuque, IA

This reach is located approximately 1,000 ft Southeast of Freemont Ave., in Dubuque, IA. A concrete pillar bridge for Freemont Ave. is located approximately 1,000 ft upstream.

The reach ran along a heavily vegetated woodland with numerous deciduous trees and railroad tracks on both sides of the reach. A dense woodland immediately surrounded the reach, but most of the basin is dominated by urban development. Stormwater drainage systems likely influence discharges; however, no inlets were observed. The channel was moderately incised with irregular meanders and had a mild slope. The channel had adequate riffle-pool sequences, consistent sand bedform, and point bar deposition. The bankfull channel was moderately defined throughout the reach. The primary bankfull indicators at the site included the back of point bars, changes in the size distribution of deposited material, changes in bank slope, and woody, perennial vegetation. The banks were moderately vegetated and lined with woody shrubs and deciduous trees. The bank material was primarily comprised of alluvium throughout most of the reach. Cut banks up to 6 ft were present in some areas and usually occurred at outer bends. The stream had limited access to the floodplain throughout the reach. The bed material was dominated by cobble in the riffles and coarse sand and gravel in the pools. The stream paralleled a railroad track and sometimes interacted with stabilized sections of the reach. Moderate channel widths, considerable bank heights, slumping bank material, and lack of floodplain access would indicate this reach is degrading and widening.

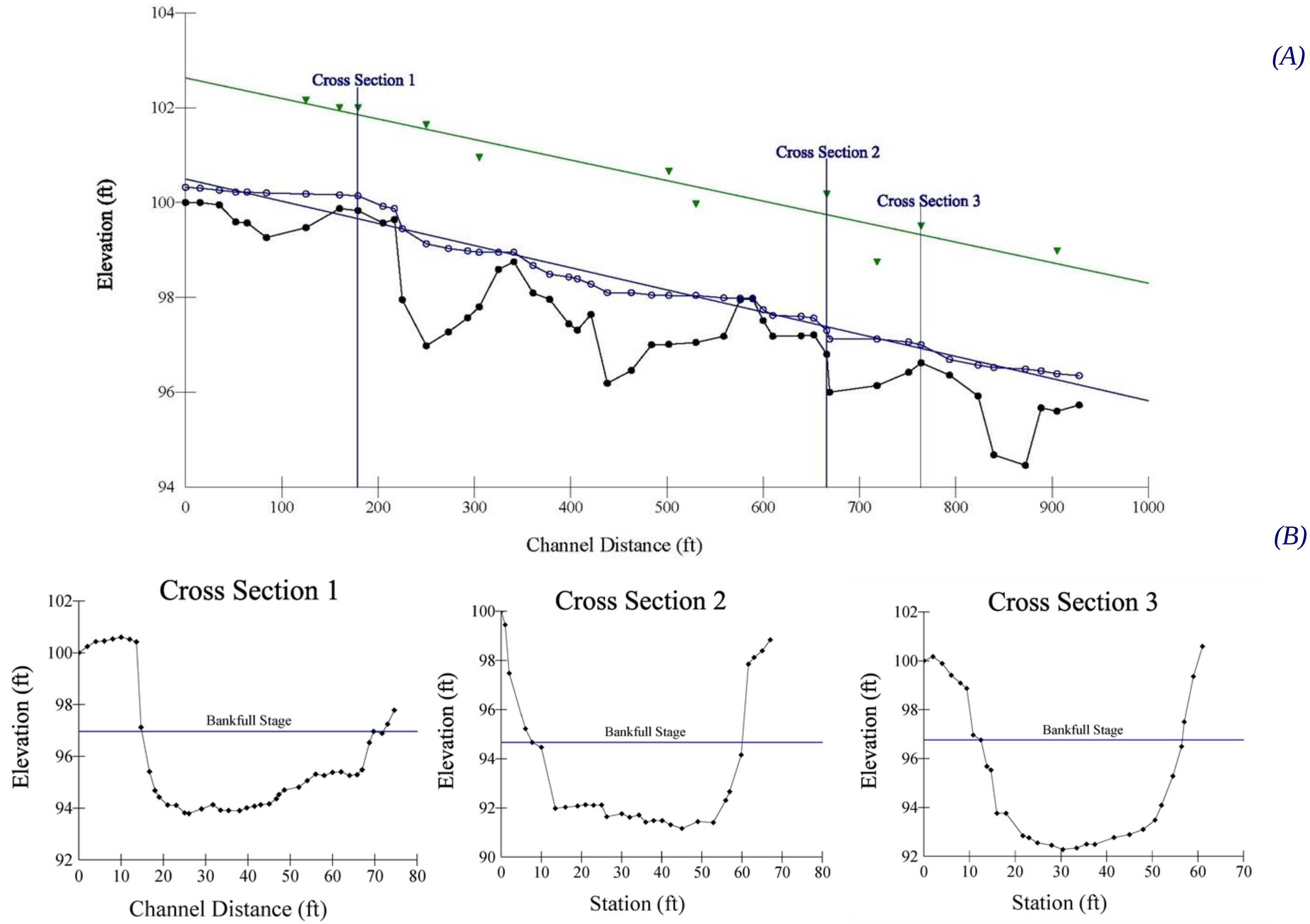

Figure A.15 Longitudinal profile (A), and riffle cross-sections (B), in study reach of Middle Catfish Creek at Dubuque.

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Station 05454090
Muddy Creek at Coralville, IA

View looking upstream at the reach of Muddy Creek at Coralville, IA

The continuous stream-flow gaging station is located approximately 5 ft upstream of a highway bridge. The bridge likely has an effect on bankfull discharge at the stream-flow gaging station. No evidence of a backwater effect was determined above the gage station.

The reach ran along a heavily vegetated woodland upstream of the stream-flow gaging station and downstream of the Brown Deer Golf Club. The land surrounding this area is dominated by urban development. Numerous outlets were observed on the right bank of the reach, which likely drained from the golf course parking area. Stormwater drainage systems likely influence discharges. The channel was wide, very deep, and straight with a mild slope. Sand bedforms dominated this channel with irregular riffle-pool sequences. The bankfull channel was poorly defined due to excessive erosion throughout the reach. The primary bankfull indicators at the site included prominent breaks in bank slope and the change in the size distribution of deposited materials. The banks were poorly vegetated with abundant root mats and large woody debris. There was excessive soughing of bank material throughout the reach with cut banks as high as 20 ft. The floodplain could not be accessed on either side of the channel at bankfull flows. The bed was sand-dominated with some gravel along the riffle sections. Large woody debris and other urban debris were found throughout the reach. Glacial till was exposed in the bottom of the channel at the lower sections of the reach. The presence of glacial till, soughing bank material, and steep banks would indicate this reach is degrading and widening.

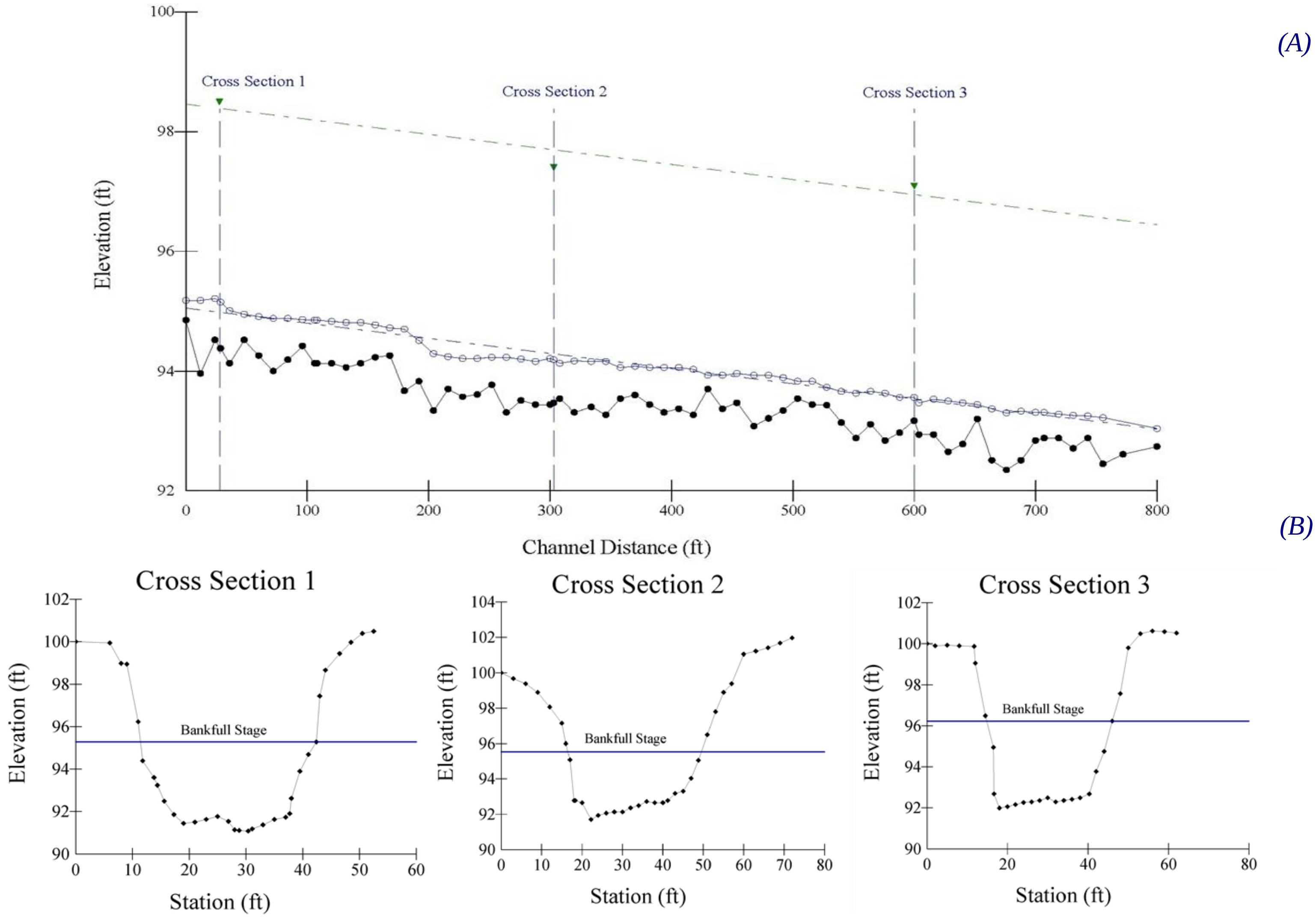

Figure A.16 Longitudinal profile (A), and riffle cross-sections (B), in study reach of Muddy Creek at Coralville, IA.

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North Catfish
North Catfish at Dubuque, IA

View looking upstream at the reach of North Catfish at Dubuque, IA

This reach is located approximately 800 ft South of U.S. Route 20, Dubuque, IA. There are no structures within the immediate vicinity of the reach.

The reach ran along a riparian area consisting of tall grass and deciduous trees on both sides of the channel. A dense woodland immediately surrounded the reach, but most of the basin is dominated by urban development. Stormwater drainage systems likely influence discharges; however, no inlets were observed. The channel was moderately incised with regular meanders and a mild slope. The channel contained some riffle-pool sequences with well-formed point bars. The bankfull channel was well defined throughout the reach. The primary bankfull indicators at the site included the changes in the size distribution of deposited material, back of point bars, prominent breaks in bank slope, and perennial vegetation. The banks were moderately vegetated with grasses and woody shrubs. The bank material was primarily comprised of glacial till throughout most of the reach. Cut banks up to 5 ft were present in the reach. The stream had access to the floodplain throughout the entirety of the reach. The bed material was dominated by cobble, gravel, and glacial erratics. Within some sections of the reach, old concrete structures were found in the channel. Appropriate channel width, lack of incision, and stable depositional surfaces indicate that this channel is in quasi-equilibrium to aggrading.

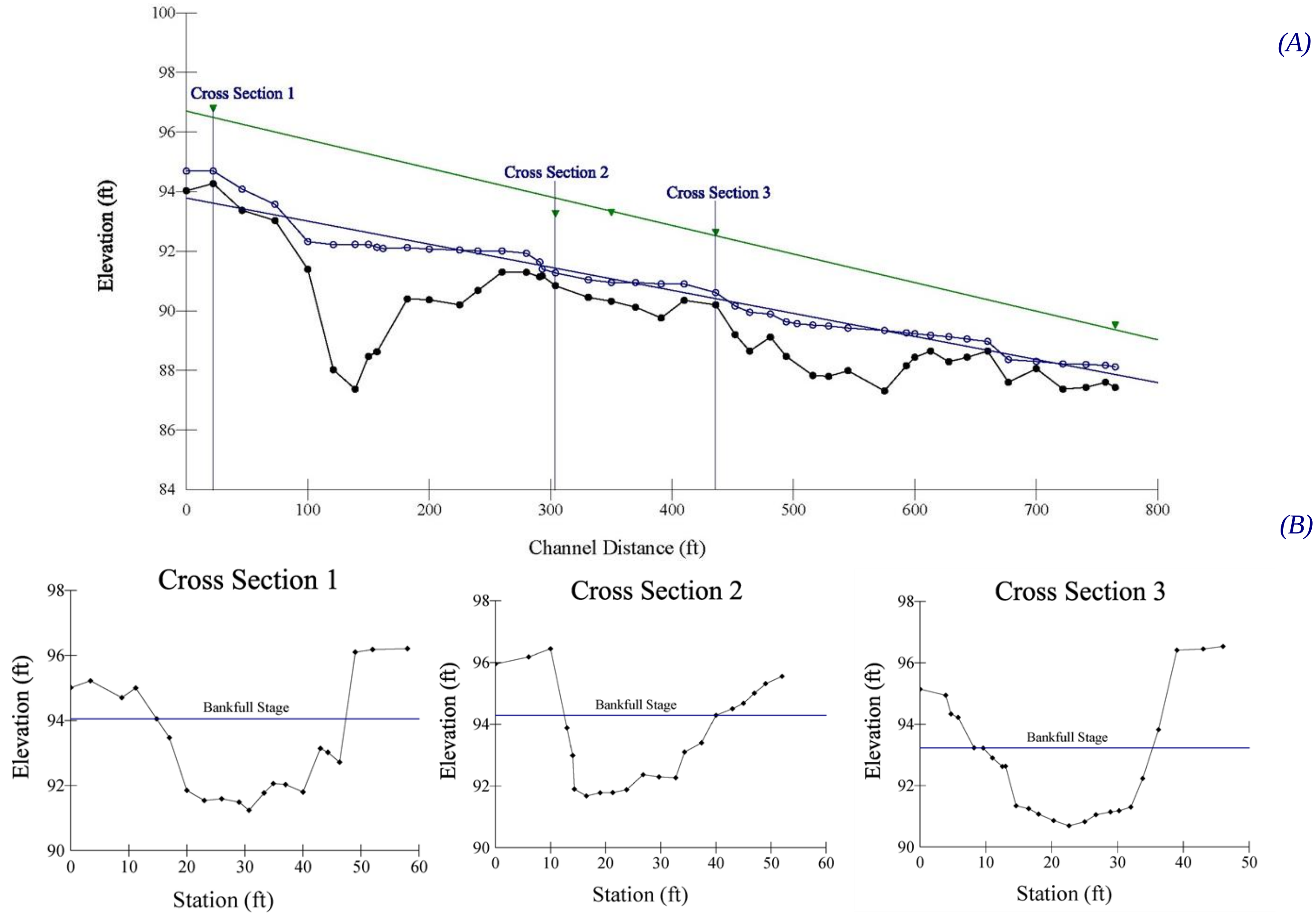

Figure A.17 Longitudinal profile (A), and riffle cross-sections (B), in study reach of North Catfish Creek at Dubuque.

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North Walnut Tributary
Unnamed Tributary of North Walnut Below Living History Farm

View looking downstream at the reach of Unnamed Tributary of North Walnut Creek below the Living History Farm Museum

This reach is located approximately 500 ft east of Interstate 80. There are no structures within the immediate vicinity of the reach.

The reach ran along a steep-walled and heavily vegetated woodland just below the Living History Farm Museum. A dense woodland immediately surrounded the reach, but most of the basin is dominated by urban development. Stormwater drainage systems likely influence discharges; however, no inlets were observed. The channel was deeply incised, highly sinuous with regular meanders, and had a moderate slope. The channel had numerous irregularly paced riffle-pool sequences and irregularly dispersed sand bedforms. The bankfull channel was well defined throughout the reach. The primary bankfull indicators at the site included prominent breaks in bank slope, the back of point bars, and changes in the size distribution of deposited material. The banks were poorly vegetated and lined with few riparian species because of the steep slopes. The bank material was primarily comprised of alluvium on top of glacial till throughout most of the reach. Cut banks up to 15 ft were present in some areas and usually occurred at outer bends. The stream could access the floodplain along inner bends throughout some of the reach. Little vegetation establishment was observed on the back of point bars. The bed was sand and gravel-dominated with some cobbles throughout. Large woody debris was commonly found in the channel. Slumped woody vegetation was apparent throughout the reach where dispersed woody vegetation was present. Moderate channel widths, considerable bank heights, slumping bank material, and moderate floodplain access would indicate this reach is degrading to degrading and widening.

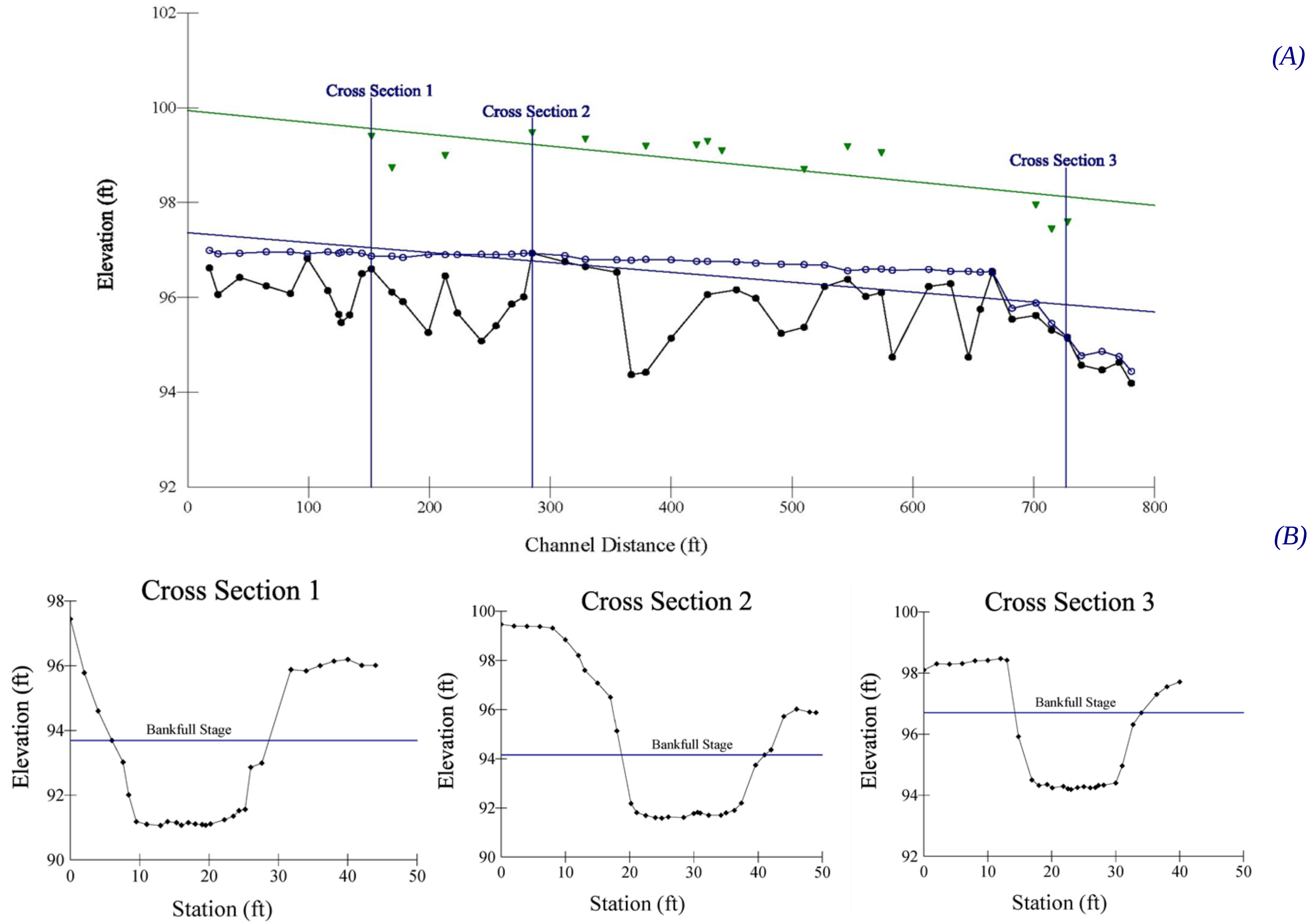

Figure A.18 Longitudinal profile (A), and riffle cross-sections (B), in study reach of North Walnut Tributary Below Living History Farm.

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Station 06605000
Ocheyedan River near Spencer, IA

View looking upstream from the bridge at the reach of Ocheydan River near Spencer, IA

The continuous crest-stage gaging station is located approximately 15 ft downstream of a highway bridge 4 miles west of Spencer. The bridge appears to affect bankfull discharge at the gage due to a backwater effect and constriction of flows, causing a scour pool downstream of the bridge.

The surveyed reach began approximately 1 mile upstream of the bridge to avoid any impact it had on the bankfull stage and find riffle-run features. The reach ran along an open grassy corridor in-between agricultural fields on both sides of the channel. The area surrounding the reach was dominated by agriculture which may affect discharges. The channel was fairly wide, had a low sinuosity with irregular meanders, and had a mild slope. The channel had numerous sand bedforms and scour pools around large woody debris and boulders with few riffle-run sequences. The bankfull channel was well defined throughout the reach. The primary bankfull indicators at the site included flat depositional features on a horizontal plane where the bank met the floodplain, back of point bars, breaks in bank slope, and change in vegetation. The banks were well vegetated and lined with numerous riparian species. Well-established willow stands lined the banks for a majority of the reach. Cut banks up to 5 ft were present in some areas and usually occurred at outer bands. The stream could access the floodplain on both sides throughout most of the reach. The bed was sand-dominated with some gravel and cobble at riffle cross-sections. Randomly scattered boulders were present throughout the reach, creating minor scour pools. Some Large woody debris was found in the channel and along the floodplain. Woody debris was likely not in-situ and transported from upstream. Moderate channel widths, small bank heights, mature riparian vegetation, and stable bedforms indicate that this channel is in quasi-equilibrium to aggrading.

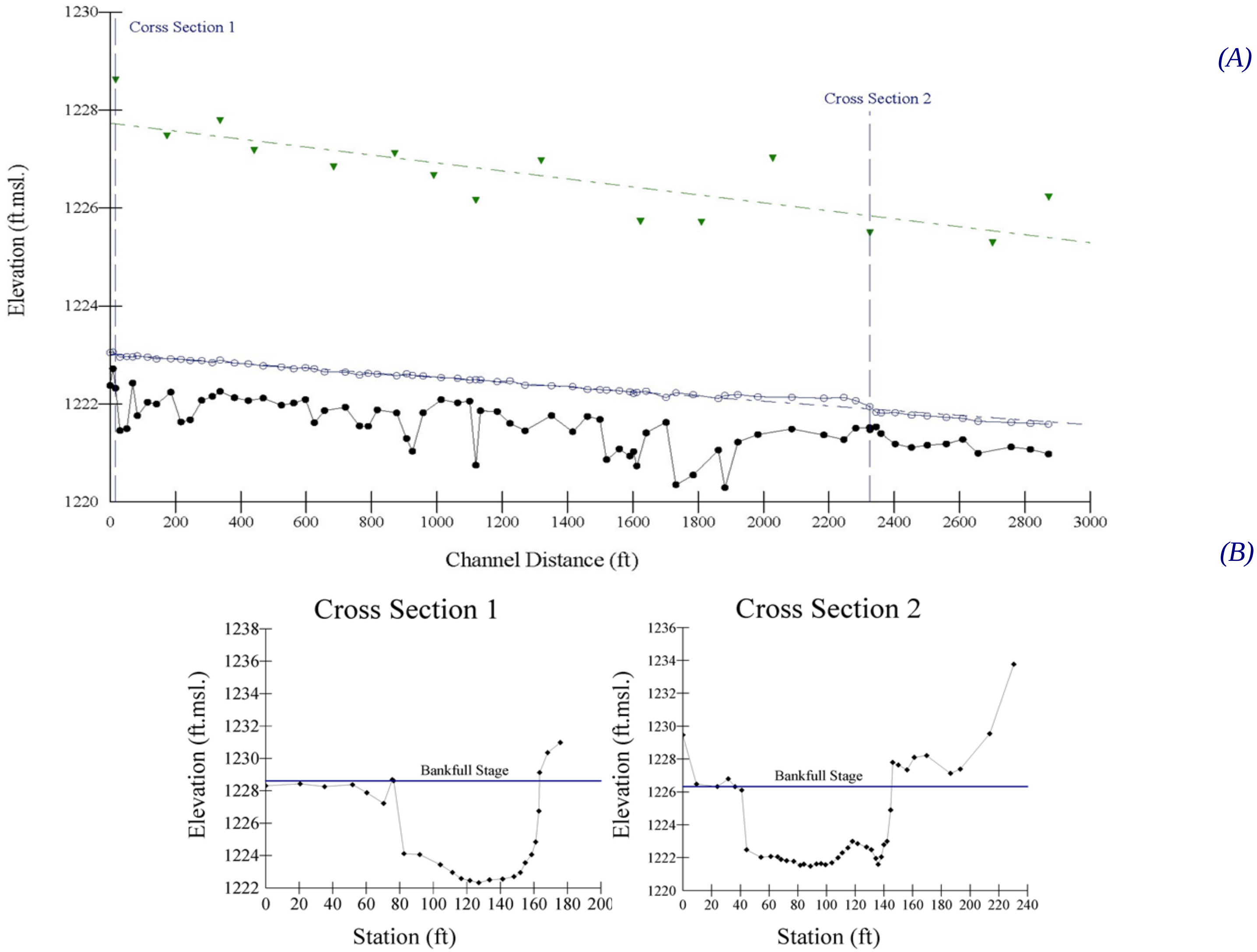

Figure A.19 Longitudinal profile (A), and riffle cross-sections (B), in study reach of Ocheyedan River near Spencer, IA.

Pigeon Creek
Pigeon Creek at McLamarrah Park

View looking downstream at the reach of Pigeon Creek at McLamarrah Park

This reach is located approximately 1200 ft Northwest of Valley Dr., in McLamarrah Park, Davenport, IA. A small walking footbridge is directly upstream of the reach.

The reach ran along a forested area within the boundaries of McLamarrah Park. A woodland immediately surrounded the reach, but most of the basin is dominated by urban development. Stormwater drainage systems likely influence discharges; however, no inlets were observed. The channel was not incised and lacked regular meanders. The channel contained some riffle-pool sequences with little deposition. The bankfull channel was well defined throughout the reach. The primary bankfull indicators at the site included the changes in the size distribution of deposited material, back of point bars, prominent breaks in bank slope, and woody perennial vegetation. The banks were well vegetated with deciduous trees. The bank material was primarily comprised of glacial till. The banks were primarily gentle sloping except for the valley confines, where cutbacks up to 4 ft were present. The stream had access to the floodplain throughout the entirety of the reach. The bed material was dominated by cobble, gravel, and glacial erratics. Appropriate channel width, moderate incision, and stable bedform features indicate that this channel is in quasi-equilibrium to degrading.

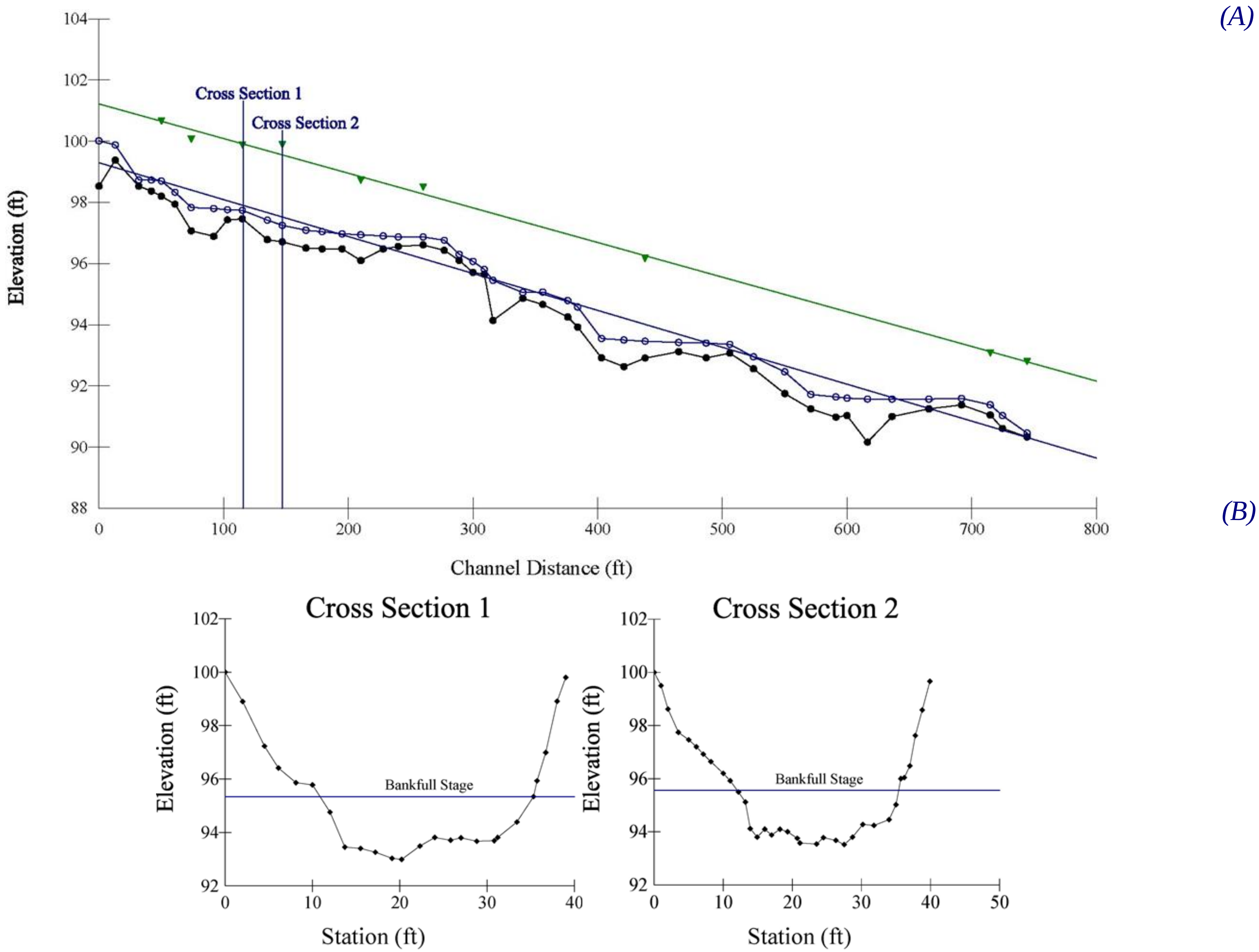

Figure A.20 Longitudinal profile (A), and riffle cross-sections (B), in study reach of Pigeon Creek at McLamarrah Park.

Richardson Branch
Richardson Branch near Iowa Arboretum

View looking downstream at the reach of Richardson Branch near the Iowa Arboretum

This reach is located approximately 0.5 miles east of the Iowa Arboretum and 1.8 miles upstream of the confluence of the Des Moines River. There are no structures within the immediate vicinity of the reach.

The reach ran along a steep-walled and heavily wooded valley floor. The channel's width was irregular throughout the reach, moderately sinuous with irregular meanders, and had a moderate to a steep slope. The channel had irregular riffle-pool sequences along with irregularly dispersed sand bedforms. The bankfull channel was well defined throughout most of the reach. The primary bankfull indicators at the site included the back of point bars and prominent breaks in bank slope. The banks were well vegetated and lined with numerous riparian species. Significant erosion was present in some areas and usually occurred where the channel met the valley wall. The stream could access the floodplain on both sides when not adjacent to its valley wall. Numerous inactive floodplain benches were overserved near the active channel floodplain. The bed was gravel-dominated with some sand, cobble, and boulders throughout. Glacial lag was abundant in some sections of the reach where large cobbles and boulders were present. Glacial till was exposed in the bottom of the channel within the upper portion of the reach. Large woody debris was commonly found throughout the channel and along the floodplain. Steep valley walls, the presence of glacial till and lag, and proximity to the Des Moines River would indicate this reach is degrading.

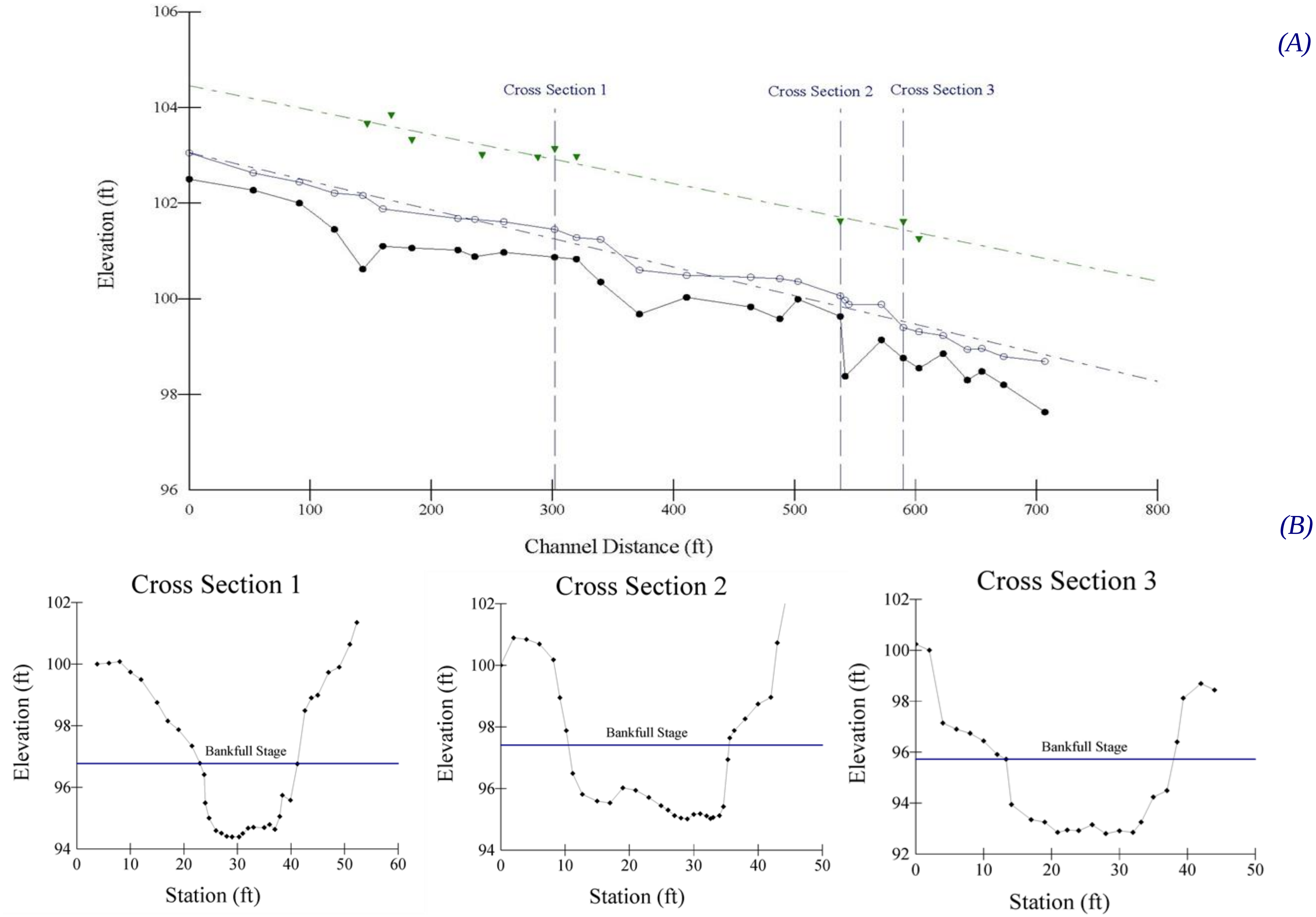

Figure A.21 Longitudinal profile (A), and riffle cross-sections (B), in study reach of Richardson Branch near the Iowa Arboretum.

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Station 05455010
South Branch Ralston Creek at Iowa City, IA

View looking downstream at the reach of South Branch of Ralston Creek at Iowa City, IA

The continuous stage-discharge gaging station is located approximately 60 ft downstream of a residential roadway bridge. The bridge was constructed as a set of three box culverts with little deposition observed within any section. There was no evidence that the bridge affected bankfull discharges upstream or downstream of the road.

The reach ran along a residential development on the left bank and an open park on its right bank. The land surrounding this area is dominated by urban development. Stormwater drainage systems likely influence discharges; however, no inlets were observed. The channel was wide, deep, and straight with a mild slope. Sand and gravel-filled pools dominated this channel with irregular and infrequent riffle-pool sequences. The channel bottom was comprised of numerous compound pools in-between riffles. The bankfull channel was poorly defined throughout the reach. The primary bankfull indicators at the site included prominent breaks in bank slope and changes in vegetation. The banks were densely vegetated with abundant introduced and invasive species. Tree removal was observed throughout the reach, leaving large tree stumps along the banks. The lower portion of the reach was heavily armored with concrete debris. The floodplain could not be accessed on either side of the channel at bankfull flows. The bed was gravel-dominated, with some sand and silt collecting within compound pools. The shape and size of the channel, steep banks, and absence of woody debris indicate that this reach has been modified to prevent flooding into residential and public areas.

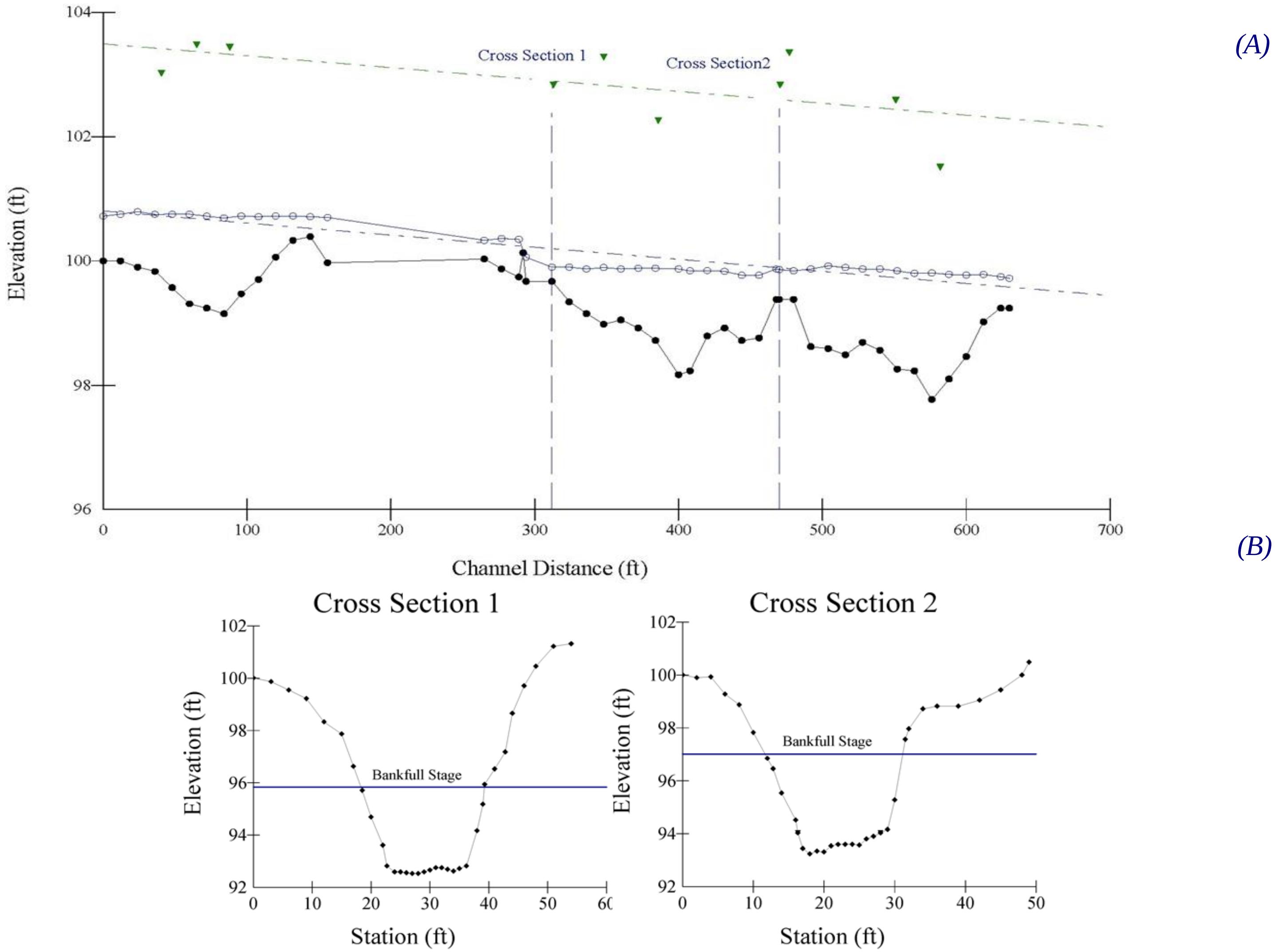


Figure A.22 Longitudinal profile (A), and riffle cross-sections (B), in study reach of South Branch Ralston Creek at Iowa City, IA.

South Pine Creek
South Pine Creek at South Pine Creek Wildlife Management Area

View looking upstream at the reach of South Pine Creek at South Pine Wildlife Management Area

This reach is located approximately 1 mile southeast of the South Pine Creek Wildlife Area Management parking area. The reach is located in a remote grassy meadow of a woodland valley green belt.

The reach ran along an open vegetated meadow within the South Pine Creek Wildlife Management Area. The area surrounding this reach is dominated by agriculture, but discharges are likely not influenced by tile drainage. Using aerial photography, Beaver activity was observed approximately 1000 ft above the reach, which may affect South Pine Creek's upstream and downstream channel morphology. The channel was very narrow, highly sinuous with irregular to tortuous meanders, and had a mild slope. The channel had numerous synchronous riffle-pool sequences with large compound pools. The bankfull channel was well defined throughout the reach. The primary bankfull indicators at the site included flat depositional features on a horizontal plane and breaks in bank slope. The banks were densely vegetated and lined with grasses and forbs. Large cut banks up to 10 ft were observed where the channel met the valley wall. The stream could access its floodplain throughout most of the reach. The bed was gravel-dominated with cobble and some sand present. Clusters of grass were present in some sections, which could be a result of low annual flows. Narrow channel widths, small bank heights, and highly sinuous pattern indicate that this channel is premodified.

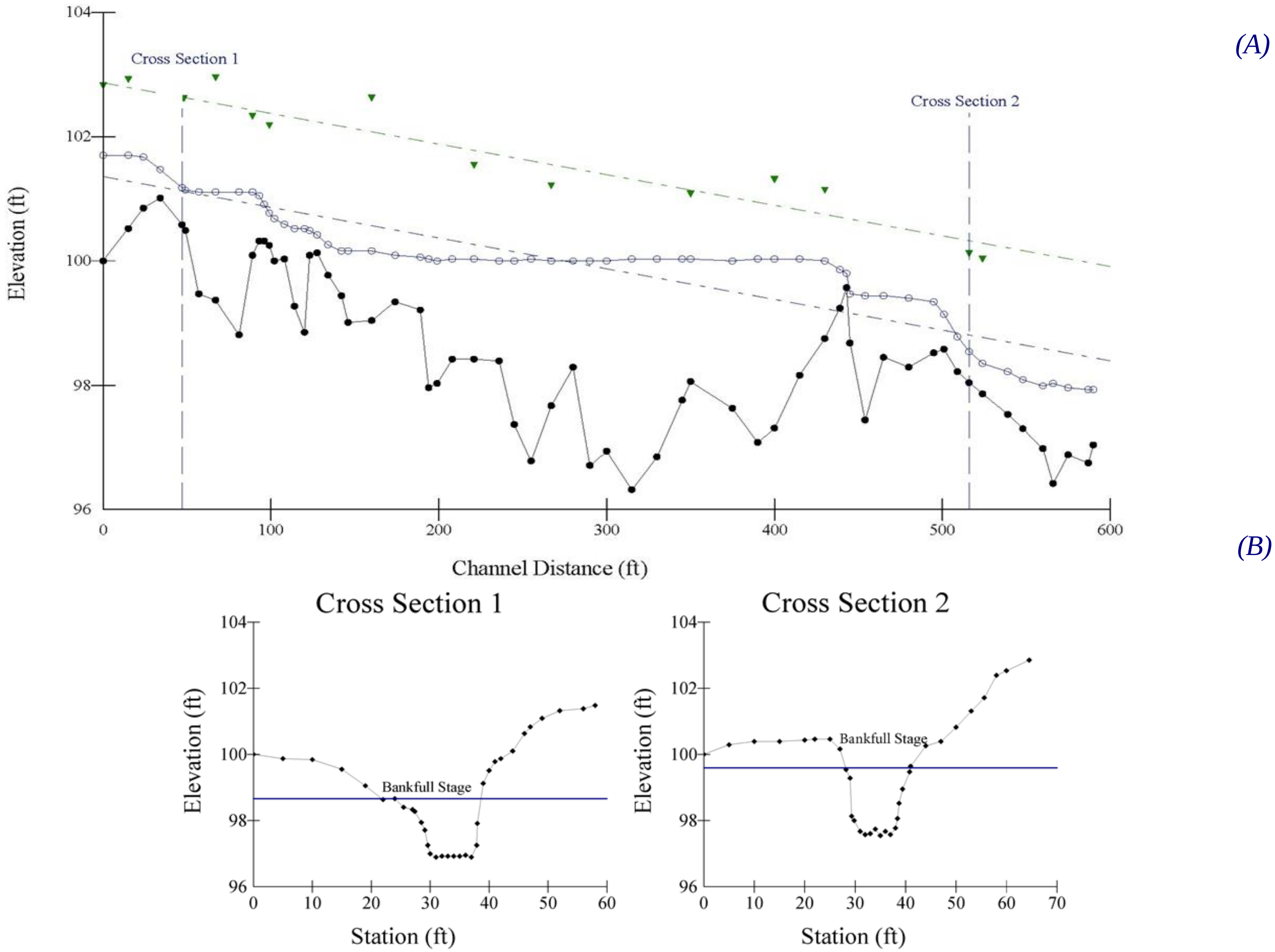
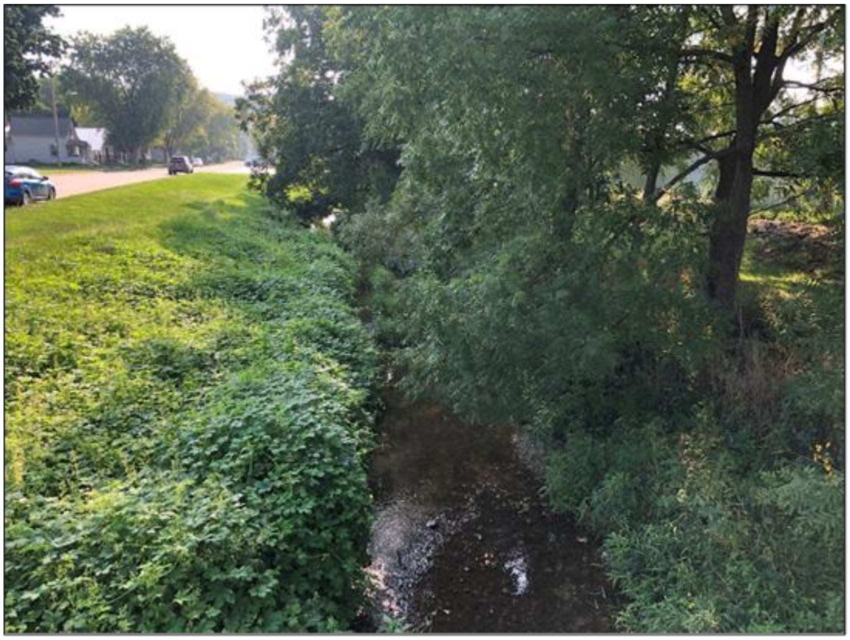


Figure A.23 Longitudinal profile (A), and riffle cross-sections (B), in study reach of South Pine Creek at South Pine Wildlife Management Area.

Upper Iowa Tributary
Unnamed Tributary of Upper Iowa at Decorah



View looking downstream at the reach of Unnamed Tributary of Upper Iowa at Decorah

This reach is located just below east of 2nd Street in Decorah. The reach began approximately 20 ft east of the 2nd Street bridge to avoid any influence on the bankfull channel.

The reach ran along an open residential neighborhood. The land surrounding the reach was dominated by urban development where a road bordered the stream on the left bank and residential homes on the right bank. Stormwater drainage systems likely influence discharges; however, no inlets were observed. The channel was narrow, fairly deep, and straight with a moderate slope. The channel had few irregularly paced riffle-pool sequences and irregularly dispersed gravel bedforms. The bankfull channel was well defined throughout the reach. The primary bankfull indicators at the site included prominent breaks in bank slope and changes in the size distribution of deposited material. The banks were well vegetated with some riparian species. The bank material was primarily comprised of alluvium throughout most of the reach. Cut banks up to 5 ft were present in some areas and usually occurred at outer bends. There was no well-defined floodplain throughout the reach due to the encroachment of urban development. The bed was sand and gravel-dominated with few cobbles throughout. Some large woody debris was found in the channel. Slumped woody vegetation was apparent at isolated sections of the reach where dispersed woody vegetation was present. Moderate channel widths, the presence of cut banks, some slumping bank material, and poor floodplain access would indicate this reach is degrading to degrading and widening.

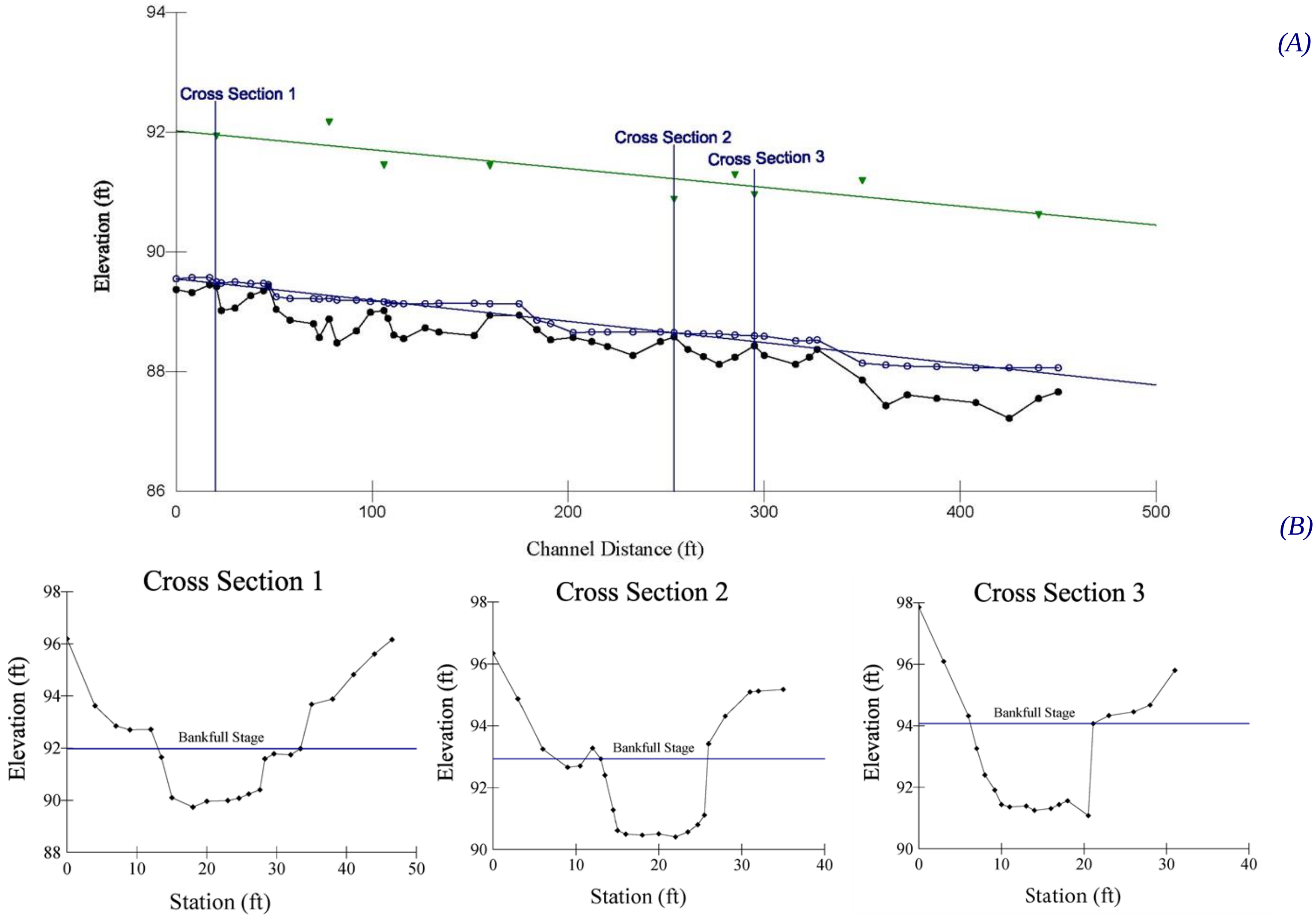


Figure A.24 Longitudinal profile (A), and riffle cross-sections (B), in study reach of Upper Iowa Tributary at Decorah.

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Station 05484800
Walnut Creek at Des Moines, IA

View looking downstream at the reach of Walnut Creek at Des Moines, IA

The continuous stage-discharge gaging station is located just downstream of the bridge on 63rd Street. The surveyed reach began approximately 1500 ft upstream of the bridge. There was no evidence that the bridge affected bankfull discharges upstream or downstream of the road.

The reach on both sides ran along a narrow marginal floodplain in a highly urbanized area. The area surrounding the reach was dominated by urban development, which likely influenced discharge; however, no inlets were observed. The channel was wide, moderately sinuous with irregular meanders, and had a mild slope. The channel had few riffle-pool sequences along with irregularly dispersed sand bedforms. The bankfull channel was well defined throughout the reach. The primary indicators at the site included flat depositional features on a horizontal plane where the bank met the floodplain, back of point bars, breaks in bank slope, and changes in vegetation. The banks were well vegetated and lined with numerous riparian species. Cut banks up to 5 ft were present in some areas and usually occurred at outer bands. The stream could access the floodplain on both sides throughout most of the reach. The bed was sand-dominated with some gravel and cobble at riffle cross-sections. Randomly scattered boulders were present throughout the reach, creating minor scour pools. Some Large woody debris was found in the channel and along the floodplain. Moderate channel widths, small bank heights, mature riparian vegetation, and stable bedforms indicate that this channel is in quasi-equilibrium to aggrading.

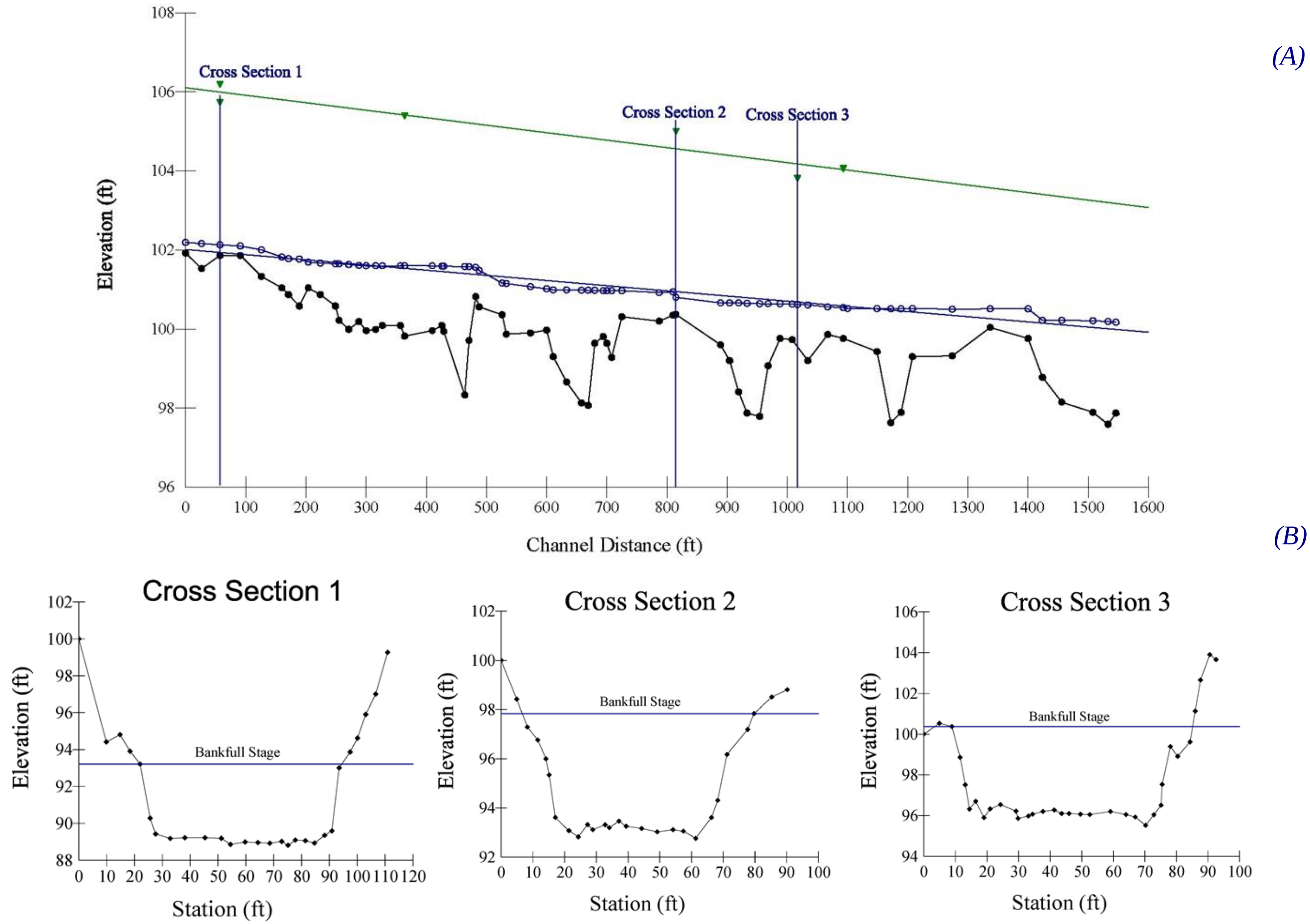

Figure A.25 Longitudinal profile (A), and riffle cross-sections (B), in study reach of Walnut Creek at Des Moines, IA.

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Walnut Creek
Walnut Creek Below 560th Avenue

View looking upstream at the reach of Walnut Creek below 560th Avenue

This reach is located approximately 1,000 ft East of 560th Avenue. There are no structures within the immediate vicinity of the reach.

The reach ran along an open vegetated pasture with a grassy meadow and dispersed woody vegetation on both sides of the channel. The area surrounding the reach was dominated by agriculture which may affect discharges. The channel was deeply incised, moderately sinuous with irregular meanders, and had a mild slope. The channel had few riffle-pool sequences along with irregularly dispersed sand bedforms. The bankfull channel was well defined throughout the reach. The primary bankfull indicators at the site included the back of point bars, changes in the size distribution of deposited material, and breaks in bank slope. The banks were poorly vegetated and lined with few riparian species because of the steep slopes. The bank material was primarily comprised of glacial outwash throughout most of the reach. Cut banks up to 20 ft were present in some areas and usually occurred at outer bends. The stream could not access the floodplain on both sides throughout most of the reach. Well-established horsetail stands lined the back of point bars. Some inactive floodplain benches were observed near the active channel floodplain. The bed was sand and gravel-dominated with some cobbles throughout. Large woody debris was commonly found in the channel. Slumped woody vegetation was apparent throughout the reach where dispersed woody vegetation was present. Moderate channel widths, considerable bank heights, slumping bank material, and lack of floodplain access would indicate this reach is degrading to degrading and widening.

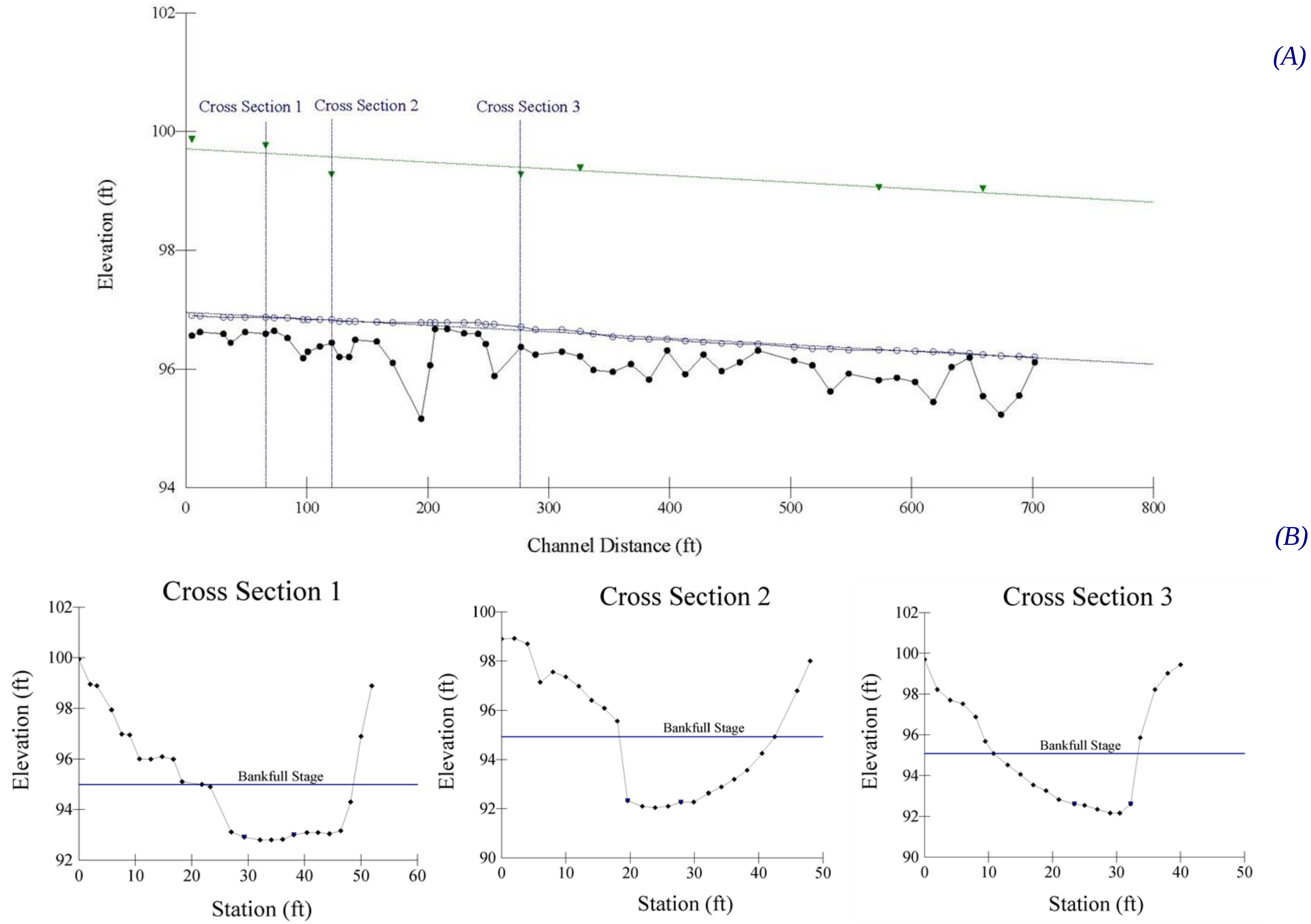

Figure A.26 Longitudinal profile (A), and riffle cross-sections (B), in study reach of Walnut Creek Below 560th Avenue.

Station NS320
Walnut Creek in Jasper County

View looking downstream at the reach of Walnut Creek in Jasper County

The continuous stream-flow gaging station is located approximately 25 ft downstream of a highway bridge. The bridge likely affects bankfull discharge at the stream-flow gaging station, but this could not be confirmed through field investigation.

The reach ran along an open vegetated meadow downstream of the stream-flow gaging station. The Neal Smith National Wildlife Refuge dominates the land surrounding this reach. Above the reach, the land is dominated by agriculture, where tile drainage systems likely influence discharges. The channel was narrow, very deep, and straight with a mild slope. Irregular riffle-pool sequences dominated this channel below the gaging station with numerous compound pools. The bankfull channel was poorly defined throughout the reach. The primary bankfull indicators at the site included prominent breaks in bank slope and the presence of elderberry on both banks. The banks were well vegetated with grasses and forbs with some woody vegetation. There was abundant soughing of bank material throughout the reach, creating in-channel grassy terraces. The floodplain could not be accessed on either side of the channel at bankfull flows. The bed was sand and silt dominated with some gravel along the riffle sections. Glacial till was exposed in the bottom of the channel throughout the reach. The presence of glacial till, soughing bank material, and steep banks would indicate this reach is degrading and widening.

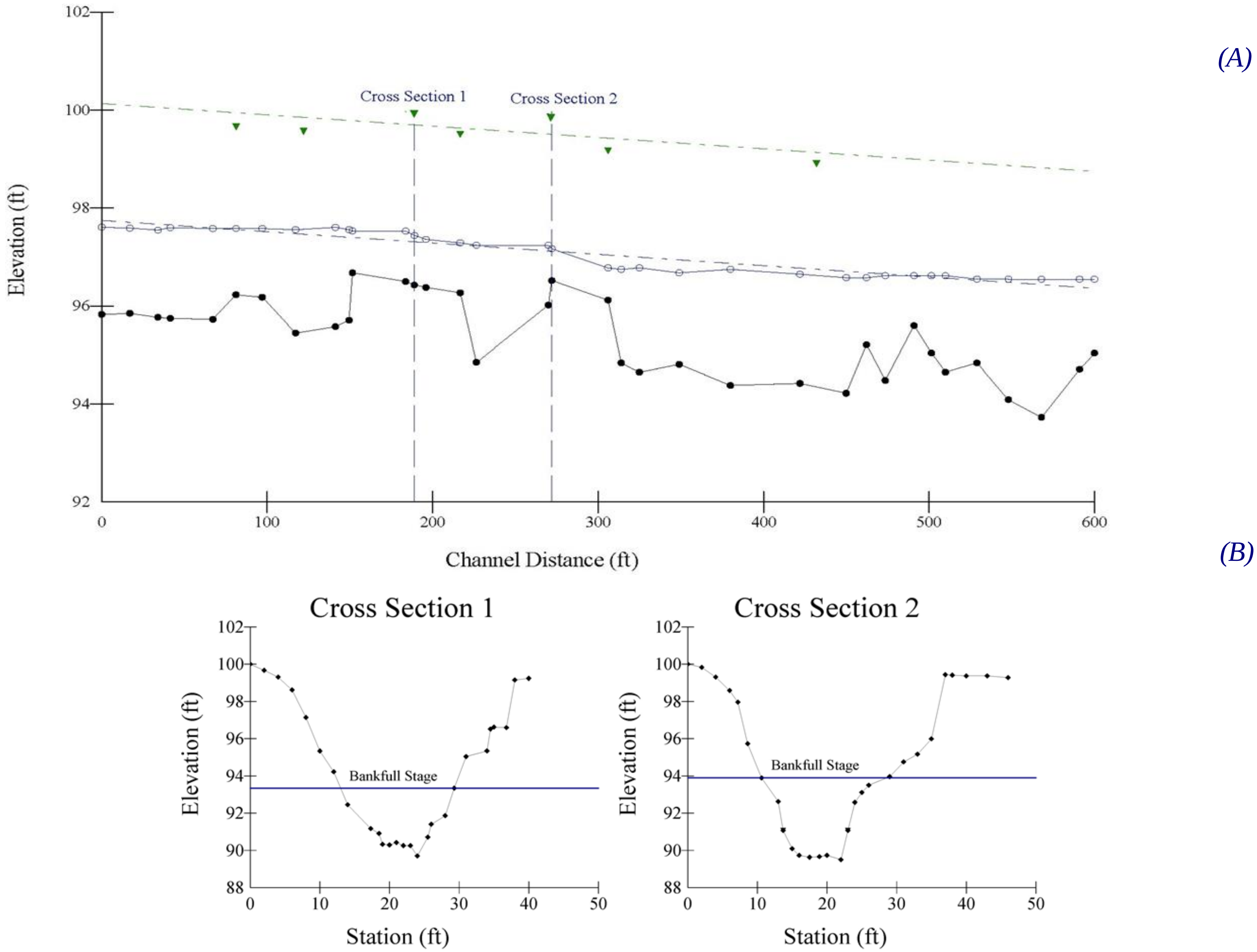

Figure A.27 Longitudinal profile (A), and riffle cross-sections (B), in study reach of Walnut Creek in Jasper County.

Station WC310
Walnut Creek in Story County

View looking upstream at the reach of Walnut Creek in Story County

The continuous stream-flow gaging station is located approximately 100 ft upstream of a high roadway bridge. The bridge does not appear to affect bankfull discharge but may constrict higher flows at the bridge crossing, causing a backwater effect.

The reach ran along an open vegetated meadow upstream of the stream-flow gaging station. The land surrounding this reach is dominated by agriculture, where tile drainage systems likely influence discharge. The channel was very narrow, deep, and straight with a mild slope. Irregular riffle-pool sequences dominated this channel above the gaging station. The bankfull channel was well defined throughout the reach. The primary bankfull indicators at the site included prominent breaks in bank slope where the stream banks met the floodplain. The banks were well vegetated with grasses and forbs with some woody vegetation. There was isolated bank erosion in the upper portions of the reach. The floodplain could be accessed on both sides throughout the reach. The bed was gravel-dominated in the upper portions of the reach, with increasing sand and silt as you move closer to the continuous stream-flow gaging station. Narrow channel widths, small bank heights, and low sinuosity indicate that this channel is modified to degrading.

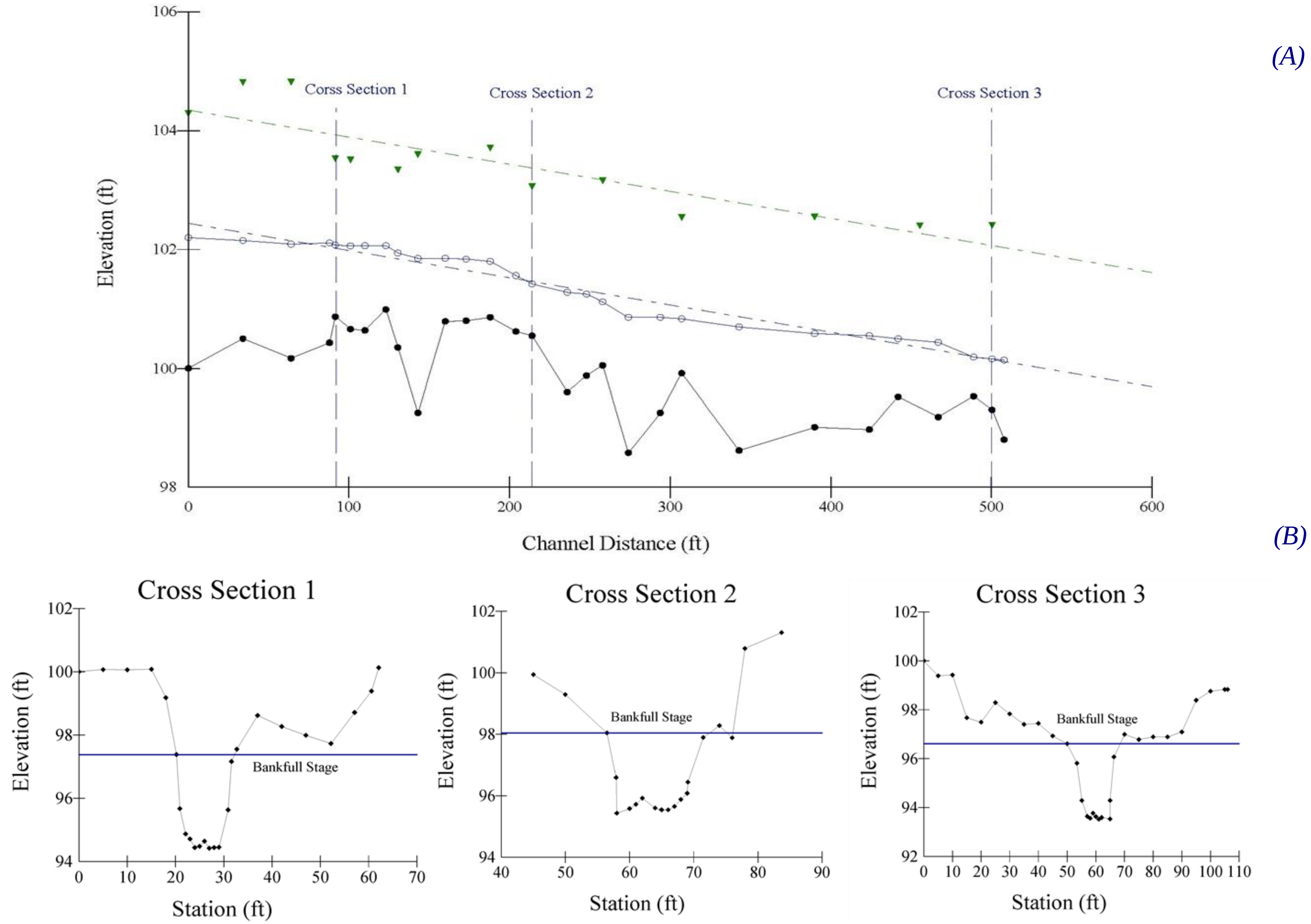

Figure A.28 Longitudinal profile (A), and riffle cross-sections (B), in study reach of Walnut Creek in Story County.

Station 05388310
Waterloo Creek near Dorchester, IA

View looking upstream at the reach of Waterloo Creek near Dorchester, IA

The continuous crest-stage gaging station is located just below a highway bridge 1.4 miles south of Dorchester. The bridge appears to significantly affect bankfull discharge at the gage due to a backwater effect and constriction of flows, causing a large scour pool around the bridge. The surveyed reach began approximately 600 ft downstream of the bridge to avoid any impact it had on the bankfull stage.

The reach ran along a densely vegetated riparian woodland area. The area surrounding this reach is dominated by agriculture, but discharges are not likely influenced by tile drainage. Discharges are likely influenced by springs and seeps due to the moderate relief of the surrounding area. The channel was wide, had a low sinuosity with irregular meanders, and had a moderate slope. The channel had minor step-pool bedforms with some riffle-pool sequences. The bankfull channel was well defined throughout the reach. The primary bankfull indicators at the site included flat depositional features on a horizontal plane, breaks in bank slope, and the top of point bars. The banks were densely vegetated and lined with grasses, forbs, and perineal woody vegetation. Small cut banks up to 5 ft were observed at outer bends. The stream could access its floodplain throughout the reach. Healthy and mature willow stands were common throughout the reach. The bed was gravel and cobble dominated with some boulders present and sand accumulations in sections with lower flow. A large log jam was in the middle of the reach, causing a large scour pool. Beaver activity was observed along the reach through the presence of abandoned dams, fresh chews, and prints. Moderate channel widths, small bank heights, mature riparian vegetation, and stable bedforms indicate that this channel is in quasi-equilibrium.

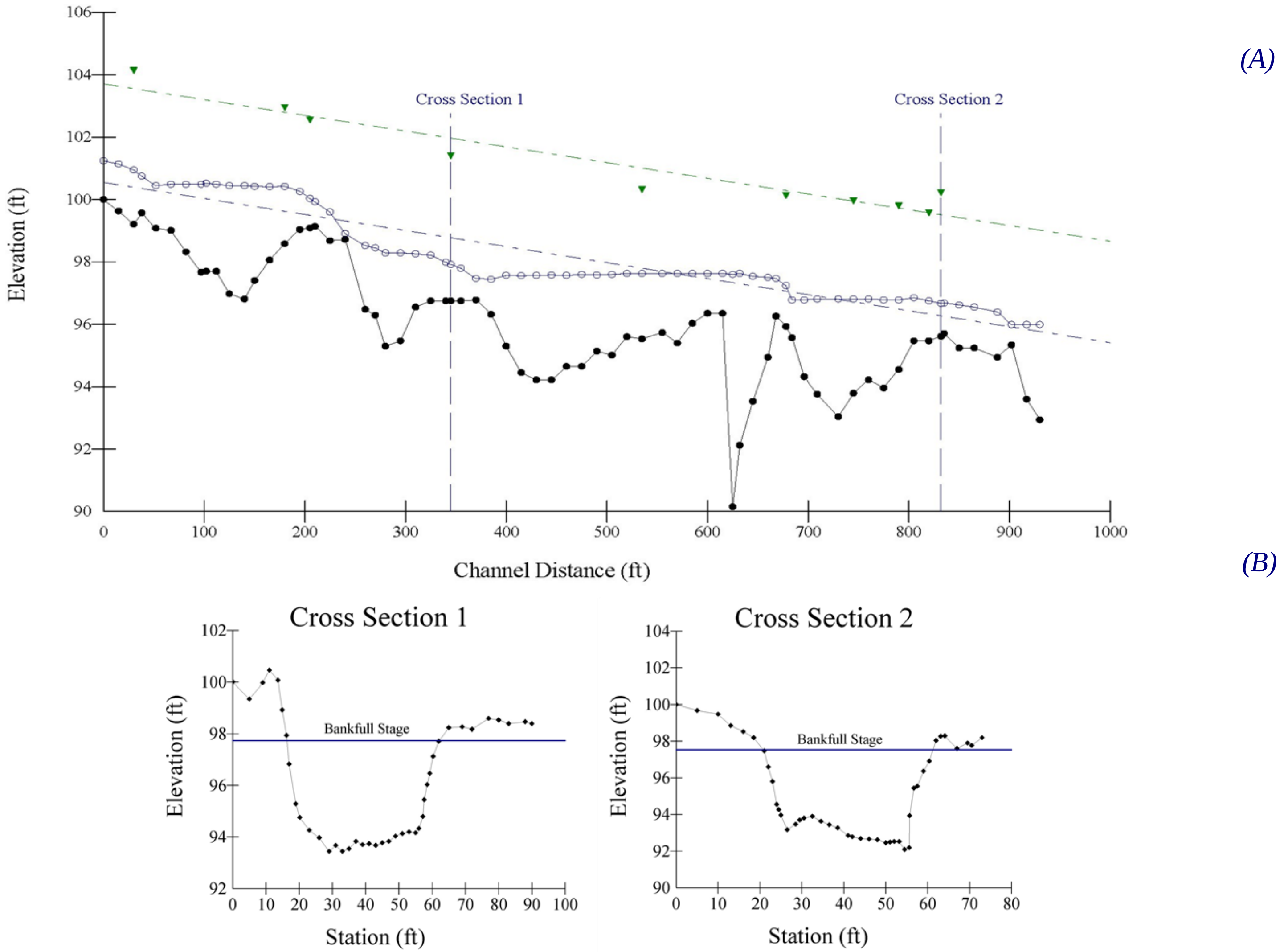

Figure A.29 Longitudinal profile (A), and riffle cross-sections (B), in study reach of Waterloo Creek near Dorchester, IA.

Waterman Creek
Waterman Creek near McCormack Prairie

View looking downstream at the reach of Waterman Creek near McCormack Prairie

This reach is located approximately 800 ft south of the 470th Street Bridge. There are no structures within the immediate vicinity of the reach.

The reach ran along an open valley bottom with a grassy meadow on both sides of the channel. The area surrounding the reach was dominated by agriculture which may affect discharges. The channel was fairly wide, moderately sinuous with regular meanders, and had a mild slope. The channel had numerous riffle-pool sequences along with irregularly dispersed sand bedforms. The bankfull channel was well defined throughout the reach. The primary bankfull indicators at the site included flat depositional features on a horizontal plane, back of point bars, change in the size distribution of deposited material, and breaks in bank slope. The banks were well vegetated and lined with numerous riparian species. Well-established willow stands lined the banks for a majority of the reach. Cut banks up to 5 ft were present in some areas and usually occurred at outer bands. The stream could access the floodplain on both sides throughout most of the reach. Some inactive floodplain benches were overserved near the active channel floodplain. The bed was gravel-dominated with some sand, cobble, and boulders throughout. Large woody debris was commonly found throughout the channel and along the floodplain. Beaver activity was observed along the reach through the presence of abandoned dams, fresh chews, and prints. Moderate channel widths, small bank heights, mature riparian vegetation, and stable bedforms indicate that this channel is in quasi-equilibrium to aggrading and widening.

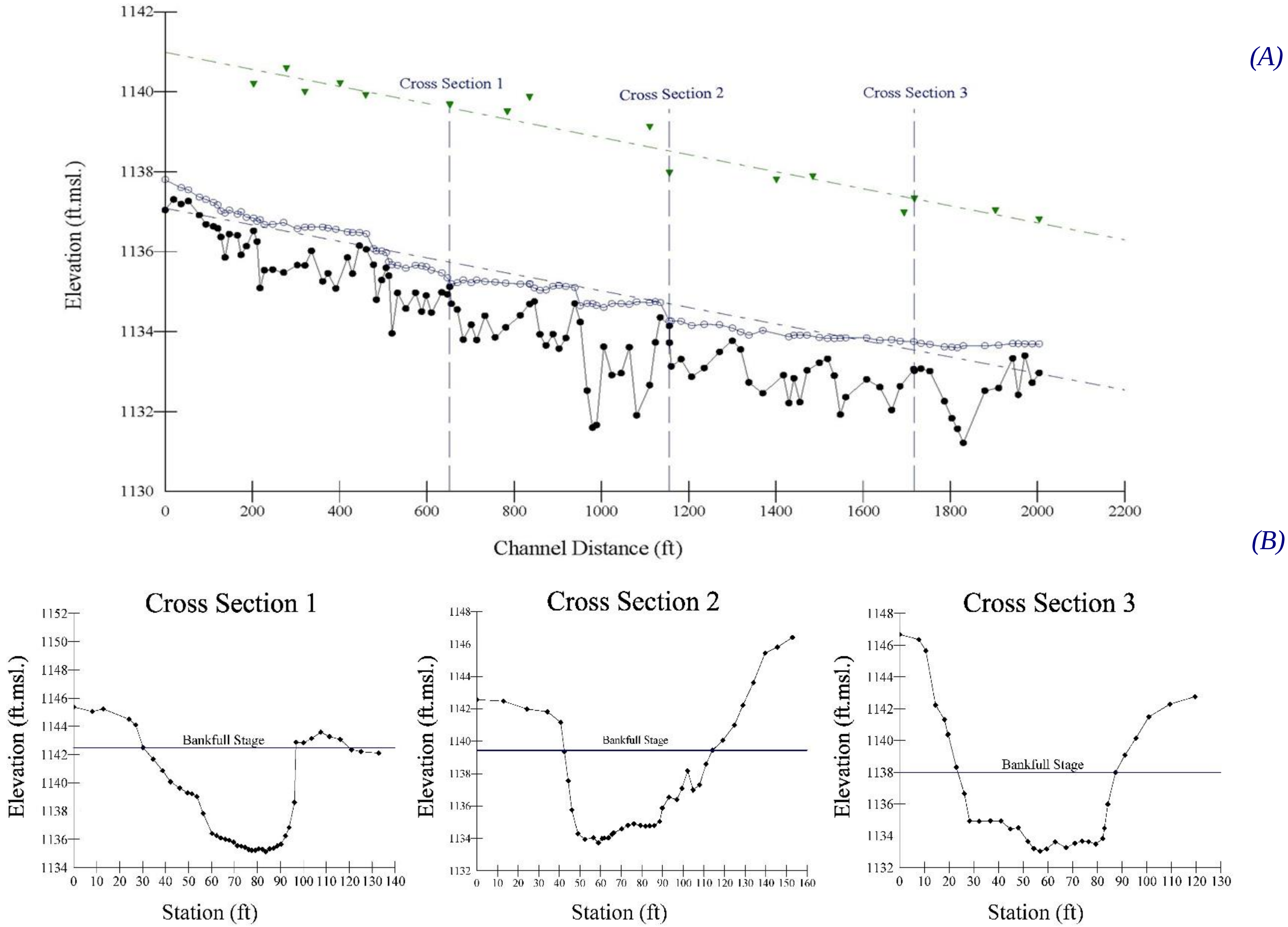

Figure A.30 Longitudinal profile (A), and riffle cross-sections (B), in study reach of Waterman Creek near McCormack Prairie.

Station 06605750
Willow Creek near Cornell, IA

View looking downstream from the bridge at the reach of Willow Creek near Cornell, IA

The continuous crest-stage gaging station is located directly below a highway bridge on the downstream side. The bridge was constructed as a pair of box culverts with little deposition observed on either side. The bridge likely affects bankfull discharge at the gaging station. A large scour pool was observed directly downstream of the bridge. The surveyed reach began approximately 1000 ft downstream of the bridge to avoid any effect on the bankfull stage.

The reach ran along an open vegetated meadow downstream of the crest-stage gaging station. The land surrounding this reach is dominated by agriculture, and tile drainage systems likely influence discharges. The channel was wide, deep, and moderately sinuous with a mild slope. Irregular riffle-pool sequences dominated this channel below the gaging station with numerous compound pools. Due to significant bank erosion, the bankfull channel was poorly defined throughout the reach. The primary bankfull indicators at the site included prominent breaks in bank slope and a change in the size distribution of deposited material. The banks were well vegetated with grasses and forbs with some woody vegetation. There was abundant soughing of bank material throughout the reach, creating in-channel grassy terraces and cut banks up to 15 ft. The floodplain could not be accessed on either side of the channel at bankfull flows throughout most of the reach. The bed was sand-dominated with gravel along the riffle sections. Some concrete debris was observed in isolated portions of the reach. Numerous gravel and cobble deposits were observed above the bankfull stage, indicating a significant flood event influenced this reach in the recent past. The wide channel with soughing bank material and steep banks would indicate this reach is degrading and widening.

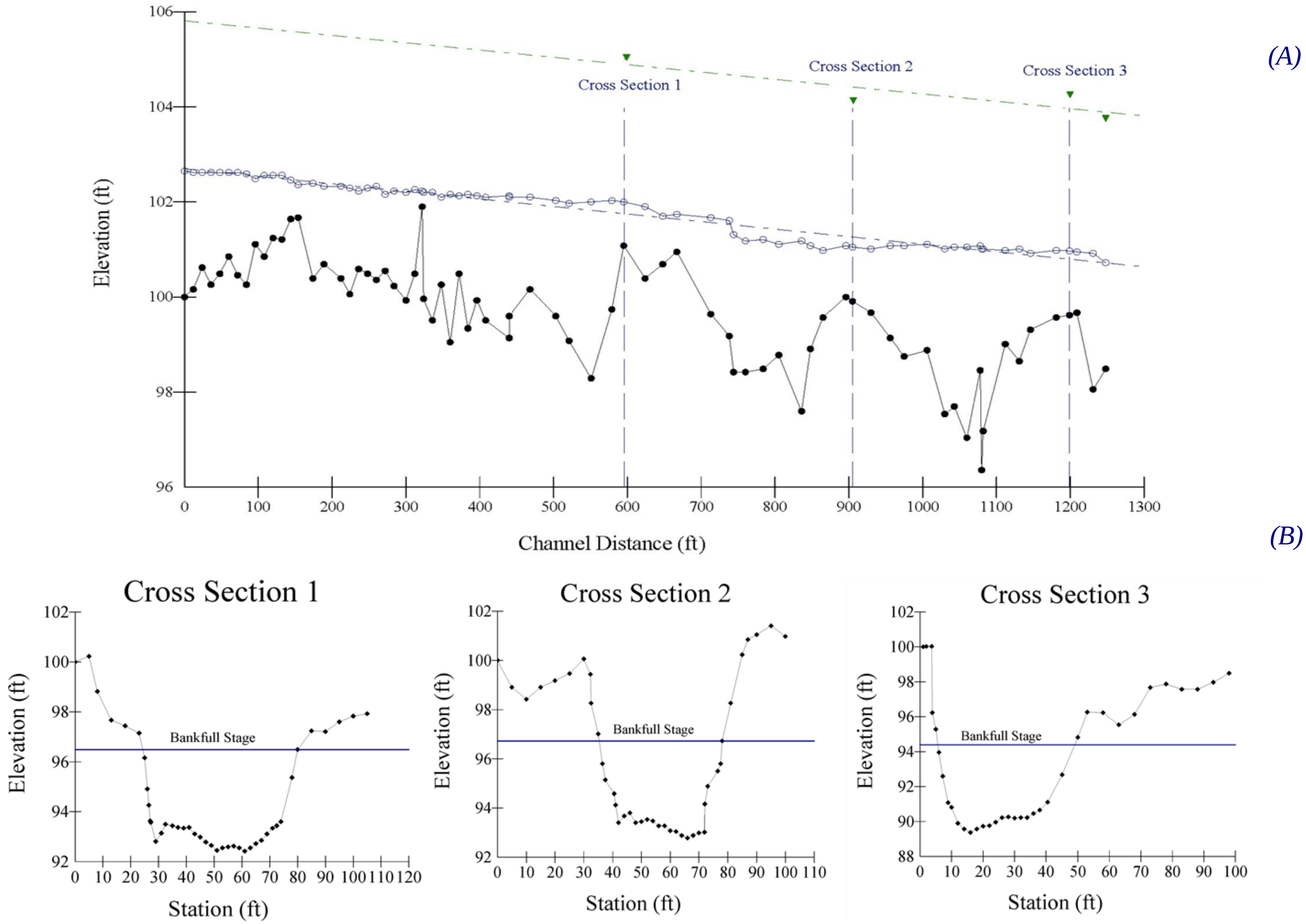

Figure A.31 Longitudinal profile (A), and riffle cross-sections (B), in study reach of Willow Creek near Cornell, IA.

Worrell Creek
Worrell Creek at Gateway Park

View looking upstream at the reach of Worrell Creek at Gateway Park

This reach is located approximately 500 ft southeast of Gateway Park in Ames. The reach is within a mixed hardwood woodland surrounded by agriculture, urban development, and public open space.

The reach ran along a densely vegetated riparian woodland corridor between Gateway Park and urban development. The area surrounding this reach is dominated by agriculture (upstream) and urban development, which likely affected discharge; however, no inlets were observed. The channel was wide, had low sinuosity with irregular meanders, and had a mild slope. Sand bedforms dominated the channel with small scour pools around large woody vegetation and few riffle-run sequences. The bankfull channel was moderately defined throughout the reach. The primary bankfull indicators at the site included flat depositional features on a horizontal plane, breaks in bank slope, and changes in vegetation. The banks were densely vegetated and lined with grasses, forbs, and perineal woody vegetation. Cut banks up to 15 ft were observed in the lower sections of the reach, where overhanging roots and sloughing of large woody vegetation were common. The stream could not access its floodplain throughout most of the reach. The bed was sand-dominated with some gravel at riffle sections. Glacial lag was common in the upper section of the reach with boulders up to 2 ft. Glacial till was exposed on the channel bottom where large scour pools existed. Large woody debris and log jams were common throughout the reach. In some places, bank material, including large woody vegetation, created terraces along the channel. Moderate channel widths, large bank heights, exposed glacial till, glacial lag, mature riparian vegetation, and sand bedforms indicate that this channel is widening and degrading.

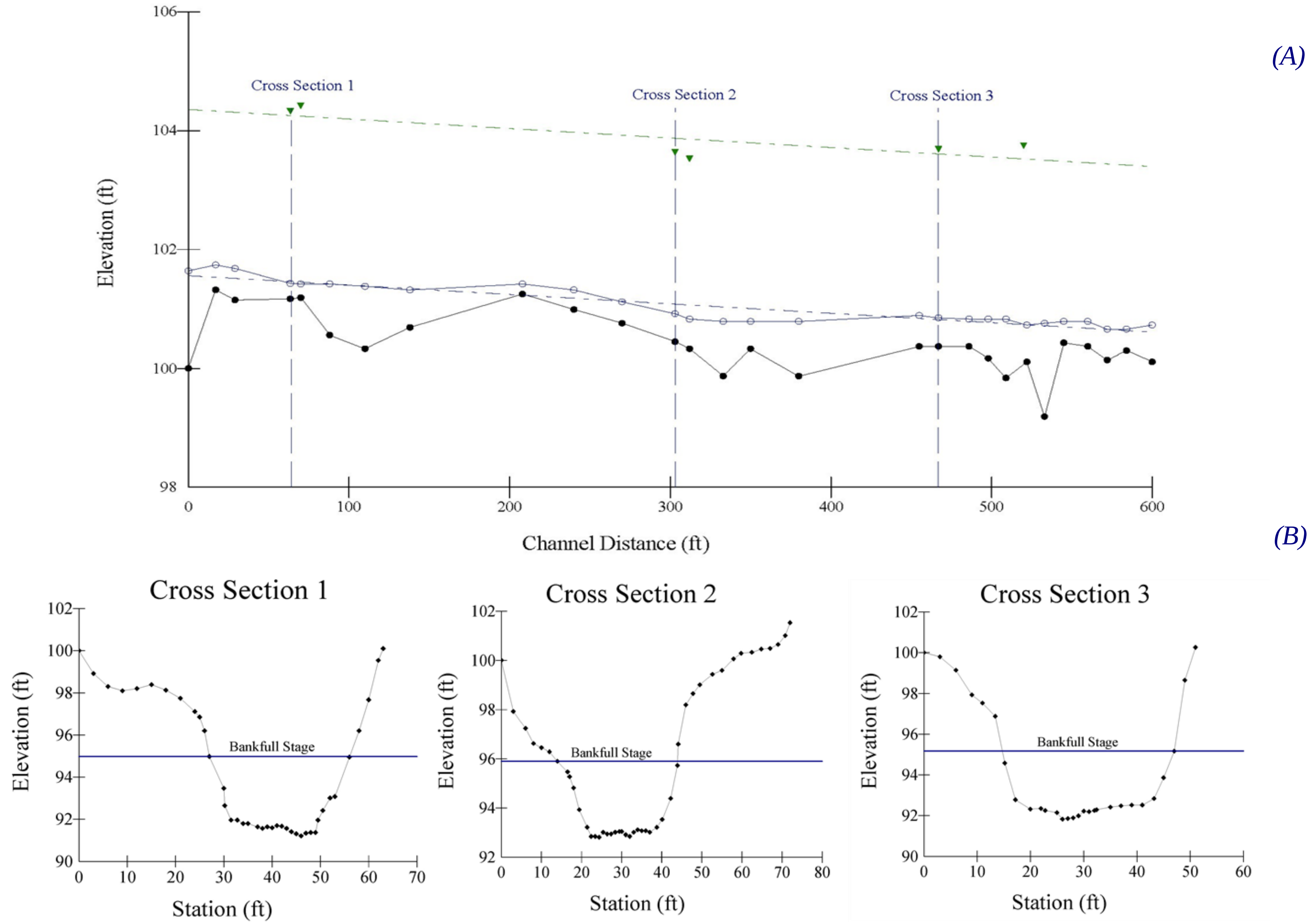

Figure A.32 Longitudinal profile (A), and riffle cross-sections (B), in study reach of Worrell Creek at Gateway Park