ASSESSING MORPHOLOGICAL ADJUSTMENTS OF STREAM CHANNELS IN THE PIEDMONT REGION OF GEORGIA, USA

by

Jeffrey William Riley

(Under the direction of Todd C. Rasmussen)

Abstract

As part of a U.S. Geological Survey (USGS) study investigating the effects of altered flow on ecosystems in the Upper Flint River Basin information was needed regarding the stability of stream channels. This was to determine if ongoing channel adjustments could be of sufficient magnitude to mask the effects of hydrologic alteration and simultaneously use channel stability as a proxy for the persistence of in-stream habitat conditions. A combination of data analysis from USGS stream gage stations supported by field studies were used to evaluate channel adjustments. Results indicate that channels have been dynamic over the course of record. Some locations exhibited distinct trends of degradation while others appeared dynamically stable. It appears that local scale disturbances are more likely responsible, due to the discontinuous nature of channel adjustments, than watershed scale land cover changes.

Index words: Stream alteration, fluvial geomorphology, hydrology, land use, channel change, hierarchical linear models, Flint River, Piedmont, Georgia

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by

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Dedication

I dedicate this thesis in memory of my grandmother, Glendon K. Riley. Her coming of age shortly after the great depression necessitated a lifestyle of hard work and conservation. While I was growing up she instilled the same values in me. I will always be grateful for the memories and having inherited such a lasting gift.

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Table of Contents

Page

Acknowledgments v

List of Figures viii

List of Tables xvi

Chapter

1 Introduction 1

1.1 Problem Statement 1

1.2 Background 3

1.3 Research Objectives 5

1.4 Organization 6

2 Literature Review 7

2.1 Channel Adjustments 7

2.2 Land Use Effects on Channel Morphology 9

2.3 Use of Stream Gage Data to Evaluate Channel Adjustments 12

2.4 Channel Evolution Models 14

3 Study Area 19

3.1 Description 19

3.2 Geologic and Climatic Setting 20

3.3 History 21

3.4 Contemporary Issues 27

4 Methods 34
4.1 Stream Gage Analysis 34
4.2 Urban Gradient Analysis 37
4.3 Field-Based Assessments 39
5 Results 44
5.1 UFRB Gage Analysis 44
5.2 Urban Gradient Analysis 46
5.3 Channel Evolution Assessments 49
6 Discussion 126
6.1 Urban Gradient Analysis 126
6.2 Channel Adjustments in the Flint River and Tributaries 127
6.3 Hypothetical Scenarios for Multiple Disturbances 130
7 Conclusions 134
8 References 136
Appendix
A Draft Manuscript - Evaluating Channel Adjustments Using Stream Gage Data: A Hierarchical Modeling Approach 147
B Data Entry Form - Channel-Stability Ranking Scheme 174

List of Figures

2.1 Six stages of channel evolution as proposed by Simon (1989). 17

2.2 Example of the different forms of disturbance and response. The duration of the disturbance is indicated by the solid bar along the x-axis; the beginning and end of the disturbance is illustrated by the dotted vertical bars (adapted from Lake, 2000). 18

3.1 Location of Upper Flint River Basin within the ACF basin 28

3.2 Counties within the Upper Flint River Basin 29

3.3 Acres of improved land in the Upper Flint River Basin 30

3.4 Total acres in farms in the Upper Flint River Basin 31

3.5 Population of the Upper Flint River Basin (1830-2005) 32

3.6 Location of USGS stream gages in Upper Flint River Basin 33

4.1 Locations where RGAs were performed. 40

4.2 Locations of stream gages used in urban gradient analysis. 41

5.1 Analysis of raw stage data at constant discharge conditions for Flint River near Lovejoy, GA (USGS Station 02344350) 55

5.2 Specific stage analysis for Flint River near Lovejoy, GA (USGS station 02344350) 56

5.3 Residual analysis of inverse stage-discharge relation for Flint River near Lovejoy, GA (USGS station 02344350) 57

5.4 Analysis of raw stage data at constant discharge conditions for Line Creek near Senoia, GA (USGS station 02344700) 58

5.5 Specific stage analysis for Line Creek near Senoia, GA (USGS station 02344700) 59

5.6 Residual analysis of inverse stage-discharge relation for Line Creek near Senoia, GA (USGS station 02344700) 60

5.7 Analysis of raw stage data at constant discharge conditions for Flint River near Griffin, GA (USGS station 02344500) 61
5.8 Specific stage analysis for Flint River near Griffin, GA (USGS station 02344500) 62
5.9 Residual analysis of inverse stage-discharge relation for Flint River near Griffin, GA (USGS station 02344500) 63
5.10 Analysis of raw stage data at constant discharge conditions for Flint River near Carsonville, GA (USGS station 02347500) 64
5.11 Specific stage analysis for Flint River near Carsonville, GA (USGS station 02347500) 65
5.12 Residual analysis of inverse stage-discharge relation for Flint River near Carsonville, GA (USGS station 02347500) 66
5.13 Spatial distribution of streamgages and the associated response inferred from residual analysis 67
5.14 Geomorphic analysis of stream gage data for Suwanee Creek at Suwanee, GA (Station number: 02334885) (A) stage and discharge; (B) stage residual time series; (C) width and discharge 68
5.15 Geomorphic analysis of stream gage data for Little River near Eatonton (Station number: 0220900): (A) stage and discharge; (B) Time series of stage residuals; (C) width and discharge 69
5.16 Geomorphic analysis of stream gage data for Peachtree Creek at Atlanta, GA (Station number: 02336300): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge 70
5.17 Geomorphic analysis of stream gage data for Line Creek near Senoia, GA (Station number: 02344700): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge 71

5.18 Geomorphic analysis of stream gage data for Sope Creek (Station number: 02335870): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge 72

5.19 Geomorphic analysis of stream gage data for Flint River near Lovejoy, GA (Station number: 02344350): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge 73

5.20 Geomorphic analysis of stream gage data for Middle Oconee River near Arcade, GA (Station number: 02217475): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge 74

5.21 Geomorphic analysis of stream gage data for Kettle Creek near Washington, GA (Station number: 02193340): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge 75

5.22 Geomorphic analysis of stream gage data for Alcovy River above Covington, GA (Station number: 02208450): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge 76

5.23 Geomorphic analysis of stream gage data for Chattahoochee River near Fairburn, GA (Station number: 02337170): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge 77

5.24 Geomorphic analysis of stream gage data for Oconee River at Milledgeville, GA (Station number: 02223000): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge 78

5.25 Geomorphic analysis of stream gage data for Ockmulgee River at Macon, GA (Station number: 02213000): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge 79

5.26 Geomorphic analysis of stream gage data for Sweetwater Creek near Austell, GA (Station number: 02337000): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge 80

5.27 Geomorphic analysis of stream gage data for Falling Creek near Juliette, GA (Station number: 02212600): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge 81

5.28 Geomorphic analysis of stream gage data for New River at GA 100, near Cornith, GA (Station number: 02338660): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge 82

5.29 Geomorphic analysis of stream gage data for Oconee River near Penfield, GA (Station number: 02218300): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge 83

5.30 Geomorphic analysis of stream gage data for Etowah River at Canton, GA (Station number: 02392000): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge 84

5.31 Geomorphic analysis of stream gage data for South River at Klondike Road, near Lithonia, GA (Station number: 02204070): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge 85

5.32 Geomorphic analysis of stream gage data for Snake Creek near Whitesburg, GA (Station number: 02337500): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge 86

5.33 Geomorphic analysis of stream gage data for Flint River near Thomaston, GA (Station number: 02346180): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge 87

5.34 Geomorphic analysis of stream gage data for Apalachee River near Bostwick, GA (Station number: 02219000): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge 88

5.35 Geomorphic analysis of stream gage data for Etowah River at Allatoona Dam, above Cartersville, GA (Station number: 02394000): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge 89

5.36 Geomorphic analysis of stream gage data for Chattahoochee River near Norcross, GA (Station number: 02335000): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge 90

5.37 Geomorphic analysis of stream gage data for Chattahoochee River near Whitesburg, GA (Station number: 02338000): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge 91

5.38 Geomorphic analysis of stream gage data for Chattahoochee River at GA 280, near Atlanta, GA (Station number: 02336490): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge 92

5.39 Geomorphic analysis of stream gage data for Murder Creek below Eatonton, GA (Station number: 02221525): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge 93

5.40 Geomorphic analysis of stream gage data for Chattahoochee River near Cornellia, GA (Station number: 02331600): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge 94

5.41 Geomorphic analysis of stream gage data for Chattahoochee River above Roswell, GA (Station number: 02335450): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge 95

5.42 Geomorphic analysis of stream gage data for Ocmulgee River near Jackson, GA (Station number: 02210500): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge 96

5.43 Geomorphic analysis of stream gage data for Ocmulgee River near Warner Robins, GA (Station number: 02213700): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge 97

5.44 Geomorphic analysis of stream gage data for Flint River at US 19, near Carsonville, GA (Station number: 02347500): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge 98

5.45 Geomorphic analysis of stream gage data for Big Creek near Alpharetta, GA (Station number: 02335700): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge 99

5.46 Geomorphic analysis of stream gage data for Flint River near Griffin, GA (Station number: 02344500): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge 100

5.47 Geomorphic analysis of stream gage data for Middle Oconee River near Athens, GA (Station number: 02217500): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge 101

5.48 Geomorphic analysis of stream gage data for Chestatee River near Dahlonega, GA (Station number: 02333500): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge 102

5.49 Geomorphic analysis of stream gage data for Chattahoochee River at Atlanta, GA (Station number: 02336000): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge 103

5.50 Geomorphic analysis of stream gage data for Tobesofkee Creek near Macon, GA (Station number: 02213500): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge 104

5.51 Relationship between width : depth ratio and impervious surface cover . . . 105

5.52 Relation between width : depth ratio and drainage area 106

5.53 Uppermost RGA location on the Flint River just above Flt0 both locations had the same response only Flt0 was more deeply incised 107

5.54 Lowermost site in the basin above Pine Mountain Ridge. This site had low well vegetated banks and appeared undisturbed 108

5.55 Representative reach for FLT1, illustration alternating bars and incipient meander. 109

5.56 Example of fluvial erosion that was present through most of the reach at Flt3. 110

5.57 Example mass wasting (right bank) and vegetation covered failed blocks that are now protecting bank toe. 111
5.58 Evidence of both mass wasting and fluvial erosion (left bank) approximately 1/4-mile upstream of gage. 112
5.59 Example of bedrock control on bed level adjustment. 113
5.60 Example of mass wasting and fluvial erosion along a very slight outward bend of the Flint River below Pine Mountain Ridge. 114
5.61 Channel downstream of pool exhibits minor fluvial erosion with low stable banks. 115
5.62 Representative reach at LINE2. Trees in stream are from mass wasting events. 116
5.63 Evidence of coarse bed downstream of small dam at LINE3 and apparent lateral stability of the reach. 117
5.64 Reach at LINE4 located upstream of the stream gage, experienced large amount of mass wasting. In the center of the photo is a vegetated bar apparently the result of a large amount of failed bank material. 118
5.65 Representative reach of PT1. 119
5.66 Representative reach of PT2. Only about 1/4-mile downstream from PT1 exhibits a more wetland character and appears undisturbed. 120
5.67 Location visited to perform RGA on Potato Creek where multiple channels were encountered. Vegetated area to the right had two smaller channels flowing through it. 121
5.68 Directly upstream of dam on Potato Creek, above location for RGA PT4. . . 122
5.69 Representative reach for RGA PT4 about 1/4-mile downstream of dam. Bar in the middle of the photo is dominated by cobbles and gravel. 123
5.70 Partially breach mill dam on Potato Creek approximately 1/4-mile above reach for RGA PT5. 124

5.71 Furthest downstream site on Potato Creek, stream is deeply entrenched. For reference, man in the stream is about six-feet tall. 125

6.1 Location and observed response at RGA locations, green flags represent areas that are wetland like and/or have multiple channels, grey circles (BR) represents sites with substantial bedrock that may inhibit adjustments 132

6.2 State of Georgia land cover classification as of 2001 133

List of Tables

4.1 Active U.S. Geological Survey stream gaging stations in the Upper Flint River Basin. 42

4.2 Urban gradient stream gage station information 43

Chapter 1

Introduction

1.1 Problem Statement

Channel stability is an important variable to consider when evaluating in-stream flow criteria needed to support functional aquatic ecosystems. This is because changing channel dimensions could alter the distribution of water and in turn habitat. This is important in regards to the temporal frame of reference. The distribution of habitat (e.g. water depth) may no longer be suitable if a minimum flow standard is set and channels are adjusting. The question that is often asked in these situations is whether this stream system in a phase of adjustment or in equilibrium? However there must first be an understanding of equilibrium before this condition can be determined.

One of the early concepts of equilibrium applied to geomorphology was pioneered by Davis (1902), where he defined a graded stream as a mature river that has attained a balance between erosion and deposition. Many researchers have followed up on the original concept to include expanded ideas of the graded stream concept (Mackin, 1948), regime channels (Blench, 1969), dynamic (Hack, 1960) and quasi-equilibrium (Leopold and Langbien, 1962; Langbien and Leopold, 1964) conditions. Although subtle differences in interpretation exist among the above terms (see, Thorne and Weldford, 1994); in much of the literature they all generally refer to a stream that assumes the most probable form (Leopold, 1994) given the current climatic/hydrologic regime. Generally stated, it is the condition that exists when a given stream is able to transport the sediment load delivered from the watershed while maintaining a stable slope and morphological form.

Natural systems remain within a range of variability, or equilibrium, without extreme events or local scale disturbances. However when land-cover changes occur over the watershed the balance of water and sediment supply may be disrupted. This usually results in either greater sediment supply than the stream can transport or excessive energy where bed and bank material may become the new source of sediment. These conditions are often referred to as a transport and supply limited system, respectively. The two possible scenarios are not mutually exclusive and in some cases operate in a sequence. As vegetation is removed from the watershed bare soil is exposed, rain drops will detach soil particles and overland flow will dominate which will often lead to sheet, rill, and gully erosion. This often causes excessive sedimentation. After land surfaces are stabilized sediment may begin to evacuate. The stream will once again adjust to regain the most efficient form for transporting the water and sediment delivered from the watershed. However this process could take years to millennia; and depending on the magnitude and duration of the disturbance, conditions prior to disturbance may never be attained. This is especially true in heavily urbanized areas where there is often a permanent change in rainfall runoff relations that leads to increased peak flows that may induce channel enlargement.

Channels may be stable, or frequently adjust, depending on many natural and anthropogenic factors. Examples of natural factors could be climatic fluctuations, soil types, or geology (Daniel and Knox, 2005; Simon and Renaldi 2006; Beechie, et al. 2008). For example, streams in the arid southwestern U.S. may adjust greatly over a single event. This is due to the boundary conditions, primarily sand lacking woody vegetation, and often large infrequent precipitation events. Hence their adjustments occur more readily over a single event than their humid alluvial counterparts. Anthropogenic factors leading to channel adjustments could be land clearing for agriculture or timber harvesting, channelization, urbanization (Knox, 2001; Simon, 1989; Wolman, 1967), as well as others. In the case of urban land cover there is usually an increase in sediment supply during the build phase. After construction is complete and the land is re-stabilized and the opposite imbalance occurs. With greater amounts of impervious surfaces, precipitation is rapidly sent to stream channels. Increases in impervious surfaces may lead to a sustained imbalance. These factors need to be identified so that past changes can be explained, and future changes can be predicted.

Changes in land-cover/land-use are a common cause of channel degradation and can have pronounced effects on the movement of water and sediments throughout a watershed (Wolman, 1967; James, 1991; Poff et al., 2006; Colosimo and Wilcock, 2007). The consequences of this alteration can be substantial. The combination of flow and sediment changes can alter the balance between sediment supply and transport capacity (Wolman, 1967), thus inducing adjustments of channel form (Simon and Rinaldi, 2006). When channel adjustments occur, in-stream habitat is frequently altered or disturbed (Shields et al., 1993; Newson and Newson 2000; Sullivan et al., 2006), thus adversely affecting aquatic species; some of which may be threatened or endangered. Due to this recognition; greater focus has been placed on stream geomorphic conditions and channel stability in ecological investigations.

1.2 Background

This study is part of the larger U.S. Geological Survey (USGS) Science Thrust Project; which is designed to assess the linkages between watershed changes and aquatic health. Specific changes in watershed features (e.g., land use-land cover, geology, geomorphology, and hydrology) are evaluated with respect to the biotic responses that these changes could induce (Hughes et al., 2007). The project, entitled “Water Availability for Ecological Needs”, uses a variety of tools to perform this assessment, including remotely sensed data as well as hydrologic and ecologic models. The end product will be a predictive model that can be used by regulators and policy makers to evaluate biological response to different water development scenarios.

The USGS Science Thrust Project focuses on the Upper Flint River Basin (HUC 03130005), Georgia, which begins in south-metropolitan Atlanta and ends just below the Fall Line in the Coastal Plain physiographic province. It flows unimpeded through over 195 miles of primarily forested landscape before it reaches Lake Blackshear (Stanley Consultants, 1973). These relatively pristine flows sustain habitats and biological diversity that have been lost from many other Eastern rivers due to impoundments and landscape alteration (Hughes et al., 2007). Yet, the Flint River, like many other urbanizing watersheds, faces increased threats due to water extraction, waste assimilation, and urban runoff.

The primary goal of the overall project is to develop models that address flow scenarios needed for ecological conditions to persist and to help guide management decisions on flow abstractions and other human interests. Included in this is how land cover and land use affects patterns of water storage and distribution, and separately addresses issues of appropriate scale when assessing the different components over a large region.

Because a large portion of the overall study is dealing with in-stream flow and ecological linkages, the long-term behavior of stream channels need to be evaluated to determine if ongoing adjustments could alter the distribution of water within the channel. If adjustments are of sufficient magnitude they could have direct implications when prescribing in-stream flows. In-stream flow recommendations often contain a minimum flow component, if channels are enlarging what was once acceptable as the minimum may no longer provide enough habitat. Channel stability can also be used to grossly approximate deteriorating or changing habitat conditions. These assumptions are based on accumulation of sediment when beds are aggrading, bank failures are occurring, or where beds degrade benthic habitat could be scoured and downstream pools filled. Because the stability of stream channels affects in-stream habitats, it is an important and perhaps essential component when investigating biotic response to changes in hydrology and land cover.

Most studies examining the geomorphological - habitat linkage have been based on empirical data (Newson and Newson, 2000). These studies are often concentrated on reach-scale habitat assessments (Newson and Newson, 2000). Generalizations about reach-scale channel form or dominant channel processes are correlated with reach scale-channel stability and habitat persistence or disturbance (Sullivan et. al, 2006, Sutherland et. al, 2002). Currently, there is no single approach for using general geomorphic (watershed-scale) indicators to predict habitat. In basins where multiple stream gages are located inferences can be made regarding the stability of habit conditions in the various locations. U.S Geological Survey (USGS) stream gage data can be used to explore bed-level fluctuations and, in some cases, width and velocity adjustments (Jacobson, 1995; Pinter and Heine, 2005; Juracek and Fitzpatrick, 2009) so that if channel adjustments are detected at these locations then other assessment methods may be used to further characterize disturbances.

1.3 Research Objectives

I enter this research with two primary questions: 1) Are stream channels in the UFBR in equilibrium or a phase of adjustment (dis-equilibrium)? 2) If adjustments are occurring are they following a systematic pattern? For example, will stream channel adjustments follow a longitudinal sequence upstream, such as in the case of headward knickpoint migration? Or may I observe a downstream progression of adjustments, in response to migrating bed forms? Or thirdly will adjustments be isolated and/or discontinuous? Initial hypotheses are that stream channels will be adjusting, at least in the extreme upper portion of the basin where it is heavily urbanized. It is also believed that stream channels will follow a longitudinal form of adjustment; however either direction is possible.

If channels are found to be in a phase of adjustment weight of evidence will be used to correlate channel adjustments to land use conditions or other possible disturbances. Land conversions; which initially was forest clearing for agriculture and more recently urbanization, are hypothesized to be underlying causes of channel instability.

This study uses a combination of data analysis, from USGS stream gaging data supplemented by additional field-based assessments. The historical stream gage data will produce information about past and present adjustments. Field assessments will support gage data analysis and explore morphological distinctions and similarities throughout the Flint River mainstem and two large tributaries of the Upper Flint basin in locations where gage data are not available.

A secondary goal of this project is to use multiple methods for analyzing stream gage date and evaluate which approach delivers the greatest amount of information. The benefits and drawbacks of each method are presented and discussed. The field-based method, similar to that of Simon (1989) is used to support the results of gage data analysis and to determine dominant processes and stage of channel evolution. This is then used to infer future channel adjustments. A third goal of this study is to explore the use of hierarchical linear models. This is a statistical technique that is rarely used in the physical sciences but well entrenched in the social sciences. It overcomes many of the assumptions that constrain classical linear regression and analysis of variance (ANOVA). A draft manuscript describing methods and results of this technique is presented in Appendix A.

1.4 Organization

Chapter 1 introduces the problem being investigated and goals of the study. Chapter 2 provides background information relating to channel adjustments and land use effects on channel adjustments. Chapter 3 provides a qualitative overview of the study area as well as a brief discussion of land use history in the basin. Chapter 4 presents the methods that are used to analyze gage data and perform rapid geomorphic assessments. Chapters 5 and 6 contain results and discussion, respectively. Appendix A contains a manuscript that presents an example of how HLMs could be used to model channel adjustments. Selected data from Flint River gaging stations as well as landcover data are used in this analysis.

Chapter 2

Literature Review

2.1 Channel Adjustments

Blench (1966) describes any channel that is either natural or manmade and has a bed that moves above some stage of flow with non restrictive sides (banks) as a “regime channel”. He proposes that a channels regime is similar to climate. So in accordance with the definition of climate, regime is defined as the behavior of a channel, over a period of time, based on conditions of water and sediment discharge, width, depth, slope and other morphological factors. A stream that is in regime is within the average conditions of the aforementioned parameters.

However there must be a sufficient amount of time to permit proper assessment of such average conditions. Knighton (1998) discusses timescales and their relevance to channel form. A short time scale (decade to century) is the most significant in terms of observational conditions; and fair relationships can be expected between the independent variable and certain elements of channel form over such a period. Thus a regime channel is one that is in dynamic equilibrium. Knox’s definition of equilibrium states: a stream is in equilibrium when it is neither aggrading nor degrading its bed. This is similar to Makin’s (1948) idea of a graded stream, “A stream delicately adjusts its slope to provide just enough velocity to transport the sediment delivered from the watershed”. This concept can be viewed using the expression of stream power proportionality (Lane, 1955):

$$Q_b \, d_{50} \propto Q \, S \tag{2.1}$$

where Q_b is bedload discharge, d_{50} is the median grain diameter, Q is water discharge, and S is the energy slope.

If any one of these parameters adjust significantly without an equal and opposite adjustment on the other side, the balance between sediment supply and transport capacity will be disrupted can result in morphological changes.

Disturbances to the relationship may be induced by natural or anthropogenic factors. Climate fluctuations over the last three centuries have not had a great effect on fluvial systems (Knighton, 1998). Climatic and catastrophic events can have a pronounced effect on channel adjustments but they are not as constant, nor persistent as those induced by man. On a short time scale (tens to hundreds of years), anthropogenic influences may have the greatest effect on stream channel adjustments (Knighton, 1998). Mankind has a long history of trying to modify and control the natural environment. Anthropogenic influences on channel adjustments can be grouped into to two categories, direct and indirect disturbances (Park, 1977).

Direct disturbances are those that are induced for some purpose, such as channelization for navigation or dams for water supply and flood and sediment control. The effects of direct disturbances on channel morphology have long been recognized (Williams and Wolman, 1984; Gregory, 2006). Indirect disturbances are those that are not intentional and most often have detrimental effects. This type of disturbance has only gained attention in the last sixty years, with the influential book, "Man's role in changing the face of the earth" (Gregory, 2006). Some of the common indirect causes of the last century are; forest clearing for agriculture, mining, and urbanization. Indirect disturbances appear to be the most influential in the UFRB. This is because the Flint River is one of the few rivers in the United States that flows for over 195 mi unimpeded (Stanley Consultants, 1973) and has escaped anthropogenic channel alteration, or documentation of such events.

Indirect disturbances can be further classified as pulse, press, or ramp depending on their temporal persistence (following terminology of Lake, 2000) (Figure 2.2). Pulses changes are characterized by a short time scale relative to the one that is being considered. A system returns to near initial state after the disturbance. This type of disturbance is usually the result of an extreme episodic event (Brunsden and Thornes, 1979). Press type disturbances occur suddenly and the conditions are sustained over a long period of time due to new controlling variables or boundary conditions. An example could be that of a dam, that will suddenly, and persistently, change previous conditions. Disturbances that are characterized by gradual increases over time are referred to as ramp disturbances. This type may reach an asymptote over time or recovery of the system may follow a similar ramp down form. Large scale forest conversion to agriculture may be such an example. In this example, the spatial extent of disturbance may also follow a similar ramp form.

2.2 Land Use Effects on Channel Morphology

Many studies have addressed channel change in response to extrinsic variables such as, climate, agriculture, and urbanization (Knox, 1983; Knox, 2001; Chin, 2006, Colisimo and Wilcock, 2008). This study will focus on historical agriculture and urbanization as the stressors affecting channel morphology. Because natural processes overlap with anthropogenic disturbances, it is hard to isolate the exact cause of channel adjustments (Knox, 2001). However, where available, weight of evidence will be used from land use data to support claims and make associations.

Channel morphology is generally assumed stable in undisturbed watersheds. However, natural adjustments may occur due to large infrequent flow events (Sloan et al., 2001), hillslope failure (Johnson et al., 2008) or large woody debris accumulation (LWD, Smith et al., 1993). Without natural or anthropogenic watershed alterations, fluvial systems provide just enough energy to transport the sediment supplied from the watershed. This results in a stable slope and cross sectional morphology that may adjust over longer time periods depending on boundary material and valley/geologic controls. In the Piedmont region of Georgia, there are not many streams remaining unaffected by historical or contemporary land use. Regional scale forest conversion to agriculture occurred with the arrival of European settlers, which generally leads to increased sheet flow and hillslope erosion. The primary control on hydrology and sediment supply is vegetation, which is also the most likely disturbed by humans (Knighton, 1998). Many geomorphological studies undertaken with regards to agriculture are in response to historical agriculture (e.g. Trimble, 1974; Knox, 1977).

In Europe, it is difficult to differentiate between the effects of land cover and climate changes on channel adjustments because land clearing began thousands of years ago. In the United States, large scale land clearing for agriculture started around 1700. Thus it is easier to relate channel change to historical land cover/land use (e.g. Ambers, et al., 2006; Magilligan and Stamp, 1997). In many locations that were subject to regional scale deforestation, excess sediment is stored in channels and floodplains, which can alter the magnitude of flooding from flows of similar recurrence interval (Knox, 1977). Often increased sediment results in aggradation of the stream channel and increases the frequency of over bank flows and subsequent floodplain aggradation. When sediment supply returns to predisturbance levels channels will often become entrenched. This is due to degradation of the bed as the stream cuts through the deposited alluvium (Trimble, 1974).

Agricultural practices have changed a great deal since arrival of the early European settlers. Presently, conservation measures are used to help prevent soil erosion and exhaustion (Strohbehn, 1986). Current regulations (e.g. TMDLs) help to prevent diffuse, although identifiable, sources of sediment from agricultural land. However other problems relating to land use remain.

Many studies have addressed the impacts of urbanization on all facets of aquatic systems. For example, Alberti et. al. (2007) used aquatic macroinvertebrates to illustrate reduced biotic integrity due to urbanization. A study conducted on tributaries to the Middle Chattahoochee River, found watersheds with the greatest impervious surface cover had fish assemblages dominated by generalist species (Helms et. al., 2008). Booth and Jackson (1997) showed altered hydrologic and geomorphic conditions in an urban setting even when stormwater control measures were present. Paul and Myer (2001), in a paper titled "Streams in the Urban Landscape" present an exhaustive account on most all aspects of degradation to aquatic systems from urbanization. All of the aforementioned studies illustrate the detrimental effects that often result from urbanization and its associated disturbances.

In terms of channel morphology, one of the first studies to address the effects of urbanization was published by Wolman (1967), who determined that sediment yields were greatest during the construction phase of urbanization, followed by early (historical) agriculture and reduced to below undisturbed forest, with the onset of mature urban cover. The disturbed soils are compacted or simply paved over after the construction phase is complete. There are less "natural" or permeable surfaces for the precipitation to infiltrate as impervious cover increases, so most precipitation is rapidly sent to stream channels. This leads to increased channel erosion, which results from an imbalance of stream power to available material to transport. Material composition will dictate whether it is the channel bed or banks that erode (Simon and Renaldi, 2006).

For example, bed degradation will be favored due to the lower critical shear stress of the sand, if the channel bed is sand and the banks are cohesive. Bank erosion will be dominant once the sand is evacuated and the bed is armored. The most prevalent effect of impervious surfaces, though, is on magnitude and frequency of peak flows, which have been shown to give way to channel enlargement, so it can convey the new "norm" in discharge (Niezgoda and Johnson, 2005). It was noted that when the construction derived sediment is transported, generally during a few large events, the streams often will become net erosional and will scour bed and banks often resulting in lateral increases (Wolman, 1967). Many studies since Wolman's (1967) have examined the effects of urbanization on stream channels with similar results (ex. Chin, 2006; Colisimo and Wilcock, 2008).

Both types of land conversions can have detrimental effects on channel processes and ecological function. Initially, they produce similar effects, with vegetation removed overland flow and entrained sediment increase, often leading to aggradation in valleys and channels.

When the land is stabilized (or covered in impervious for urban areas) sediment supply is decreased and sediment in storage will begin to evacuate. For the urbanized areas, most often peak flows increase and the flows will have disproportionate energy to the amount material available to transport (Lane, 1955). This leads to the channel bed and banks becoming the new sediment source. Often streams in urban areas are much larger than their rural counterparts with similar attributes (e.g. drainage area, slope, stream order, etc.) (Wolman, 1967).

2.3 Use of Stream Gage Data to Evaluate Channel Adjustments

Channel adjustments can be evaluated using stream gage data in basins where gages are present and have a long enough record. Empirical models can be constructed that relate discharge to other morphological parameters (Blench, 1966; Pinter and Heine, 2005). Advantages of using stream gage data is that it offers temporal continuity and measurements that cover a range of discharge conditions. Another asset of gage data is that both bed adjustments and width adjustments can be determined if the same cross section is measured each time (Jacobson, 1995). Often stream gaging measurements provide the only source of consistent stream cross sectional data (Juracek and Fitzpatrick, 2009). Depending on the length of record, historical conditions can also be assessed to determine when and where a disturbance may have occurred.

Many studies, using several methods, have analyzed stream gage data to determine channel adjustments (e.g., Blench, 1966; James, 1991; Wilson and Turnipseed, 1994; Jacobson, 1995; Smelser and Schmidt, 2001; Pinter and Heine, 2005). Most were used to evaluate bed level adjustment and use water surface elevation (stage) to infer changes in bed-level. Mean stream bed elevation (MSBE) is a technique where mean depth is subtracted from water surface elevation. When time-series of MSBE are constructed adjustments can be visualized temporally. Trends in MSBE can also be assessed spatially if multiple gages are available on a stream (Jacobson, 1995; Smelser and Schmidt, 1998).

Specific gage technique is another method which uses annual rating type curves fit to discharge and other morphological parameters (ex, stage, width, velocity) for constant discharge conditions (blench, 1966; Pinter and Heine, 2005). This allows morphological adjustments at specific discharges to be determined. If a stream is controlled by different physical barriers at different levels (ex. Riffle, bars, channel, valley) of flow, the barrier(s) that are adjusting can be determined.

Another technique that has received less attention is analysis of residuals from the inverse relationship of discharge and morphological variables, similar to that of James (1991). This technique is similar to specific gage but instead fits a function to the entire record, rather than annually, and then analyzes the residuals over time. This method allows adjustments to be viewed independent of discharge. However if adjustments other than bed level are to be determined (e.g. width, velocity) data must be from a consistent cross section.

All of the above methods have been used to determine channel adjustments, and are often correlated or indirectly associated with some direct or indirect disturbance. The most prevalent is direct disturbances to the channel such as channelization (Simon, 1989) or other engineering activities (Pinter and Heine, 2005). Others have also evaluated adjustments to possible land disturbance (Jacobson, 1995).

Although most stream gaging locations are at bridges and are not the ideal locations for geomorphic assessments, they present a unique source of historical data. One of the criteria for gage locations is channel stability (Juracek and Fitzpatrick, 2009). However, streams are dynamic and if morphological adjustments are occurring they can often be detected with gage data. Which method is better depends largely on the research question at hand. If the question is concerned with overall changing channel conditions, such as highlighting the effects of impervious cover or downstream effects of dams and “hungry water” (ex. Williams and Wolman 1984; Kondolf, 1997) residual analysis requires considerably less time and provides information on overall channel adjustments independent of discharge (James, 1991).

For studies that are concerned with habitat conditions in regard to in-stream flow, the analysis of raw stage data (constant discharge) or specific gage method may provide greater information. However the specific-gage technique produces less scatter and often allows more data points for the analysis. Many in-stream flow studies use summary statistics of hydrological metrics (e.g. summer low flows, high flow pulses, duration, flashiness, etc.).

When discharge values (or ranges of values) are assigned to the suitable metrics, the channel conditions at selected discharges can be assessed. Because different stream levels are controlled by different physical barriers they can be analyzed separately. Low flow channels are often controlled by a riffle or in sand and gravel bed streams, by bars. Although bars are transient bed features some display considerable stability (Knighton, 1998).

It is possible to assess how the low flow channel has changed over time by examining the stage-discharge data. The same can be done with higher flows that are controlled by the channel, however when flows spill into the floodplain and valley control takes effect, relationships are much weaker due to the relatively low frequency of measurements as well as varying degrees of roughness during different times of the year.

Geomorphic analysis of stream gage data has inherent limitations. However, it should always be considered if gages are available in the study watershed. Often it should be the first line of analysis when channel changes are of concern. If multiple gages are located in a watershed, adjustments can be interpreted longitudinally to gain insight as to where a perturbation may have/or be occurred(ing), or how far a disturbance has migrated up or down stream (e.g. Jacobson, 1995). The information generated can also help in the formulation of hypotheses and direct further field data collection.

2.4 Channel Evolution Models

In alluvial settings, channels often respond to natural and anthropogenic disturbances by adjusting form. Many authors have noticed a sequence of systematic forms that channels pass through (Schumm, 1984; Simon and Hupp, 1986; Simon, 1989; Beechie et al., 2008).

Simon (1989) developed a conceptual model to predict morphological adjustments of stream channels in response to direct and indirect watershed disturbance. These are often referred to as channel evolution models (CEMs). They provide a simplified means of analyzing distinct morphological and/or dominant process stages. If specific evolutionary stages can be recognized, it can allow spatial and temporal relationships to be developed; which can then provide insight into to future adjustments in processes and form (Bledsoe, et al., 2002). CEMs often follow location for time substitution (LTS, Schumm, 1984) where forms and processes from the initial disturbance can be extrapolated to other areas in the watershed. This is often based on decreasing rates and magnitude as a disturbance migrates away from the initial area of disturbance or area of maximum disturbance (AMD, Simon, 1989).

Many CEMs have been proposed that use different variables to denote specific stages (Wolman, 1967; Schumm et al., 1984; Simon, 1989; Colosimo and Wilcock, 2007; Beechie et al., 2008). For example, the CEM proposed by Wolman (1967) and a similar variation by Colosimo and Wilcock (2007) was used to assess channel response to urbanization, the main focus of the model was to assess in-channel sediment storage to infer channel form and future morphological adjustments. Three stages of evolution were recognized in Colosimo and Wilcocks (2007) CEM. There is an aggradational phase that reflects increased sediment from urban development. Recognition of this stage relies on the presence of fine grained material accreted on bar formations or present on the streambed. Next is the early erosional stage, which has relatively smaller bars and less fine grained sediment. Lastly, the late erosional stage is almost entirely devoid of fine sediments and shows consistent increases in cross sectional area.

In contrast, the CEM of Simon and Hupp (1986) and Simon (1989) is more focused on dominant erosional or depositional processes and particular morphological indicators. Six stages of channel evolution are used in this model (Figure 2.1) where stage I refers to undisturbed. Stage II is used when direct disturbances are present such as channelization. The channel evolution begins when a stream is subject to a bed lowering event, which often results in knickpoint migration. As the channel bed degrades, banks become over steepened. This is stage III, which can be recognized by steep banks and often a near rectangular cross section. Next fluvial erosion will begin to occur at the bank toe which can lead to undercutting and reduced bank stability, this is stage IV. In the field it is easily identified by overhanging bank material in straight reaches. When the force of gravity overcomes the resistive forces of the bank material, mass wasting of the bank will follow. Stage V may be more difficult to identify in the field. Often mass wasting and lateral adjustments will still be occurring however the stream bed will be aggrading. Assuming no other disturbances occur, aggradation will continue on both bed and banks to reduce slope angles of the bank and reform a stable cross section. As aggradation proceeds channel slope will reach a quasi-equilibrium state (Simon, 1989). The stage VI channel is often viewed as a channel within the old channel, as a new floodplain is constructed within the terraces. The above described models are conceptual and in reality all streams may not pass through all of the stages.

Although these type of assessment are largely qualitative, many studies have linked the various morphological stages of evolution with quantitative variables; such as slope (Bledsoe et al., 2002; Beechie et al, 2008), suspended sediment concentrations and the slope of sediment rating relation (Kuhnle and Simon, 2000) as well as other categorical variables, such as dominant boundary material and slope class (Beechie et al, 2008).

In this study, I use assessments based on the CEM outlined by Simon and Hupp (1986) and Simon (1989). In this particular model, six stages of evolution are recognized. However one of the stages is constructed, which results immediately after channelization. For this study the stage II, or constructed, will be excluded as there is no documentation of channelization in the study area.

This model was originally developed for modified streams in Tennessee. However, it has been successfully used to assess channel adjustments in a wide array of settings (Simon, 2008, Personal communication).

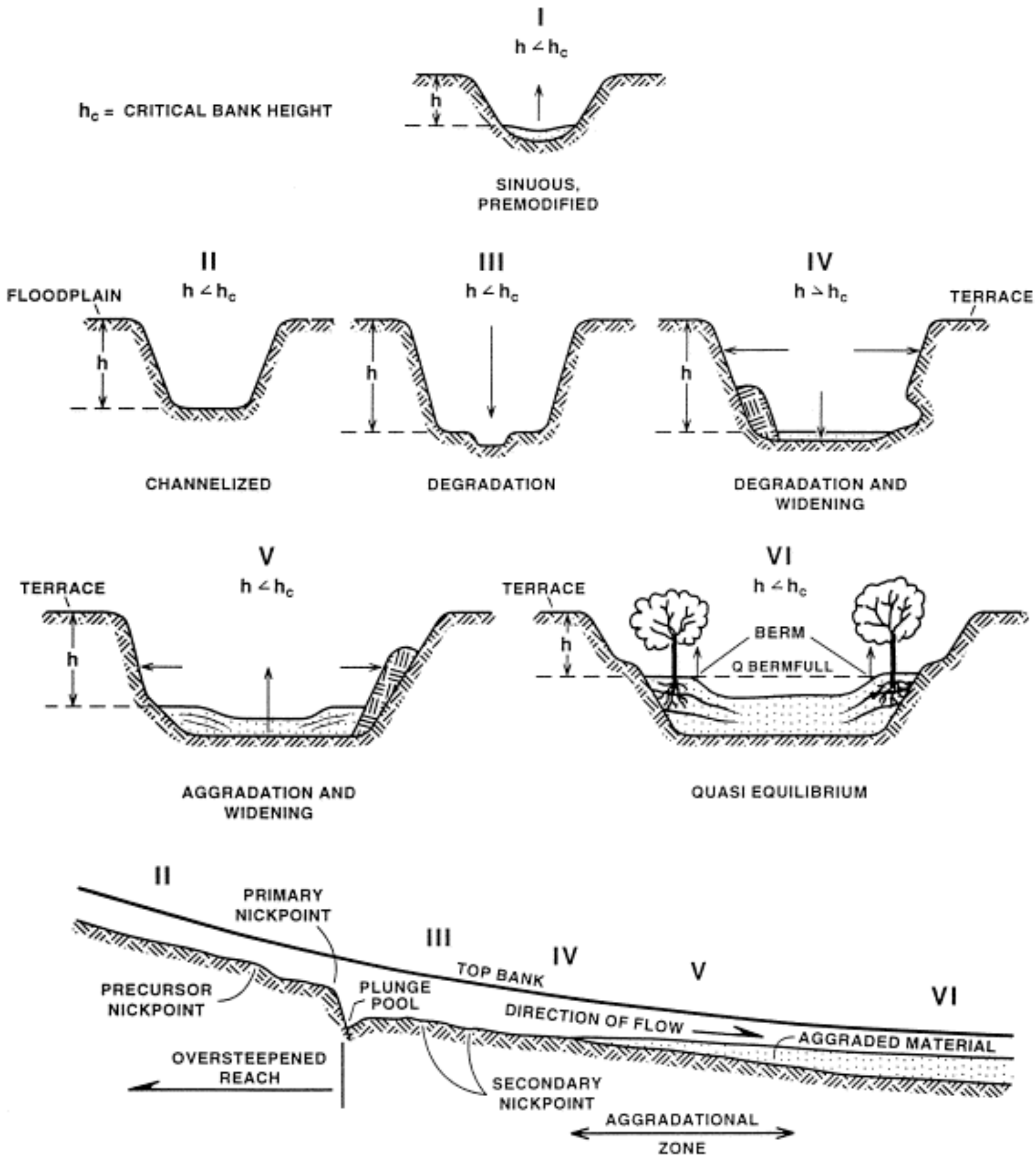

Figure 2.1: Six stages of channel evolution as proposed by Simon (1989).

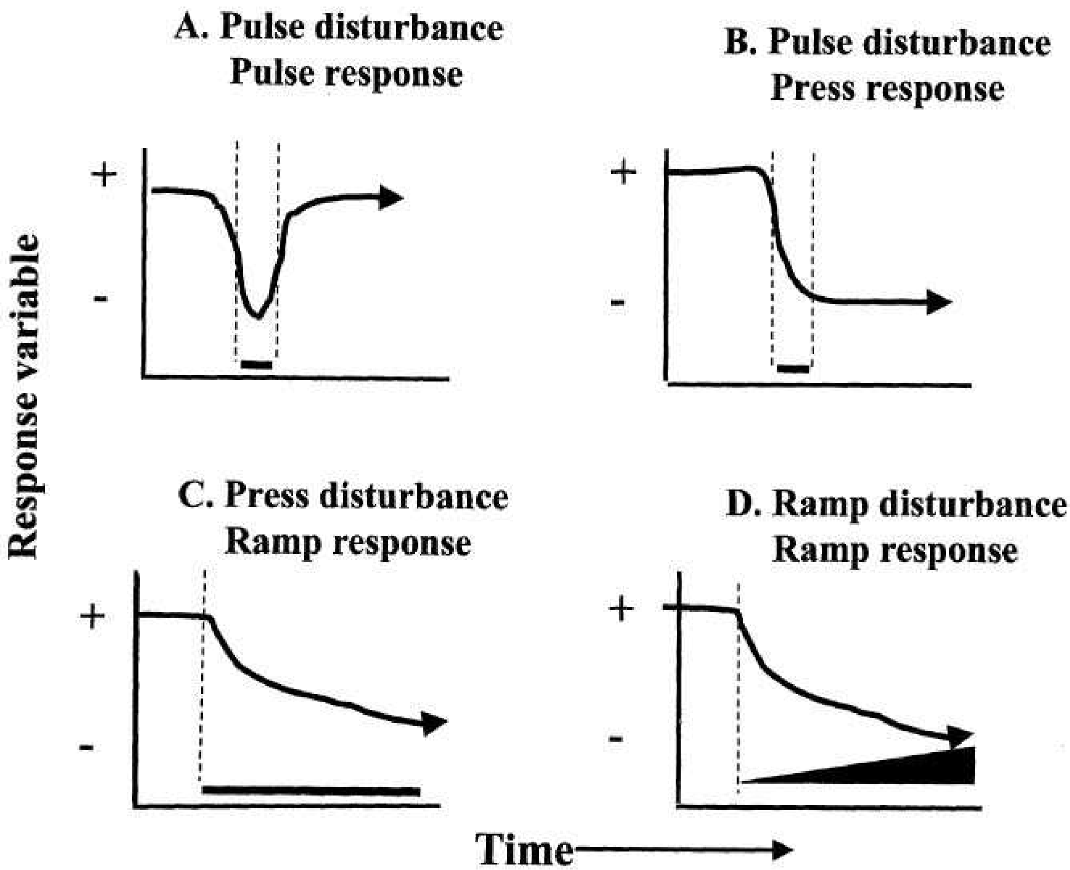

Figure 2.2: Example of the different forms of disturbance and response. The duration of the disturbance is indicated by the solid bar along the x-axis; the beginning and end of the disturbance is illustrated by the dotted vertical bars (adapted from Lake, 2000).

Chapter 3

Study Area

3.1 Description

The Flint River is unique in the fact that it is one of only forty rivers in the U.S that flow unimpeded for 195 miles (Stanley Consultants, 1973). However reservoirs and old mill dams are present on many of the Flint's tributaries. For the overall Flint River Thrust project, the study area includes the entire Upper Flint River Basin. This is generally the portion within the Piedmont physiographic province and very upper coastal plain, stretching from south Atlanta to the fall line area (Figure 3.1). This study focuses mainly on the portion above the Pine Mountain ridge.

The Upper Flint River basin has a drainage area of approximately 2,630 square miles and encompasses all or part of 19 counties (Figure 3.2). Land use in the basin consists of about 57 percent forest, 17 percent agriculture, and 12 percent urban, with most of the urban land concentrated in the extreme northern part of the basin (Georgia Land Use Trends [GLUT], 1998). The Flint River begins as a groundwater seep and flows through a culvert under a runway of Hartsfield-Jackson Atlanta Airport. The Upper portion of the Flint is typical of an urban stream dominated by storm-water runoff. Immediately south of the airport the Flint flows through an incised channel with steep banks. However by the time it reaches Jonesboro (approximately 15 river mi downstream), it encounters the first of many forested (riparian) wetland areas. Here the channels become more gradual sloping with broader floodplains. From this point down to the Pine Mountain area (approximately 65 river mile downstream)the Flint transitions in some areas from a well defined single channel to wetland like and sometimes multi-channeled. All of the USGS stream gages used in this study, besides Flint River at Carsonville, GA are located in the upper portion of the basin above the Pine Mountain area (Figure 3.6). When the Flint reaches the Pine Mountain area, channels are under greater geologic controls; exposed shoals and rock outcrops become more numerous. This portion of the basin received less attention from a geomorphic adjustment standpoint, due largely to the lack of existing data and because much of the boundary material is not readily erodable. Therefore most the sites in this study focus on the drainage area above this region. The exception was gage data analysis at the Flint River near Carsonville, GA and RGAs performed on Potato Creek and the Flint River both at Po Diddy Rd. approximately 18 river miles south of the Spreewell Bluff area. These sites were largely exploratory, to assess how channels responded after leaving the area of greater gradients.

3.2 Geologic and Climatic Setting

The Upper Flint River Basin is located almost entirely in the Piedmont physiographic province of Georgia with only a small portion extending onto the Coastal Plain province. Topography of the Southern Piedmont plateau has gently rolling hills with elevations usually less than 500 feet. The exception to this is the Pine Mountain ridge which rises 1200 feet. It extends from the Chattahoochee River in the west to east of the Flint River. Geologically, it consists of Hollis quartzite, metamorphosed quartz sandstone, as well as metamorphosed mudstone (Hanley, 2006). Piedmont soils commonly consist of kaolinite, halloysite, and iron oxides that produce their distinct color (Geology of Georgia accessed 3/13/2009, http://www.gly.uga.edu/railsback/GAGeology.html#DISC). They result from the intense weathering of feldspar-rich igneous and metamorphic rocks. Texture of piedmont soils is generally sandy-loam to sandy-clay.

The Upper Flint River Basin has a humid subtropical climate. Average temperature during the summer is 89 degrees Fahrenheit and 56 degrees Fahrenheit during the winter. The warmest months are July and August and the coolest are December and January. Rainfall in the lower piedmont is on average about 49 inches per year. However, dryer years occur frequently but are usually localized. March and July are the wettest months of the year. On average the piedmont receives one inch of snow annually, though it is usually less in the south west. Annual Evapotranspiration (ET) is around 70% of total precipitation (Rasmussen, 2003 NGE), or 34 inches. The greatest monthly ET occurs in June and July, about seven inches, and the least in December and January, about two inches.

3.3 History

The purpose of this section is to account for events and changes that have had a lasting influence on the landscape in the Flint River Basin. This area of Georgia has a long history of inhabitants, from Native Americans, such as the Creeks and Cherokees, to small civilizations of early Europeans. Much of the land in the Flint River Basin was colonized by European settlers from Virginia and the Carolinas as well as the more eastern counties of Georgia. The Treaty of Indian Springs was signed in 1821, which initiated a migration to this area of Georgia (Cooksey, NGE 2006). When the vast tract of land between the Ocmulgee and Flint Rivers was ceded by the Creeks, the state held land lotteries for the newly acquired land. Many of the counties comprising the Upper Flint River Basin came as a result of this treaty.

From Trimble (1974), it appears that the amount of prehistoric erosion on the Piedmont is small. However one may argue that the long presence of indigenous cultures in this region substantially altered much of the landscape by continually setting fires to maintain fields and hunting grounds (Rostlund, 1957). Rostlund (1957) also believes that there were far more primeval forests 1850 than 1650, believing that the Indian population had begun to collapse due to disease and much of the forest were recovering from widescale burning. If Rostlunds postulations are correct, when compared to the Europeans to come, there are still little similarities in terms of magnitude of disturbance. Much of the initial characterization of the Georgia Piedmont is by way of journals of early settlers and the expeditions of John and William Bartram. These sources offer qualitative and often detailed accounts of the landscape and particular features but are sometimes suspect of embellishments. The famed *Bartram*

Trail follows a general path just above the southern fall line of Georgia and crosses the Ocmulgee, Flint, and Chattahoochee Rivers. Bartram describes one of the camping locations (p.241), which is between the Ocmulgee and Flint River as, “Close to a beautiful brook called Sweet Water, the glittering wavy flood passing along actively over a bed of pebbles and gravel. The land between the Ocmulgee and the Flint are generally ridges of low swelling hills and plains supporting grand forests, vast cane meadows, savannahs and verdant lawns.” And the next day crossing the Flint River, We forded the River, about 250 yards over, and camped next to a large and deep creek, a branch of the Flint. The high land excellent, affording grand forests, and the low land vast timber and canes of great height and thickness The adjacent low grounds and cane swamp afforded excellent range for our horses (Harper, 1998). From this account, this region of Georgia appears to be a heterogeneous landscape, lacking large scale disturbances that would be readily observable to someone lacking a temporal frame of reference. Although Bartram described many plants in great detail in this area (western GA Piedmont), it still lacks systematic pre-European records to compare current conditions of water, soil, and vegetation distributions (Cowell, 1998).

When the lands were controlled by the Native Americans, much of the disturbances were from subsistence farming. They learned to farm in the rich bottomlands of the Ocmulgee and Flint Rivers where the soil was more fertile. They practiced slash and burn agriculture and set fires to drive game animals for easier hunting. Otherwise their methods of farming were much more conservative than the Europeans to come (Trimble, 1974). The Native Americans practiced crop rotation and were very skilled farmers. It can be ascertained that one of the major differences between the types of farming was the economic incentives that were in place for the Europeans whereas the Native Americans were only subsistence farming.

There are many accounts in the journals of the settlers describing swollen rivers still flowing clear or only stained with a brownish color from vegetable matter (Trimble, 1974). One of these journal entries was from a British Geologist, Sir Charles Lyell, of his accounts on the Altamaha River, which has a large tributary (Ocmulgee) adjacent to the Flint River.

‘Our canoe was scudding through the clear waters of the Altamaha, Mr. Cooper mentioned a fact which shows the effect of herbage, shrubs, and trees in protecting the soil from the wasting action of the rains and torrents. Formerly even during floods, the Altamaha was transparent or only stained of a darker color by decayed vegetable matter, like some streams in Europe that flow from peat mosses. So late as 1841, a resident could distinguish on which of the two branches of the Altamaha, the Oconee or Ocmulgee a freshet had occurred, for the lands in the upper country (Piedmont), drained by one of these (the Oconee) had already been partially cleared and cultivated, so that the tributary sent down copious amounts of red mud, while the other (Ocmulgee) remained clear though swollen. But no sooner had the Indians been driven out, and the woods of their old hunting grounds began to give way before the ax of the new settlers, then the Ocmulgee also became turbid” (from Trimble, 1974).

This is believed significant to the upper Flint because the Ocmulgee is the adjacent basin to the east. Also, many of the counties in the Upper Flint Basin were formed as a result of the land ceded by the Native Americans. This illustrates the westward movement of settlers, as soil was exhausted to the east they just kept pushing westward. As of 1810, the Piedmont region east of the Oconee River was well populated where as to the west had very few settlements. By mid Century, after the land had been ceded by the Indians, the population in the Piedmont was as great as or greater in the west than the east (Brown, 2002).

Agriculture was the means of livelihood for most settlers in Georgia, and at this time cotton was king. Cotton got its start in Georgia around 1786 in the Savannah area (Giesen, 2004 NGE). However, this was Sea Island cotton and was only suitable to the coastal regions. The short staple cotton that would grow in the Piedmont region of the state was not as productive and was more difficult to separate from the seeds. In 1793, Eli Whitney invented the cotton gin. This invention alone had a major impact on the Georgia Piedmont. It was now profitable for small scale farmers as well as huge plantations to grow cotton on the interior of Georgia. From 1840 until the early 20th century, acres of improved land increased steadily in the Upper Flint River Basin (Figure 3.3). This so called improved land was land that had been wiped clean of vegetation and was ready to be cultivated.

This invention led to massive increases in the amount of cotton farms as well as total acreage of these farms. Because of the huge population boom surrounding the relatively flat topography and the fertile soil of the Piedmont, transportation was forced to expand as well. The farmers had to have means to get their product to the river so they could make it to the mills. Towns began to spring up everywhere along railroads. There was now a need for more banks and other services to the farmers that were cashing in on cotton. The rapid growth of the cotton industry continued to surge and was the economic driver of the South.

In 1896, The Georgia Geologic Survey performed a study to document the Water Powers of Georgia. The purpose was largely to encourage economic development in areas where there was sufficient power to generate direct water power or place a generator for electricity. In the UFRB mills began to spring up in many of the towns where a sufficient source of water power was available and finished goods were marketable. Many of the towns or county seats in the UFBR were moving toward a manufacturing economy. By 1896 there were, by conservative estimates, over 30 mills located on the Upper Flint River and its tributaries. These mills were accounted for in the survey, however, county by county reports would raise this number to over 140 mills (Georgia Department of Agriculture, 1901). Most of the mills were powered by direct water power with a small portion indicating steam power (Georgia Department of Agriculture, 1901). The majority of these mills were small, that powered flour, grist, and saw mills utilizing less than 50 horsepower. However one large mill, on the Flint River, utilized 4,255 HP and was shared by Meriwether and Pike Counties.

The first sign of the cotton industry slowing was at the start of the Civil War. During this time, much of the land was abandoned. Land that was not abandoned changed from cash crops to wheat, corn, and other cereal crops. After the war, there were issues with labor on the larger plantations as slavery had been abolished. The downfall of efficient plantation management in the Georgia piedmont was evident. Without slave labor, the planters encountered much difficulty (Aiken, 1998). Some of the freed slaves migrated west. Many of the new free men took up tenant farming. This type of farming generally led to greater erosion, simply because they did not own the land and were less inclined to practice erosion control measures (Trimble, 1974). While plantations were waning in the Piedmont region, they were beginning to flourish in the Coastal Plain. King Cotton was on the increase again after the civil war; only now on smaller scale farms.

This small scale farming continued to be a significant portion of the economy until the early 20th Century. Between 1909 and 1929 counties in the basin experienced a 40 percent decrease in farm acreage (Figure 3.4). When the boll weevil reached the western edge of the Georgia Piedmont, the stage was set for disaster. The boll weevil was the just the pinnacle. The building scenario was that of poor land management, that led to soil erosion and exhaustion. By the 1920s, agriculture infrastructure was focusing on small agribusiness complexes (Aiken, 1998). After the downfall of cotton post-depression, it remained an attractive crop, but prices were falling and did not provide the same incentives. By 1970, there were few agricultural islands remaining in the sea of pine trees. Only one of them was located in the Flint River Basin, centered on Pike County (Aiken, 1998).

The cotton era can be summarized by land decimation. The early settlers had an attitude that land was an expendable resource (Trimble and Brown, NGE 2003). They would farm a plot until the soil was eroded and exhausted, then pack up and move to a new piece of land. Trimble (1974) estimated that the entire Georgia Piedmont region lost approximately 7.5 inches of top soil from 1700 - 1970. Many of the stream channels were filled with sediment as deep as 10 feet. When these stream channels filled, they flooded valley bottoms until they could cut through the alluvium, once again forming a channel. In another study that was conducted in an adjacent watershed east of the Flint; Jackson et. al. (2005) found nearly uniform floodplain deposits of 5.4 feet on top of the historical A-horizon. This corresponded to about 0.40 feet of topsoil across the Murder Creek watershed.

One of the great attributes of the Piedmont region was that the streams had nice shoals and consistent flows that were ideal for mill dams. When the channels filled in with sediment, it would reduce power or completely burry dams (Trimble, 1974). In a report by the Georgia Department of Agriculture (1901) by 1900 much of the land in the eastern piedmont had stabilized, and although gullied was suitable for cropping; whereas much of the land in the west was still actively eroding. It reported for Marion county, in the lower potion of the study area, that the once most fertile portion of the county was injured by injudicious cultivation. By the mid 20th century much of the abandoned land was going through the succession to become a forest once again. The soil conservation society was encouraging land owners to plant kudzu to prevent further erosion and convert crop land/idle land into pastures. Many of the old barren fields were successing naturally and some of the land was being bought up for timber planting and harvesting.

After WWII most of the counties in the basin were switching from an economy based largely, if not entirely, on cotton. Many of the counties already had other sources of revenue, such as manufacturing crops other than cotton. Most of the counties in the northern portion of the study area have been becoming increasingly urbanized. After the construction of interstate 75, even some of the counties further away from Atlanta were beginning to experience the sprawl and economies relying more on manufacturing and services. The counties that lie to the far south and west of the study area still rely on agriculture and forestry. Much of the agriculture is now in livestock and fruits. The timber industry flourishes on the Coastal Plains and on the less populated portions of the Piedmont.

Although the current amount of upland erosion is near negligible when compared to that of colonial times, the export of stored sediment is still a concern. In the Murder Creek watershed it was estimated that sediment exports exceed imports and that at the current rate of export, it will take between six and ten millennia to remove the historical sediment in storage (Jackson, et. al, 2005). It is believed that large amounts of cotton era sediment are also in storage in the Upper Flint Basin; however there is no knowledge of the magnitude.

This could have detrimental consequences for aquatic ecosystems of the basin for millennia, as habitats may be frequently disturbed by sediment mobilization and deposition.

3.4 Contemporary Issues

Now the Georgia Piedmont is faced with a whole new set of environmental variables. Rather than poor agricultural practices leaving land gullied and dissected it is now being covered up and paved over. Now that the once barren fields have reverted to mature forests they are being cut down in increasing numbers for urban and suburban development. In the upper Flint River basin, population growth expanded on a nearly linear trend from 1830 until about 1970, there after the rate increased greatly until about 2005 (Figure 3.5). Out of the fifty states in the nation, Georgia has the fifth fastest growing population. Between 1990 and 2000, the population saw a 26 percent increase (GLUT, 2005). Increased growth contributes heavily to the conversion of crop and forest land to an urbanized landscape (Kundell, 1982). This exacerbates the spread of impervious cover, altering water and sediment delivery to streams. While sprawl is a problem throughout Georgia, the Atlanta metropolitan area has experienced the most. A recent study by the Sierra Club ranked Atlanta first among the “most sprawl threatened” metropolitan areas of one million people or more (NPG special report). In 1990, metro Atlanta measured about 65 miles from north to south. As of a 2004 study it was about 110 miles across. By 2018, its range is expected to include suburbs like Athens and Dalton (NPG special report). The UFRB experienced a 111 percent increase in impervious surface between 1991 and 2005 (GLUT, 2005); during this same period urbanized area (both high and low intensity) increased 72 percent. However with the dramatic increase in impervious cover it only accounts for 5 percent of basin area, and the majority is concentrated in the most northern portion of the basin around Atlanta. Although urbanization is not yet a problem throughout the basin, it is likely to expand since much of the Flint River is between or near the interstate 75 and 85 corridor. Furthermore the city of Atlanta continues to expand in all directions.

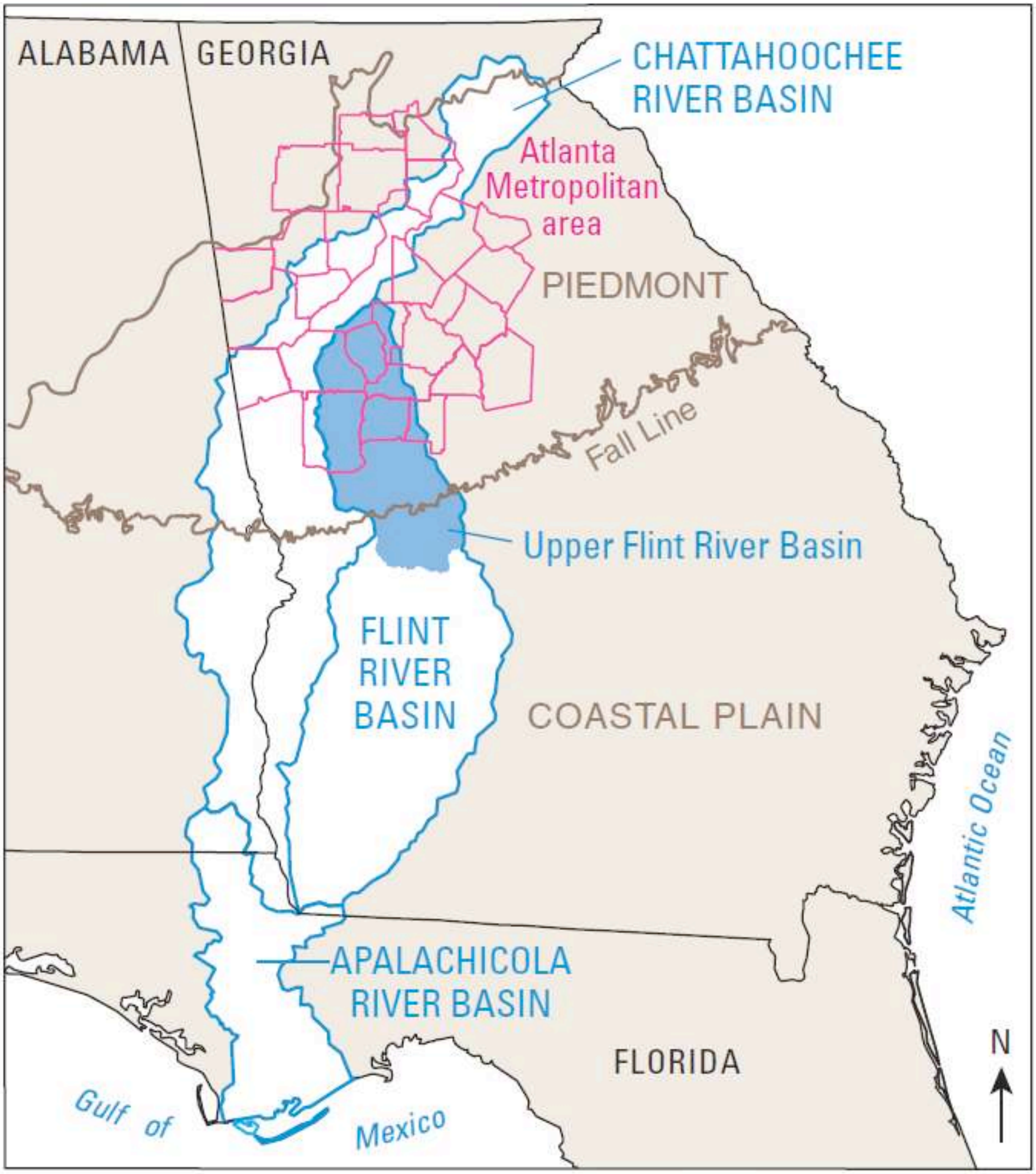

Figure 3.1: Location of Upper Flint River Basin within the ACF basin

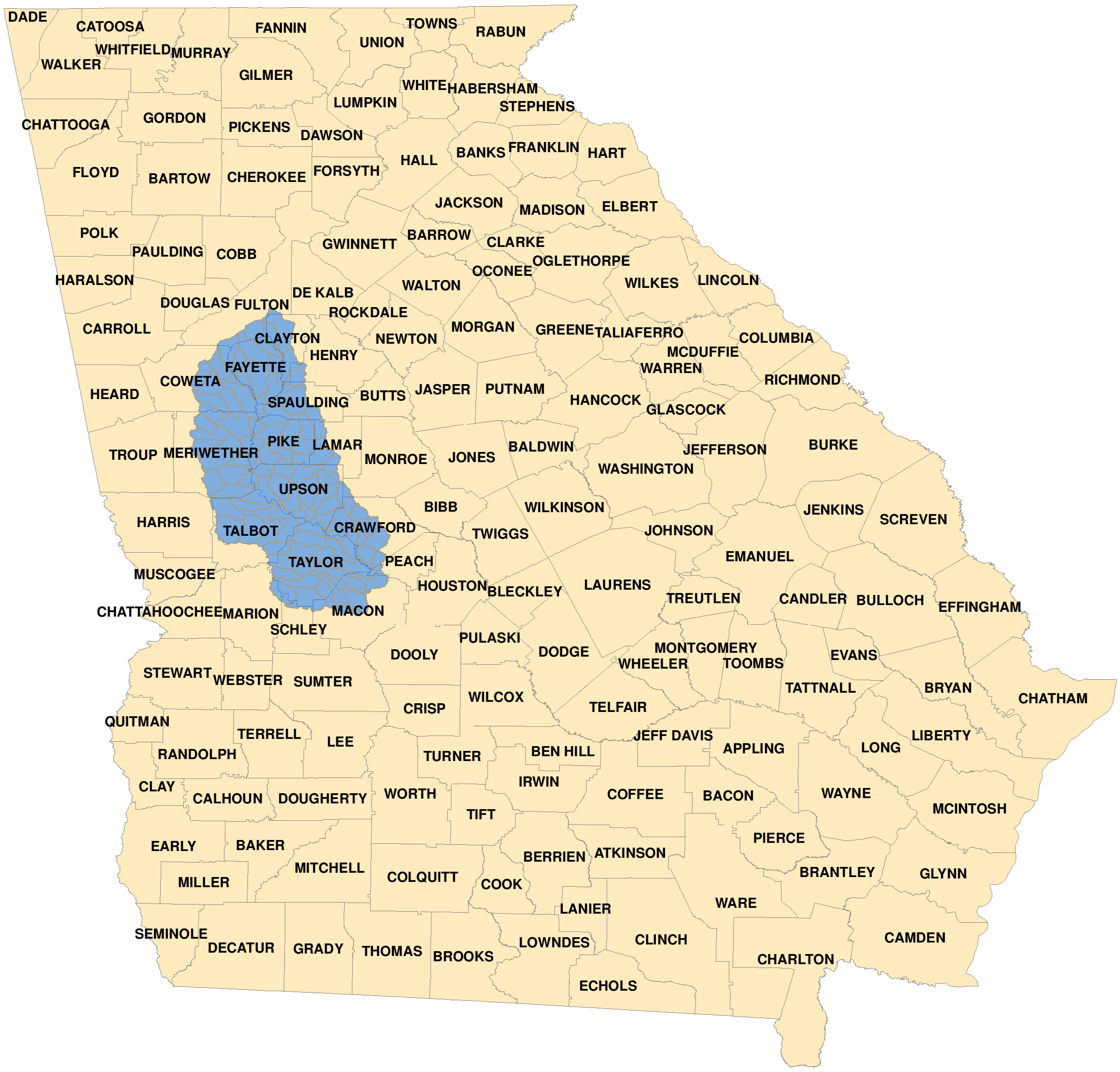

Figure 3.2: Counties within the Upper Flint River Basin

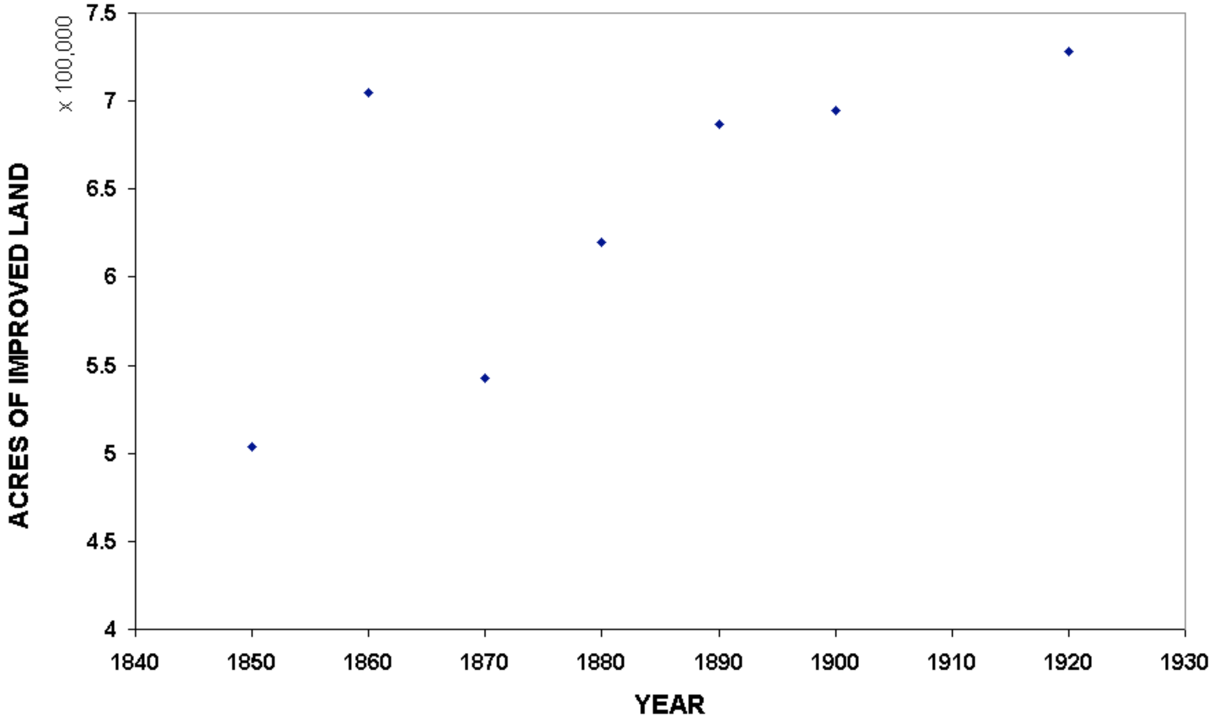

Figure 3.3: Acres of improved land in the Upper Flint River Basin

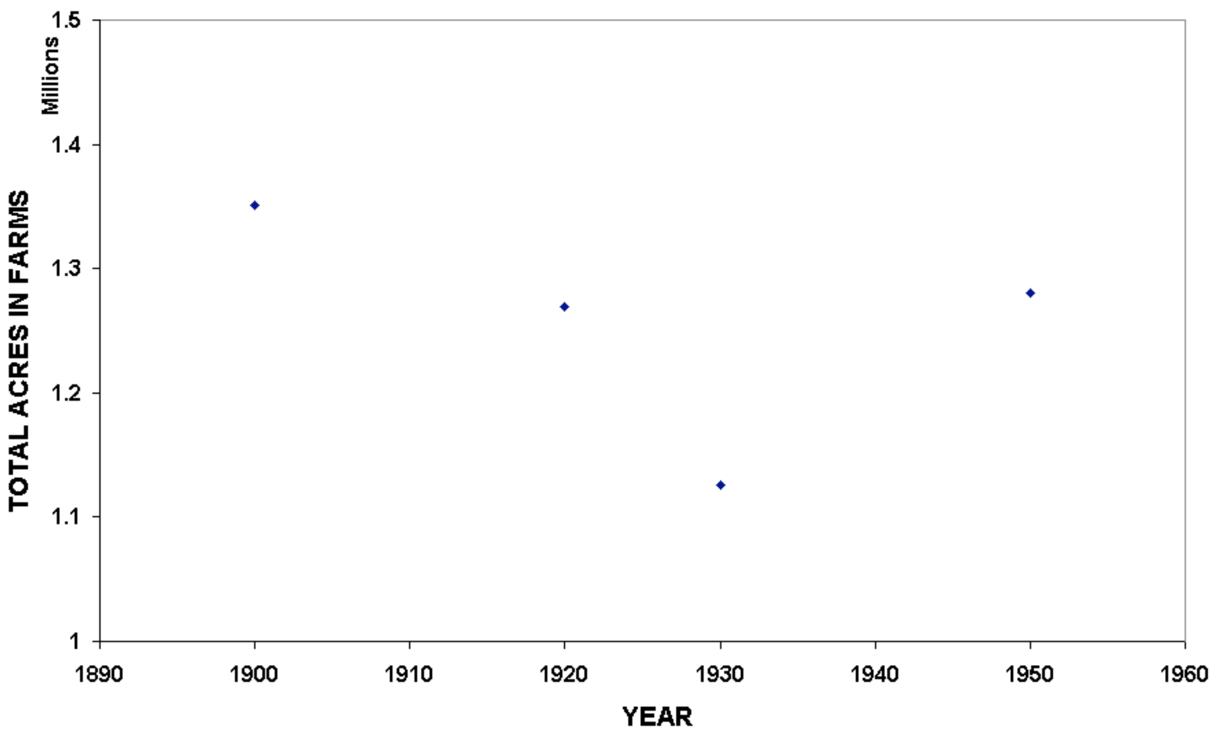

Figure 3.4: Total acres in farms in the Upper Flint River Basin

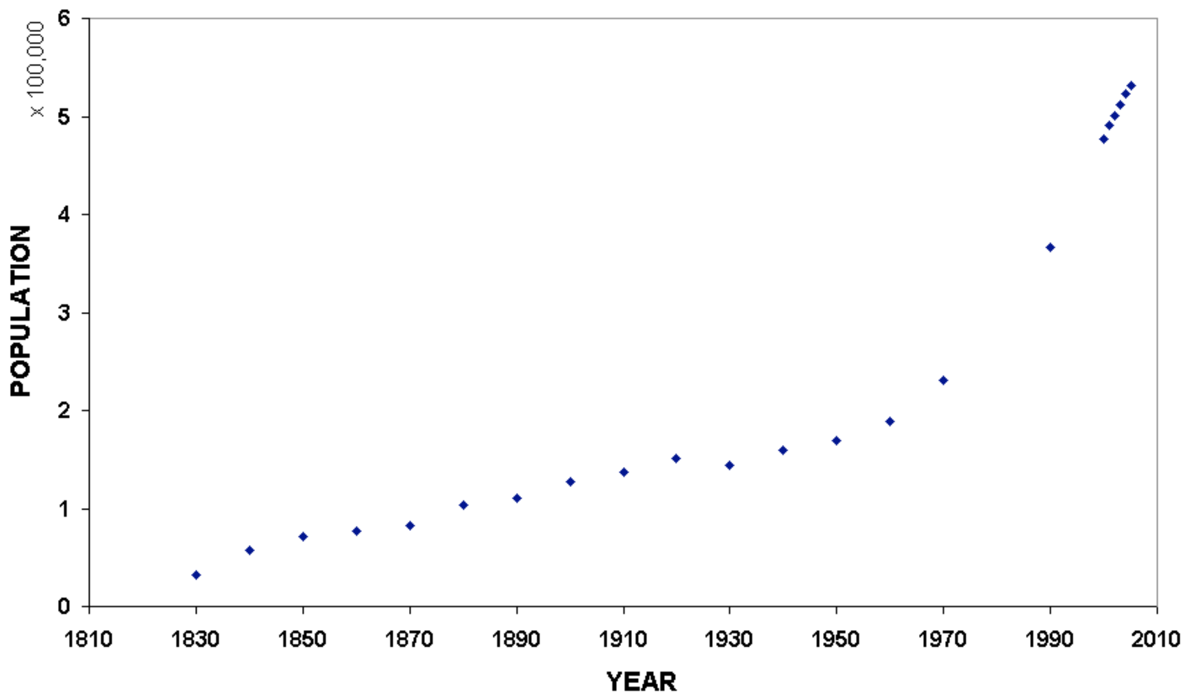

Figure 3.5: Population of the Upper Flint River Basin (1830-2005)

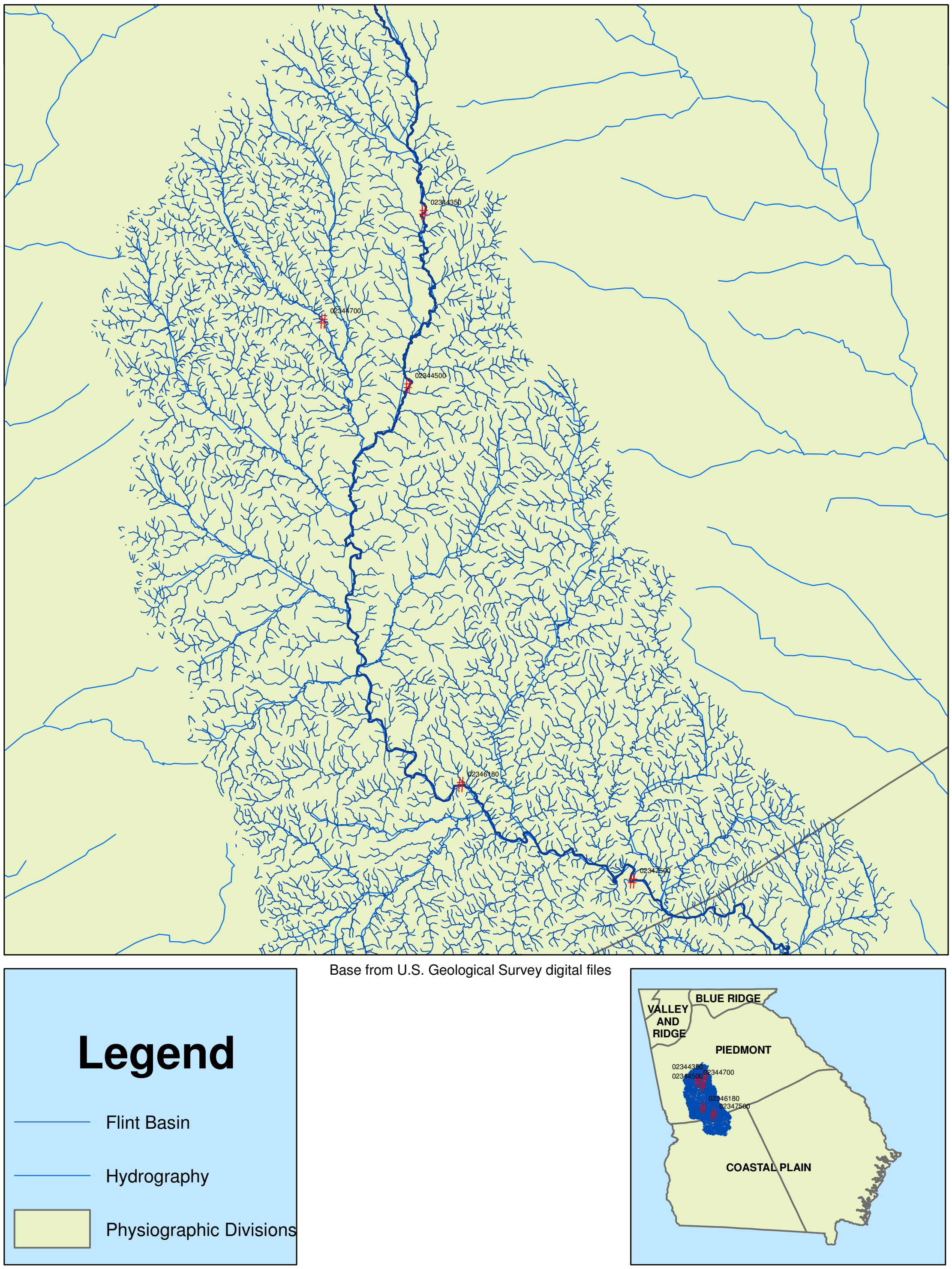

Figure 3.6: Location of USGS stream gages in Upper Flint River Basin

Chapter 4

Methods

4.1 Stream Gage Analysis

For this study, discharge measurement field data were obtained from the USGS National Water Information System (NWIS) database and from paper files located at the Georgia USGS Water Science Center in Atlanta, Georgia for selected stream gages. Station description files were then obtained to check for continuity in the record. At some locations, gages were moved up or downstream due to bridge construction or altered channel conditions and data needed to be edited to reflect the current location of the gages.

Initially, other aspects of channel form that co-vary with discharge were to be analyzed (width, depth, velocity), for this reason all data were edited to reflect the current gage location. However, combinations of wading and non-wading discharge measurements complicate this analysis. For example, wading measurements are typically made at locations that are best suited for making an accurate discharge measurement; therefore the actual location for the measurement may change with flow conditions, resulting in different cross sections measured. This, in turn, produces different average width, depth and velocities for a wading site. Alternatively, bridge measurements are consistently made at the same location, assuming the bridge has not been rebuilt or significantly altered. If there is a sufficient density of bridge measurements, they can be analyzed separately for changes in the other channel parameters, since the same channel cross section was always measured. Depth, width, and velocity can also be analyzed for wading measurements if discharge field notes are obtained and there is sufficient density of measurements at specific cross sections (Jacobson, 1995). However, in the event that only the stage-discharge data is to be used, datum corrections can be performed to render all historical data functional. This procedure is outlined by Smelser and Schmidt (2000).

For this study, three different methods are explored using stage-discharge data from the USGS NWIS database. Bed level adjustments or stability are determined based on how the relationship between stage and discharge has changed over time. The adjustments are inferred from changes in water surface elevation. First, stream gages within the upper Flint River basin are identified. They then are checked for years of record. In humid climates, morphological adjustments often are much slower than in arid climates (Knighton, 1998). It was predetermined that at least 20 years of record were desired to detect changes that could potentially involve lags or longer response times. In the Georgia Piedmont, field measurements were performed between 6 and 12 times a year to update rating curves. On the larger rivers (ex. Mississippi, Missouri) measurements are made biweekly and more frequently during high water periods (Pinter, 2005). Compared to other studies using similar techniques (Jacobson, 1995; Smelser and Schmidt, 1998; Pinter, 2005), suitable data for the Upper Flint Basin was limited.

Before any data analysis could be performed, all of the data has to be sorted and checked for erroneous values, and corrected for missing values. At most gage locations, two stage values are available. The inside gage height, which is from the stilling well or recorder and the outside gage height, which is from either a staff gage or wire weight gage. For this analysis, the outside gage data was used because this is generally accepted as the base gage as to which the other is set and usually has a more complete record. When outside gage data are missing, a simple linear regression, with previous values of inside and outside stage, is performed to calculate outside stage.

Initially, the specific gage method was the chosen form of analysis (Blench, 1966; Pinter and Heine, 2005). This method is somewhat labor intensive. In most cases annual rating type curves are produced. However, toward the end of the records sites were only gaged four times a year, so for 2000-2006 every two years of data are combined. Rather than using stage to predict discharge the variables are switched and discharge is used to predict stage. From the best fit statistical model, a single data (stage value) point is calculated for each year of data. This procedure can be repeated for the different discharge values of interest. How the rating relation has changed over time will be reflected in the calculated stage values from year to year. Pinter (2005) found that the specific gage technique produces less scatter than analyzing raw hydrologic data. For this method, criteria must be set as to how good a fit must be to include that particular rating in the analysis; for this study models explaining 95 percent or greater variability were included. It is also not appropriate to use a rating relation if the selected discharge values are outside (extrapolate past the measured values) of the values measured to produce the curve (Pinter and Heine, 2005). Other morphological parameters can be analyzed in a similar manor assuming that fair relationships can be constructed with discharge.

Another method used plots time series of the stage residuals, similar to that of James (1991). The advantage of this method is that all of the data can be used and it is fairly simple. Once the data has been checked and corrected, a function is fit to the entire data set. This is accomplished by regressing stage against discharge similar to a rating curve; only the predictor variable (independent) is switched. For example, rather than using stage to predict discharge, discharge would be used to predict stage. For these analyses, curves are fit to the entire corrected record. Systematic fitting is required to find the best regression model, generally a power function or double exponential worked the best for most locations. From this regression, residual values can be obtained by subtracting predicted values from measured values. These residual values are then plotted against time to evaluate trends independent of discharge (James, 1991). Stream bed adjustments are illustrated by the deviation of the residual from zero or the initial intercept. If the stage-discharge relationship has not changed, the result of the residuals should be a relatively flat line with associated scatter. If there is aggradation the slope will be positive and negative if degrading. Because changes in the relation of stage to discharge can vary due to changes in flow velocity or channel width, it is necessary to evaluate these possibilities simultaneously. However this can prove difficult in smaller streams that are often waded, because different cross sections are measured. Due to the amount of usable data and ease with which data can be analyzed, the residual method was chosen for subsequent analyses using gage data.

Time series of raw stage values (constant discharge) are also analyzed. For this method, data were obtained and corrected as stated above. After data has been corrected they are then sorted by discharge. Data then are explored to identify the discharge values that have been measured most frequently. Then all of the near constant discharge values ($\pm 2.5\%$ of the chosen discharge value) have to be separated out and resorted by date to produce the time series. The low flow channel is the primary focus but higher flows are assessed as well. For this reason, more values are selected near or below the median flow over the course of record, and usually one above to capture both low water control adjustments and overall channel adjustments or where the channel is control of all stages. Past that criterion it was based upon the values with greatest reoccurrences and fairly spaced in relation to the previous discharge value selected. After the data has been sorted by discharge and date it is then simple to plot all of the channel parameters over time. The one drawback of this method is that the analysis is dependent on constant discharge conditions. More often than not, there can be many years that a particular discharge is not measured; hence limiting the available data and temporal continuity. This method was performed for all of the long term gages in the Flint River basin. It was largely employed to compare trends in the raw stage data to the trends from the computational methods.

4.2 Urban Gradient Analysis

In the UFRB only six long-term gaging stations exists and two of them have been discontinued for over ten years. For this reason we chose to branch out into other basins in the Georgia Piedmont and analyze data from other long term stream gages meeting the criteria. When selecting stream gages, we chose also to test the hypothesis that streams will adjust systematically along an urban to rural gradient. This was in the hope of inferring future adjustments to the Flint basin, since it is currently facing increasing urbanization, especially in the headwater area. The purpose of this analysis is to try and fill in gaps where data is not available in the Flint Basin by making generalizations about channel response to varying land-cover/land-use conditions.

For this analysis, thirty-seven stream gages (Figure 4.2)are selected throughout the Georgia Piedmont with varying degrees of urbanization. The idea was to use location for time substitution (LTS) (Schumm, 1991). This method allows different streams in different erosional (or depositional) states to represent a single stream over time. This method is often used to assess changes that occur over timescales that are nor readily observational. The reliability of this method depends on how well other variables are controlled. For example in this analysis land cover is the primary variable of concern; the only control factor is physiographic region which should account for gross topographic and geologic controls but may not accurately represent local conditions.

Gage locations in the same physiographic province (Piedmont) as the UFRB were selected. This was so inference of channel response to future urbanization or current urbanization that influences slower processes could be extrapolated to channels in the UFBR. Sites selected had at least 20 yrs of record, past this they were of varying drainage area and degree of urban land cover (Table 4.2). Peak flow files for each gage were obtained from USGS NWIS. From the peak flow files (annual duration series) 2- yr recurrence interval floods were calculated and used as a proxy for bankfull discharge. The field measurements were then checked for discharges corresponding to the 2 yr flood discharge. The associated width and depth were used to calculate width:depth (W:D) ratios; with the hypothesis being that greater degrees of urbanization would be associated with larger W:D ratios. Plots of width and discharge were also produced to help in the identification of bankfull conditions. Residual analysis was also performed on all of the sites selected for the urban gradient analysis. This was to determine if there were trends with channel response (aggradation, degradation, or stability) with the degree of urban cover, or if there were longitudinal trends in basins with multiple gages.

4.3 Field-Based Assessments

Field based assessment were undertaken in the vicinity of the gage location, and concentrated on two large tributaries of the Flint River. Due to persisting drought conditions most sites were accessed via bridge crossings. At most sites, rapid geomorphic assessments (RGAs) were performed up and down stream of the bridge (Figure 4.1). Reaches varied as a function of channel width (6-20x). The actual reach length depended largely on access to the site. At each site, field forms (Appendix B) were filled out that address nine unique criteria that relate morphological form to dominant channel process (Kuhnle and Simon, 2000). Criteria address issues of channel bank stability, dominant erosional process, extent of riparian vegetation as well as other factors affecting channel stability. Each criteria is assigned a point value, all values are summed to get an overall score that helps when determining stage of channel evolution.

The goal of this was to support inferences from gage data, and explore morphological adjustments in two major tributaries. The method used was similar to that of Simon and Hupp (1986) and Simon (1989). This method is largely qualitative, concentrating on the observable morphological distinctions that can be visually inspected to determine dominant processes and other factors that affect channel stability. Although they are qualitative in nature some studies have correlated quantitative variables with stage on evolution (e.g. Beechie, et. al, 2008). RGAs performed in the vicinity of gages will be used to support results from gage data analysis. RGAs from gages and throughout the watershed will be compared and responses correlated to potential influential factors.

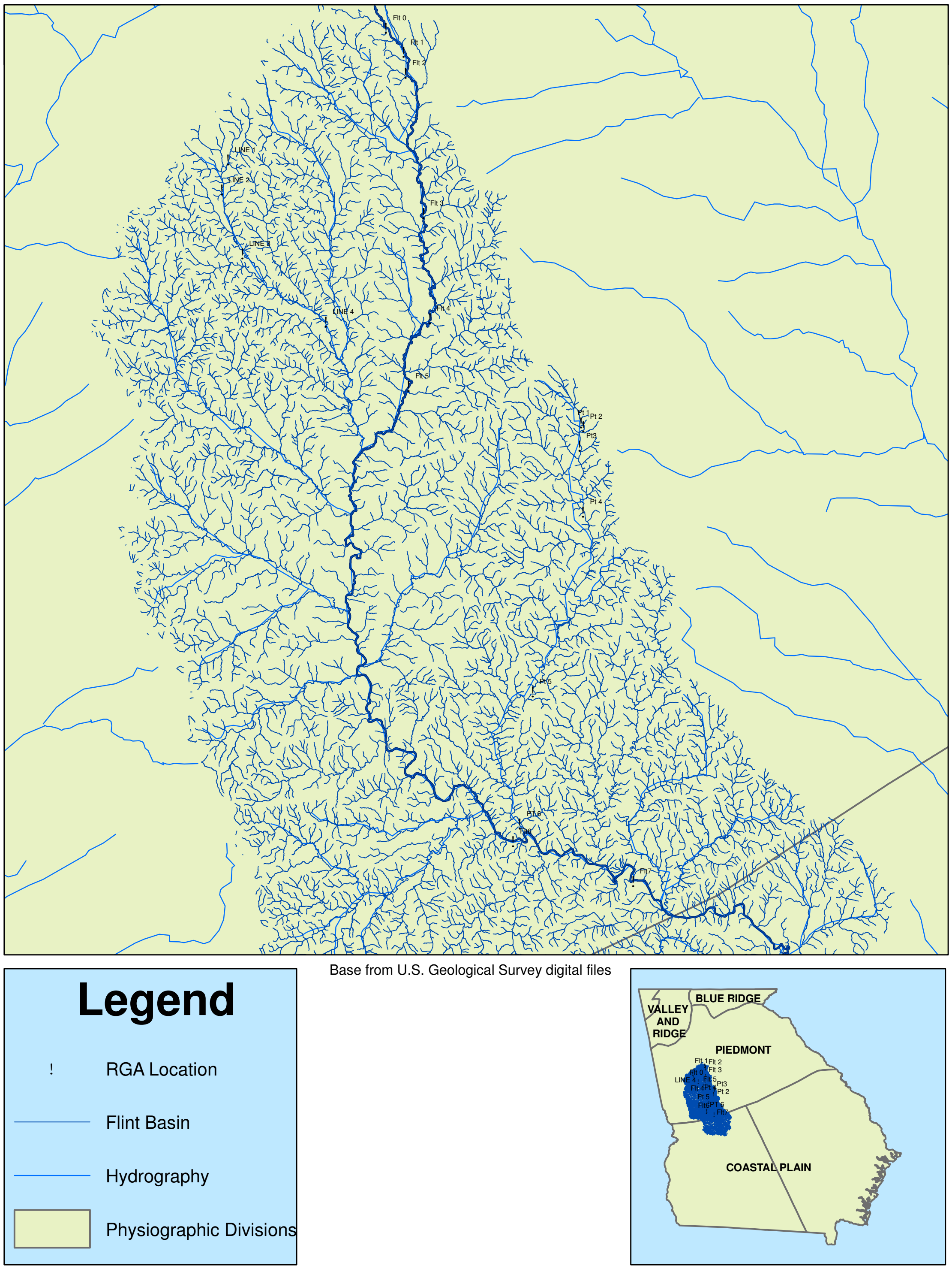

Figure 4.1: Locations where RGAs were performed.

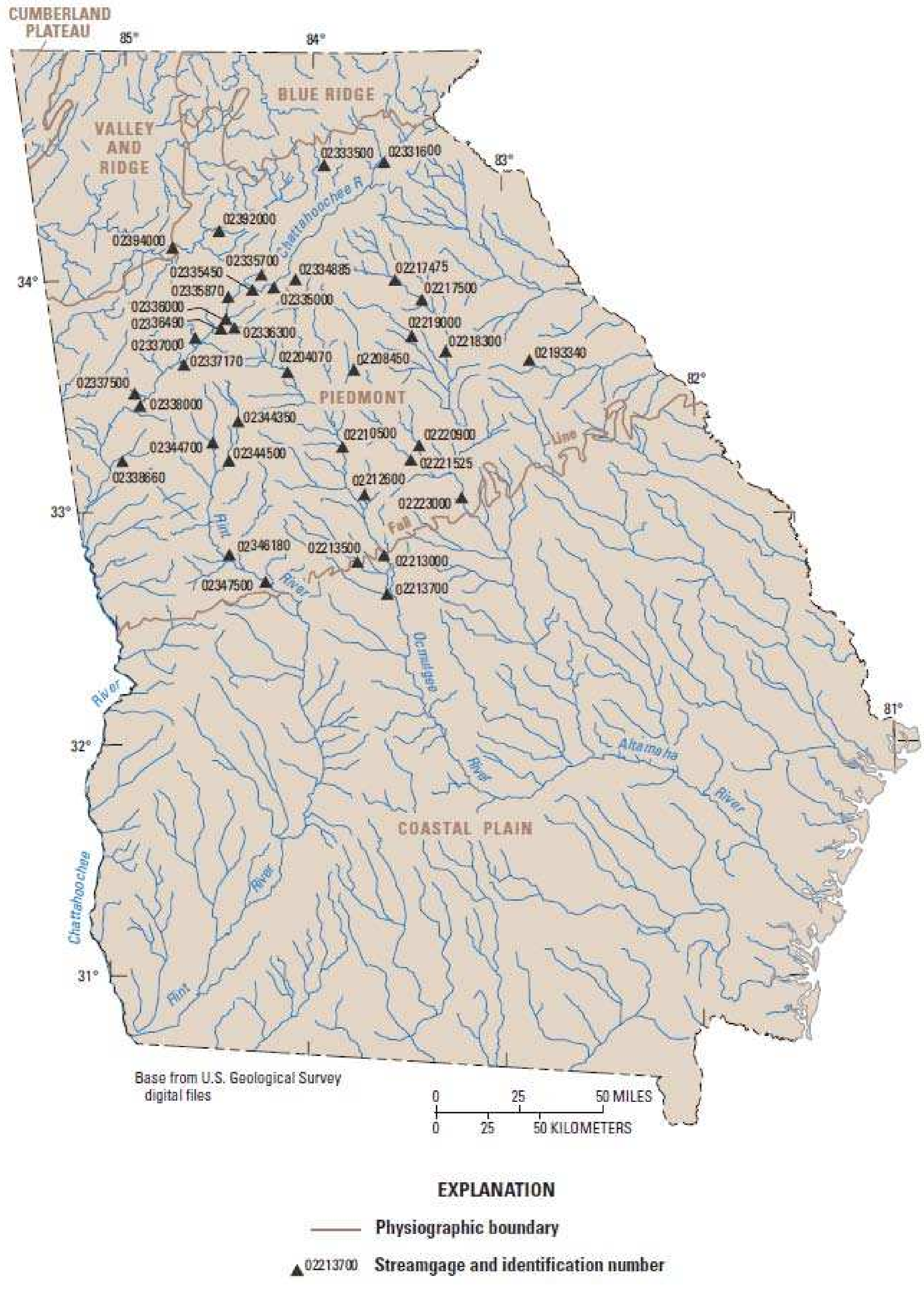

Figure 4.2: Locations of stream gages used in urban gradient analysis.

Table 4.1: Active U.S. Geological Survey stream gaging stations in the Upper Flint River Basin.

USGS ID	Station Name	Record Length (years)	Drainage Area (mi^2)
02344350	Flint River near Lovejoy, GA	23	129.09
02344500	Flint River near Griffin, GA	66	271.05
02344700	Line Creek near Senoia, GA	42	101.79
02347500	Flint River at US 19, near Carsonville, GA	66	1,868.49

Table 4.2: Urban gradient stream gage station information

USGS ID	Station Name	Response	Stage-Discharge Relationship	p†	R^2	Area: Total (mi^2)	Area: Imperm. (%)	Q_2‡ (cfs)	W_2§ (ft)	$W_2:D_2$♮ (ft/ft)
02193340	Kettle Creek near Washington, GA	Degrading	Exponential	3	0.9605	34.32	0.0	2,300	N/A	N/A
02204070	South River at Klondike Road, near Lithonia, GA	Stable	Double Exponential	5	0.9975	186.81	26.8	5,880	127	18.93
02208450	Alcovy River above Covington, GA	Degrading	Double Exponential	5	0.9518	183.30	5.0	2,470	146	17.91
02210500	Ocmulgee River near Jackson, GA	Stable	Double Exponential	5	0.9901	1,446.12	10.8	21,400	655	64.71
02212600	Falling Creek near Juliette, GA	Aggrading	Power	3	0.9885	72.93	0.0	2,600	N/A	N/A
02213000	Ocmulgee River at Macon, GA	Aggrading	Exponential	3	0.9617	2,270.97	7.9	27,800	375	23.05
02213500	Tobesofkee Creek near Macon, GA	Stable - degrading	Power	3	0.9846	186.81	1.6	4,540	125	12.30
02213700	Ocmulgee River near Warner Robins, GA	Stable	Double Exponential	5	0.9923	186.81	1.6	30,500	N/A	N/A
02217475	Middle Oconee River near Arcade, GA	Degrading	Power	3	0.9948	335.01	4.2	6,350	N/A	N/A
02217500	Middle Oconee River near Athens, GA	Wavy	Power	3	0.9802	397.41	5.0	7,270	172	14.94
02218300	Oconee River near Penfield, GA	Aggrading	Power	3	0.9836	951.60	4.6	13,500	470	41.76
02219000	Apalachee River near Bostwick, GA	Stable	Double Exponential	5	0.9920	177.45	3.4	3,690	106	23.71
02220900	Little River near Eatonton, GA	Degrading	Power	3	0.9839	269.10	1.0	5,600	N/A	N/A
02221525	Murder Creek below Eatonton, GA	Stable	Power	3	0.9645	192.27	0.3	3,200	N/A	N/A
02223000	Oconee River at Milledgeville, GA	Degrading	Power	3	0.9521	2,970.24	2.1	35,300	1130	100.54
02331600	Chattahoochee River near Cornelia, GA	Stable	Power	2	0.9902	320.97	1.7	12,400	200	16.88
02333500	Chestatee River near Dahlonega, GA	Degraded-stabilized	Power	3	0.9315	151.71	1.2	6,460	227	27.41
02334885	Suwanee Creek at Suwanee, GA	Degrading	Double Exponential	5	0.9723	46.80	12.4	1,660	252	95.07
02335000	Chattahoochee River near Norcross, GA	Stable	Power	3	0.9949	1,183.26	4.4	11,900	202	13.25
02335450	Chattahoochee River above Roswell, GA	Stable	Power	3	0.9785	1,231.62	5.1	9,980	238	24.10
02335700	Big Creek near Alpharetta, GA	Wavy	Double Exponential	4	0.9499	73.32	10.4	1,910	57	5.32
02335870	Sope Creek near Marietta, GA	Degrading	Double Exponential	5	0.9770	30.81	27.1	3,910	105	12.12
02336000	Chattahoochee River at Atlanta, GA	Aggraded-stabilized	Double Exponential	4	0.9655	1,465.23	7.7	17,000	283	22.31
02336300	Peachtree Creek at Atlanta, GA	Degrading	Power	3	0.9845	86.97	41.5	6,270	145	15.46
02336490	Chattahoochee River at GA 280, near Atlanta, GA	Stable	Power	3	0.9933	1,607.19	10.4	21,500	645	56.45
02337000	Sweetwater Creek near Austell, GA	Aggrading	Double Exponential	5	0.9894	240.63	11.6	4,060	96	10.07
02337170	Chattahoochee River near Fairburn, GA	Degrading	Power	3	0.9863	2,075.58	11.7	22,300	N/A	N/A
02337500	Snake Creek near Whitesburg, GA	Stable	Power	3	0.9810	35.49	2.4	2,900	N/A	N/A
02338000	Chattahoochee River near Whitesburg, GA	Stable	Power	3	0.9960	2,436.72	10.6	27,200	563	47.81
02338660	New River at GA 100, near Corinth, GA	Aggrading	Double Exponential	5	0.9902	126.36	2.5	3,140	253	44.14
02344350	Flint River near Lovejoy, GA	Degrading	Power	3	0.9926	129.09	22.9	4,690	N/A	N/A
02344500	Flint River near Griffin, GA	Stable/slightly wavy	Double Exponential	5	0.9681	271.05	14.2	4,430	323	50.65
02344700	Line Creek near Senoia, GA	Degrading	Double Exponential	5	0.9921	101.79	8.0	3,040	158	15.70
02346180	Flint River near Thomaston, GA.	Stable	Power	3	0.9958	1,231.62	5.0	N/A	N/A	N/A
02347500	Flint River at US 19, near Carsonville, GA	Stable	Power	3	0.9914	1,868.49	3.7	26,400	618	51.47
02392000	Etowah River at Canton, GA	Aggraded-large variance	Power	3	0.9648	619.71	1.9	11,600	438	52.56
02394000	Etowah River at Allatoona Dam, above Cartersville, GA	Stable	Double Exponential	4	0.9820	1,129.05	4.7	9,170	351	43.08

NOTES:
† Number of model parameters
‡ Two-year flood discharge, from USGS peak-flow files (annual duration series)
§ Width from field measurement at approximately two-year discharge
♮ From width and mean depth of field measurement at approximately two-year discharge

Chapter 5

Results

5.1 UFRB Gage Analysis

Specific gage analysis and analysis of raw stage data at specific discharges were performed on all the long term gages in the UFRB. Both analyses provided similar information. Results from both indicate that morphological adjustments have been occurring in the UFRB. However there was considerably more scatter when analyzing raw stage values. Either type of analysis can be interpreted semi-quantitatively. Due to the sometimes nonlinear nature of the adjustments, and often times intermediate wavy patterns, it is difficult to determine precise magnitudes and rates. However direction of adjustments and estimates of magnitude and mean rate can be obtained.

All of the rating type curves used to predict stage from discharge for the residual analysis had excellent fits; $R^2 = 0.99$ for all sites except Flint River near Griffin, GA (02344500) which had an $R^2 = 0.97$. The smaller sites, least drainage area and furthest upstream, Flint River at Love Joy (02344350), mainstem, and Line Creek at Senoia (02344700), large tributary, exhibited decreasing stages over the course of the record. The residual plots confirm the overall adjustments independent of discharge, whereas the constant discharge and specific stage plots illustrate how different stages of flow adjust in different directions and/or magnitudes. The two mainstem sites located lower in the basin station 02344500 and Flint River near Carsonville, GA (02347500) had somewhat different responses than the upper locations.

Flint River at Love Joy (02344350) is the furthest upstream gage in the basin. Results of the specific stage and constant discharge analysis at this station indicate mild degradation (slightly less than 0.5 feet) trend at all selected discharges (Figure 5.1)(Figure 5.2). However this site had more scatter of the data. The residual analysis supports the findings of this showing a slight degrading trend (Figure 5.3) In general, the response has been somewhat wavy with an overall tendency toward slight degradation. This site exhibited the most variable specific gage plot.

At Line Creek (02344700), adjustments were more pronounced above the median (55 cfs) discharge. Both discharge dependent analyses corroborate this finding (Figure 5.4) (Figure 5.5). The lowest discharge examined at this location (22 cfs) exhibited low magnitude scatter, with no distinct trend of bed adjustment, rather more of a scour and fill effect. The other selected discharges showed a slight degrading trend of approximately 0.5 ft over the record. Residual analysis confirms overall stage adjustments (Figure 5.6).

The next gage in the longitudinal sequence is Flint River near Griffin, GA (02344500). This gage exhibited a more variable response than the upper gages on the constant discharge and specific gage plots. The trend at this location is different from the upper locations as well. The lowest discharge selected (22 cfs) revealed a very minor aggrading trend of only about 0.2 ft over the record, whereas the other selected flows displayed a wavy response with no overall trend with the exception of the highest flow of 190 cfs, which revealed a minor degrading trend of about 0.5 ft (Figure 5.7) (Figure 5.8). The wave that appears around 1982 was further explored by obtaining discharge measurement notes from this period. The only explanation that could be derived from the notes, is that three relatively dry years could have led to sediment accumulation in the gage reach. When flows returned to normal, stored sediment was then transported downstream. From the residual analysis (Figure 5.9), it appears fairly stable with a low magnitude wavy pattern. The lack of an overall trend in residuals could be the result of conflicting trends on each end of the discharge spectrum (i.e. aggradation at lower flow and degradation at moderate flows) canceling out the effects of each other.

Station 02347500 is a considerable distance downstream of the other gages (about 65 miles from the previous gage) and is below the Pine Mountain area. Constant discharge and specific gage analysis were performed for flows at and below the median (approximately 1300 cfs) discharge (over the record). Both indicate there has been little shifting of the rating (Figure 5.10) (Figure 5.11) over the recorded period. The constant discharge has the appearance of very slight degradation, whereas the specific stage shows more of a wavy pattern, possibly indicative of a dynamic equilibrium condition. The difference in response could be due to the amount of data points available for the respective analysis. Residual analysis at this location reveals the most stable relationship of the Flint gages. However variability in the residual plot appears to increase around 1975 for an unexplainable reason (Figure 5.12). The overall response of the residuals appears to be relative stability with associated scatter of the data. Possibly due to scour and fill depending on timing of measurement (i.e. rising or falling limb or time since storm event).

5.2 Urban Gradient Analysis

Results of the urban gradient analysis provided little insight into systematic adjustments in W:D ratio to impervious surface cover. Results of the linear regression were insignificant ($R^2 = 0.03$ and $p = 0.243$). Drainage area was a better predictor of W:D ratio but was still weak and insignificant at alpha = 0.10. Adjustments in the W:D ratio may manifests in opposite directions depending on boundary material. If channels adjust laterally often there will be an increase in the ratio of channel width to depth. However it is also possible that the channel will respond by incising the bed, thus increasing the W:D ratio. The information that was gained came from the residual analysis of the stage discharge data. Although it was not directly applicable to the LTS objective, it further supported that many stream in the Georgia Piedmont are dynamic and are adjusting in various ways.

To test whether stream response was related to impervious surface cover a one-way analysis of variance (ANOVA) was performed. The response, as inferred from the slope of residual analysis was categorized based on the dominant trends of: aggrading, stable, degrading. The other categories (wavy and dual response) were excluded from this analysis because of small sample sizes and more than one trend was observed. Results indicated that there was not a significant ($p=0.441$, $F=0.9923$) difference in the mean percent impervious cover for the different type of observed responses.

Analysis of gage data indicates that streams in the Georgia piedmont have been adjusting over their recorded periods. There was no apparent systematic trend in channel response with impervious surface cover (Figure 5.51)or drainage area (Figure 5.52). Streambed responses were varied with no identifiable variable(s) responsible for the specific type of response (Figure 5.13).

Eleven of the thirty-seven gages analyzed showed distinct trends of degradation, as inferred from declining water surface elevations. The magnitude of the degradation was variable as was the general form of response. Some gages exhibited a linear trend of degradation (Figure 5.14) and (Figure 5.15) others had a somewhat wavy response or breaks in the slope of the trend. For example, Peachtree Creek at Atlanta, GA (Figure 5.16), Sope Creek near Marietta, GA (Figure 5.18), and Line Creek near Senoia, GA (Figure 5.17) all demonstrated the break in slope response, they degrade for a while, then level off and begin degrading again. Figures (Figure 5.19), (Figure 5.20), (Figure 5.21), and (Figure 5.22) represent degrading sites with shorter periods of record where trends other than general degradation were difficult to determine. The two largest sites (greatest drainage area) that experienced degradation were the Chattahoochee River near Fairburn, GA (Figure 5.23) and Oconee River near Milledgeville, GA (Figure 5.24), which are in the vicinity of a sand pumping operation and downstream of a large dam respectively.

Only six of the thirty seven sites had a trend of overall aggradation. For this study all of the aggrading trends were in general of lower magnitude than the degrading trends. Ocmulgee River at Macon, GA (Figure 5.25) was the exception to this, aggrading approximately three feet until the mid 1990's then starting to evacuate and degrade. Of the other sites that aggraded Sweetwater Creek near Austell, GA (Figure 5.26) had a near linear trend with the exception of a large increase of about one foot and subsequent decrease around 1965. As with degradation, some of the aggrading sites exhibited a slight wavy pattern while aggrading (Figure 5.27) and (Figure 5.28) while one had a more pronounced wavy pattern (Figure 5.29). The Etowah River at Canton, GA (Figure 5.30) was aggrading steadily until about 1980, thereafter variance increases and any discernable trend disappears.

Fourteen of the gage locations had relatively stable ratings over the course of the record. Some of these exhibited substantial stability (Figure 5.31), (Figure 5.32), (Figure 5.33), (Figure 5.34)), lacking the scatter associated with many of the residual plots. The Etowah River below Allatoona Dam (Figure 5.35) exhibited similar stability only with greater amounts of scatter. The other pattern observed was general stability. Most of these sites showed more variability in the residuals but maintained a near flat slope or a very small wavy pattern (Figure 5.36) (Figure 5.37)(Figure 5.38)(Figure 5.39)). Plots that demonstrated very slight adjustments over the period of record were also included in this group (Figure 5.40), (Figure 5.41), (Figure 5.42), (Figure 5.43), (Figure 5.44)

Only one location displayed a substantial wavy pattern possibly indicating waves of sediment passing the gage (Figure 5.45). Many sites had small low magnitude waves, but Big Creek near Alpharetta, GA showed a systematic trend, with degradation occurring for about 15 years then followed by a rapid aggradation period, followed by about 15 years of relative stability which rapidly degraded again to a lesser degree, and is aggrading once again. Two other sites are included in this category (Figure 5.46), (Figure 5.47), however their wavy patterns appear more random and not as well defined.

A few of the gages had variable responses that made them difficult to put in a single response category. For example, stage residuals for the Chestatee River near Dahlonega, GA (Figure 5.48) start out at two feet above what would be expected from the stage discharge relationship, it appears to degrade approximately 2 feet from 1940 - 1960 then the relationship is stable around zero up to the present. A nearby tributary, Yahoola Creek, located upstream of this gage has a history of gold mines and associated sediment from hydraulic mining. This could have contributed to the greater than expected stage and subsequent degradation. At the Chattahoochee River at Atlanta, GA (Figure 5.49) there was aggradation from about 1920 - 1940, and then remained stable up to the present. Another station with a dual response was Tobesofkee Creek near Macon, GA (Figure 5.50). This site was stable until around 1990 when it abruptly began to degrade. Given this station is located downstream of an impoundment, there could have been a change in the operation.

Although this analysis did not provide direct evidence to extrapolate to the UFRB, it did confirm that many piedmont streams of various sizes are adjusting in various directions and magnitudes. For this study average impervious surface was not a significant variable to explain the observed responses. Some of the issues that could be affecting this analysis will be discussed later.

5.3 Channel Evolution Assessments

Channel evolution models were used to support results of gage data analysis as well as explore morphological adjustments in two large tributaries of the Flint River. Determining the amount of bank erosion and dominant fluvial processes can help in determining the actual boundary that is adjusting. If entire reaches are experiencing mass failure, it is possible that the width adjustment could cause the appearance of degradation in the gage records. If beds are armored with cobbles and boulders, and devoid of fines, it is likely degradation has occurred and the most adjustable boundary will be the channel banks. Even though widening was observed at many of the sites, it is hard to say which morphological or hydrological variable adjusted sufficiently to appear as degradation in the long term gage analysis. This method also allowed for the correlation with land use in the vicinity of the reach to be compared with stage of channel evolution. This was to test the hypothesis that streams may adjust initially on a reach scale in the vicinity of a disturbance or land cover that alters the delivery of water and/or sediment. The most upstream Flint River RGA site (FLT0) was in an area dominated by urban land cover. Two reaches assessed above this reach were nearly identical in processes and appearance, thus FLT0 is used to represent the extreme upper portion of the basin. The bed and banks of FLT0 had large pieces of concrete (rip-rap) protecting them (Figure 5.53). The channel at this site was deeply incised and the bed was composed mostly of cobbles and boulders, possibly placed there for bed protection. In terms of its stage of channel evolution it has the appearance of a III, however this is due to human interjection. It appears that degradation occurred, banks began to fail and at this point measures were taken to stabilize the channel. In reaches that have anthropogenic modifications it is difficult to determine future adjustments. It is likely that the reach will remain stable and the energy will be translated to downstream reaches.

The next location (FLT1) was about 2.5 river miles downstream. This area is also dominated by urban area. Between these two reaches, it takes on a more wetland character. Channel response was very different at this site, the bed was dominated by sand and had alternating bars forming an incipient meandering pattern (Figure 5.55), and banks were low compared to best estimate of normal low water (Simon, 2008, Written Communication). A small terrace was also visible on the right bank. This helps support the stage V designation, which is often viewed as a channel with-in the old channel (Simon, 1989). It is unlikely this reach will fully recover to a stage VI, because of the large amount of urbanization, future disturbances are likely. Two miles downstream, at FLT2, the channel exhibited deep sluggish flow with low banks and appeared relatively undisturbed, Stage I. In this area the channel had more of a wetland appearance but was still single threaded.

The next site (FLT3) is the uppermost USGS gage on the Flint and approximately ten miles downstream of the last assessment. The Flint is flowing through wetlands up to this point and beyond. This site exhibited slight decreasing stage from gage data analysis. Up stream of the assessed reach was a short section of exposed boulders. The reach assessed had a sand bed with low left bank and higher steeper right bank. There was a small area around the bridge that had experienced a large mass wasting event but was not characteristic throughout the entire reach, this site resembles stage III, with some down cutting and steepening banks. Fluvial erosion at the bank toe was the dominant process in this reach (Figure 5.56) A few locations between this site and the next were visited to perform RGAs but were wetland/anastomosing areas with multiple channels, which this particular CEM is not appropriate for. The location of the multichanneled areas may be loosely associated with floodplain width and distance of the main channel from the edge of the floodplain or valley. These areas of wetland /multichannels dominated the accessible locations all the way down to FLT4 where the next streamgage is located. Only one location between here flowed in a single channel, and this site had quite a bit of human modifications of the stream bank.

The next site (FLT4) is located at the next USGS stream gage in the longitudinal sequence (02344500) approximately 15 mi downstream. Here, as with most others, the flow is deep and sluggish, however this reach exhibited extensive mass wasting on both banks. Most failures along the right bank appeared to be fairly old with large amounts of vegetation covering the failed blocks (Figure 5.57) that are now protecting the bank toes. Large portions of the left bank were failing but appeared to be a combination of mass wasting and fluvial erosion (Figure 5.58).The bed is very heterogeneous, with small areas of exposed rock, some areas of cohesive clay and other areas of unconsolidated sand and fines. From gage data analysis, this site exhibited only slight shifting. From the constant discharge and specific stage plots, the lowest and highest flows demonstrate the hypothesis that slab failures displace water at low flow but the increased width above the slabs allow flows above this level to spread out more and reduce stage. This is largely anecdotal due to the poor linear fits of the lower and upper flows ($R^2 = 0.16$ and 0.43 respectively).

Another location was visited about 2 miles downstream of the previous location. At this site, the Flint had returned to a wetland like state containing a single channel. This site looked undisturbed and exhibited no indications of disturbance. Banks were very low with shallow angles and appeared to be a stage I (Figure 5.54). Downstream of this site the Flint takes on a new character. Large areas of shoals and exposed rock are the norm with gradients increasing. I believe this portion of the Flint (Pine Mountain area) can be viewed as the sediment transporting section (Schumm, 1977). With increased gradients and greater valley control, influencing concentrated flow, transportation of sand and finer material is favored at most stages. RGAs were performed at two sites in this section of the Flint but will not be included. Although the channels had broadened and lost much of the valley control, there was still considerable bedrock on the bed (Figure 5.59) which would inhibit adjustments in the evolutionary sequence (Simon, 1989). Large amounts of mass wasting (Figure 5.60) were observed but with restrictive beds the evolutionary sequence would differ.

Line Creek is one of the larger tributaries to the UFRB. It originates just south of a heavily urbanized area of Atlanta. It has a similar character to the Flint, with a single channel giving way to multiple channels and back, with much of the stream being low gradient and having a wetland character. The first RGA performed on line creek was the uppermost site (LINE 1) about 10 miles downstream from the source. This location had a wetland character with low banks and shallow slope. This site was largely forested and appeared undisturbed and was a stage I (Figure 5.61). The next site, LINE 2, was about 6 mi. downstream from the previous site. Land use at this site was largely low density residential on the left bank with a lesser degree on the right. This site exhibited considerable instability on the banks with residential landscaping. Moderate amounts of mass wasting were observed in this reach (Figure 5.62). This reach most closely resembled a stage IV, with evidence of initial width increases. The next site in the longitudinal sequence (LINE 3) was located near Peachtree City. This site has a large amount of residential land use as well as large expanses of impervious cover and is unique because it is located downstream of a small pond. The effects of the pond on sediment retention were quite noticeable. All the sites above this location had beds composed mostly of fines and sand. The bed of this site was composed almost entirely of bedrock and large cobbles and boulders (Figure 5.63). There were large riparian areas on both banks and no evidence of lateral adjustments. This site appeared to be an undisturbed stage I. The last site (LINE 4) was located about 15 mi downstream at the USGS stream gage location (Line

Creek near Senoia, GA). The upstream portion of this reach was deeply incised (Figure 5.64) with mass failures prevalent on the left bank. The right bank was not as steep and appeared more stable. From the gage data analysis this location showed a slight degrading trend. This site appears to be a stage IV, exhibiting high banks and failed material with entire root wads and trees.

Potato Creek was the other large tributary to the Flint that was explored using RGAs. This stream begins further south than Line Creek, originating around the Griffin area. It is similar in physical setting and exhibits the same wetland character in its upper reaches. This basin has less development than the Line Creek basin.

The first location on Potato creek (PT1) is about three miles downstream of its headwater tributaries. Land cover around this site is largely forested and wetlands. The stream has low banks and a bed composed entirely of sand (Figure 5.65). It was hard to determine if this reach was an undisturbed stage I or a recovered stage VI. The appearance of fines deposited on the banks and sandy bed better supports a stage VI. However, no terraces were observed. The next site was about a 1.5 mi downstream of the previous location. This site became deep and sluggish and has more of a wetland appearance (Figure 5.66). Banks were low and heavily vegetated and appeared undisturbed, stage I. Three miles downstream from here the channel was more like a swamp with multiple channels and large vegetated bars dissecting the flow and did not fit an evolutionary sequence (Figure 5.67). PT4 was the next site; it is located about 2 mi below a fairly large mill dam (approximately 20 ft high) (Figure 5.68). This site lost much of the wetland character. It had a single channel that was somewhat entrenched and had a bed dominated by cobble and gravel (Figure 5.69). This site was a stage III exhibiting moderate entrenchment and bank steepening. Downstream of this site was PT5 which was immediately downstream of another old mill dam (Figure 5.70). The right side (looking downstream) of the dam had a hole about one forth the width of the channel. There was a large depositional island below here that split the channel in half. Further down there was moderate development on the stream banks. It was somewhat entrenched with copious amounts of fines deposited on top of more coarse bed material, it most closely resembled a stage III. As with the lower Flint sites, Potato Creek also enters an area with greater bedrock control where adjustments would not follow the expected evolutionary sequence. However at the Potato Creek site furthest south, about 1.5 mi above confluence with the Flint River, much of the bedrock had been covered in sand and mass wasting was prevalent throughout. This reach was deeply entrenched as well (Figure 5.71). Mass wasting was the dominant process in this reach probably due to the presence of bedrock in the stream bed.

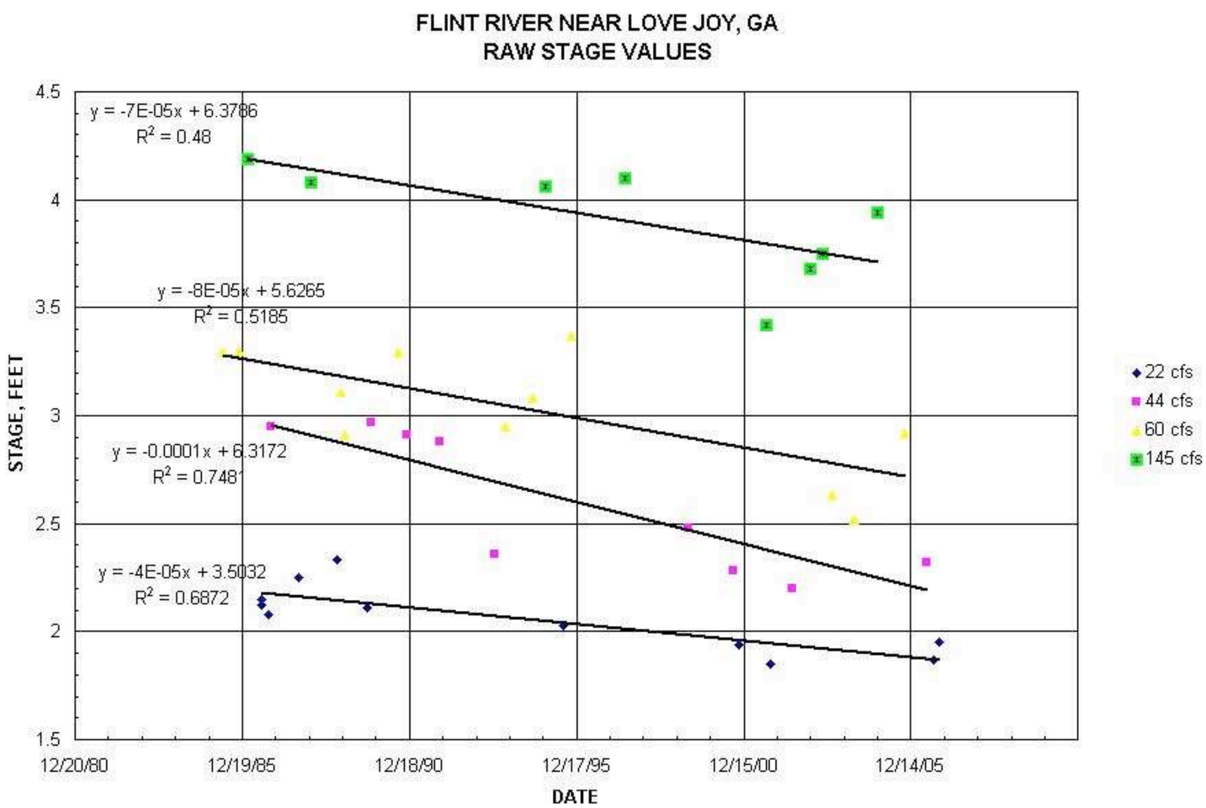

Figure 5.1: Analysis of raw stage data at constant discharge conditions for Flint River near Lovejoy, GA (USGS Station 02344350)

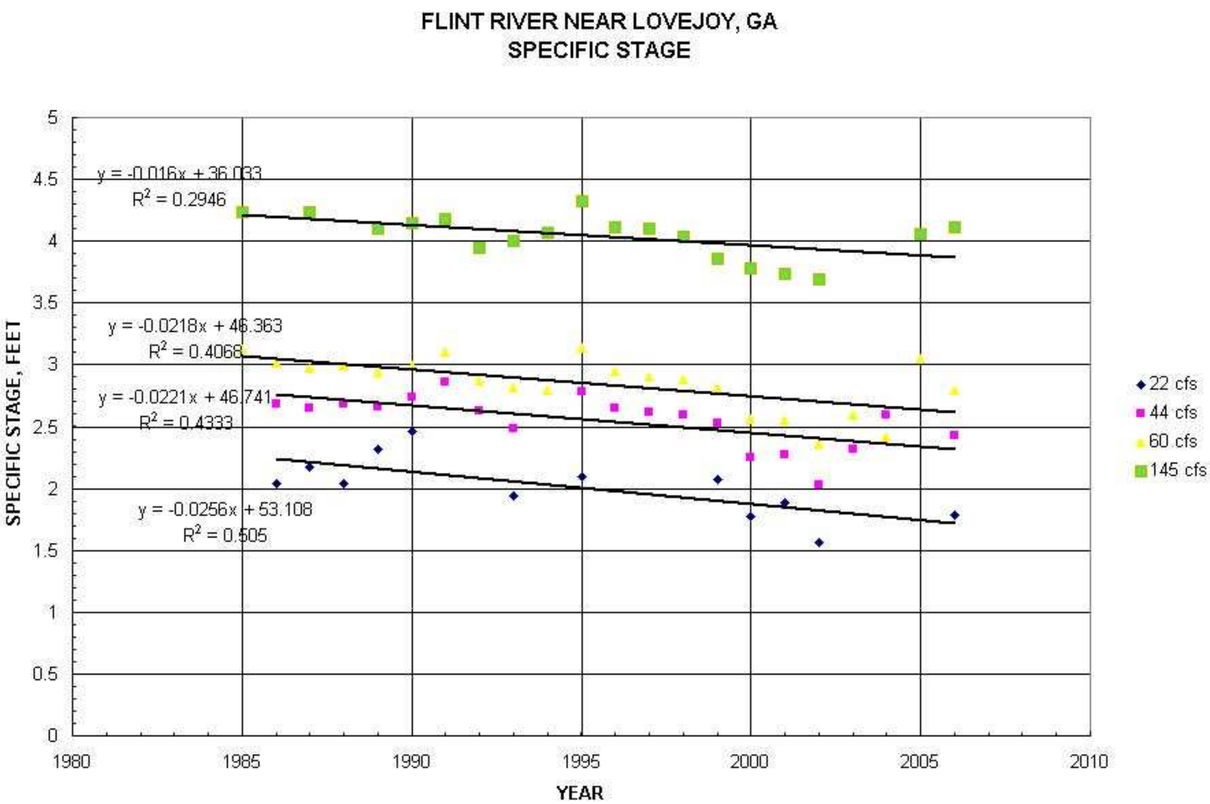

Figure 5.2: Specific stage analysis for Flint River near Lovejoy, GA (USGS station 02344350)

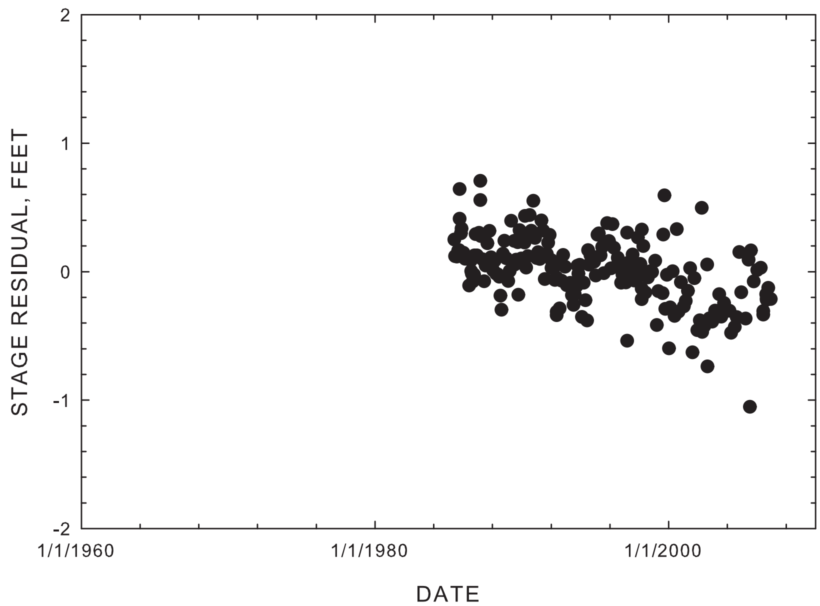

Figure 5.3: Residual analysis of inverse stage-discharge relation for Flint River near Lovejoy, GA (USGS station 02344350)

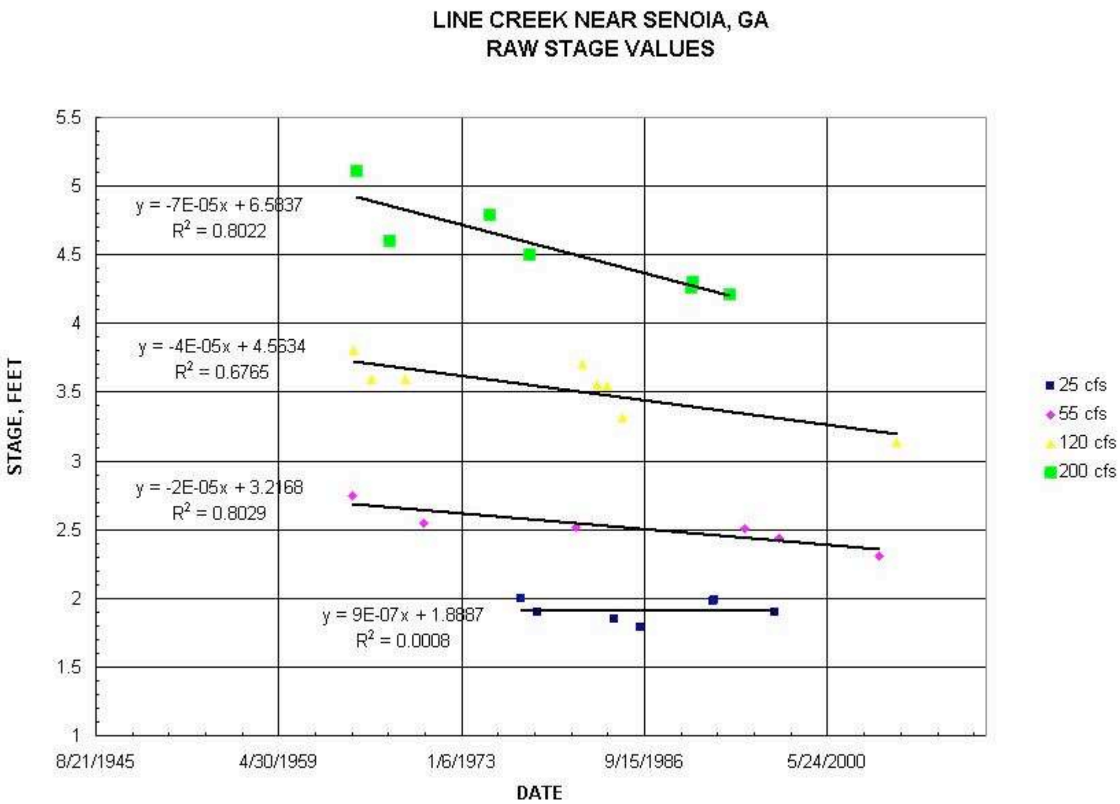

Figure 5.4: Analysis of raw stage data at constant discharge conditions for Line Creek near Senoia, GA (USGS station 02344700)

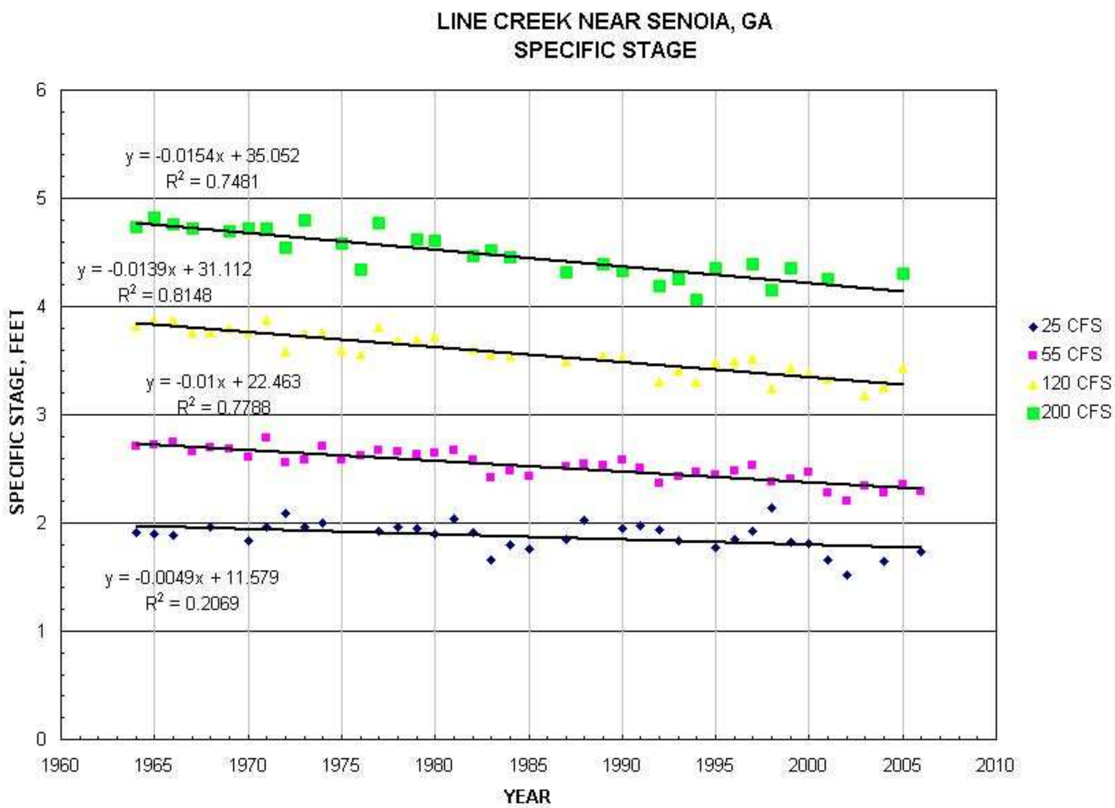

Figure 5.5: Specific stage analysis for Line Creek near Senoia, GA (USGS station 02344700)

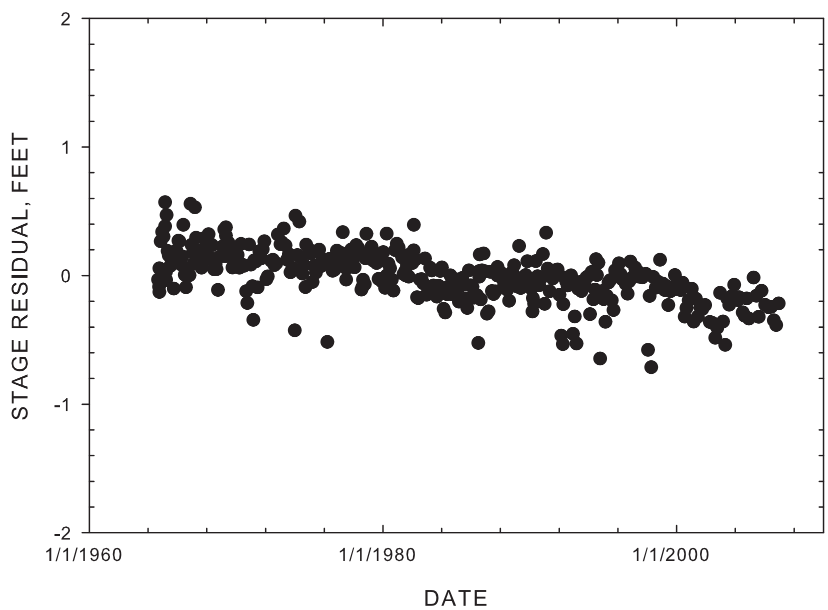

Figure 5.6: Residual analysis of inverse stage-discharge relation for Line Creek near Senoia, GA (USGS station 02344700)

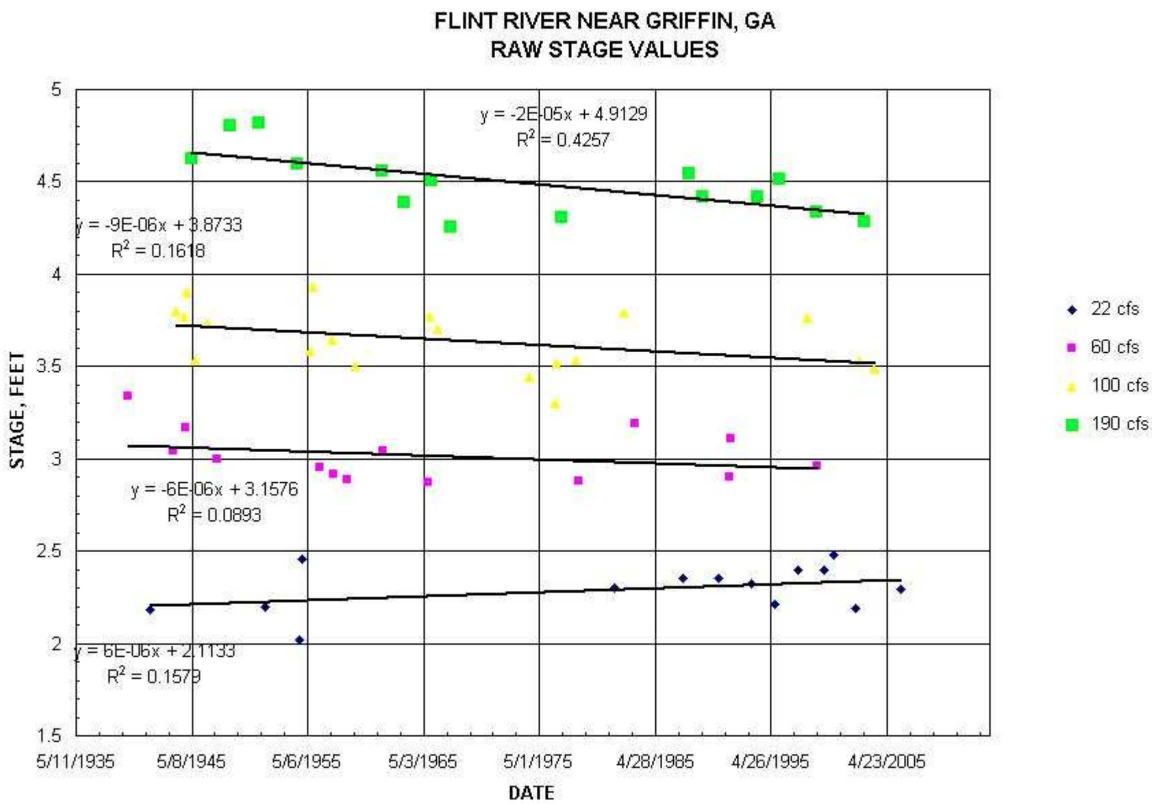

Figure 5.7: Analysis of raw stage data at constant discharge conditions for Flint River near Griffin, GA (USGS station 02344500)

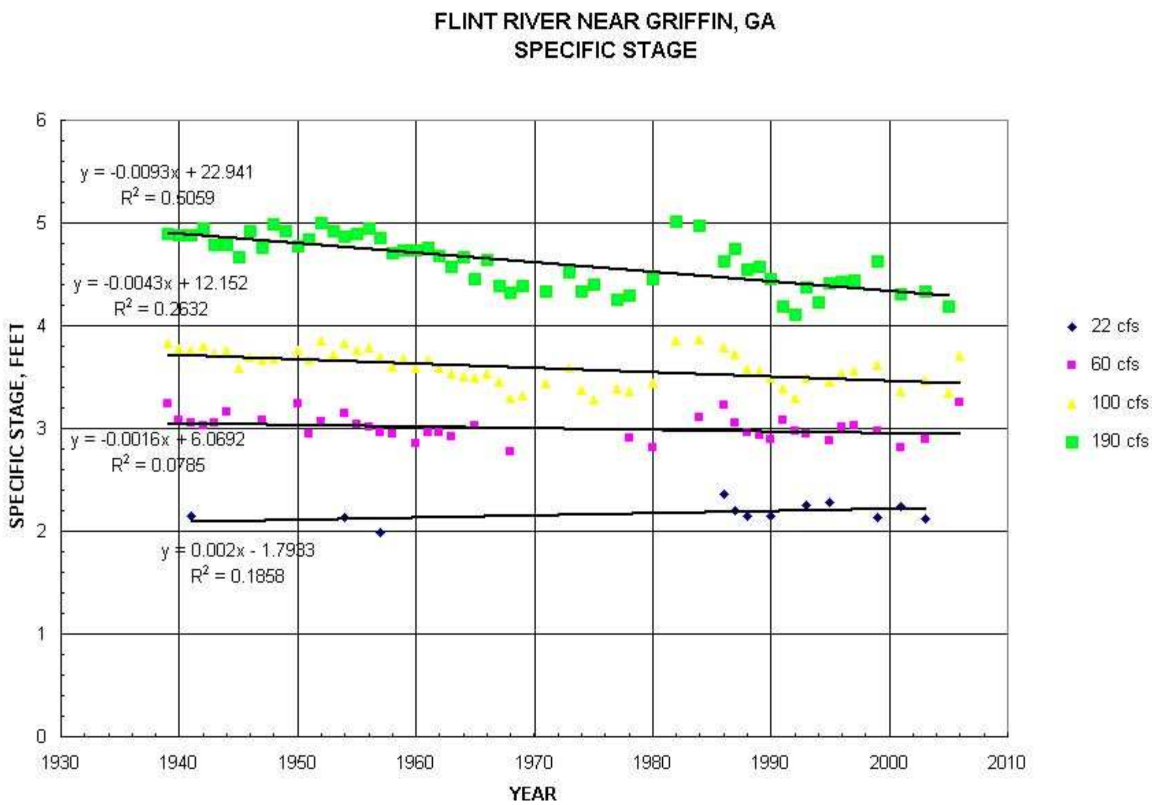

Figure 5.8: Specific stage analysis for Flint River near Griffin, GA (USGS station 02344500)

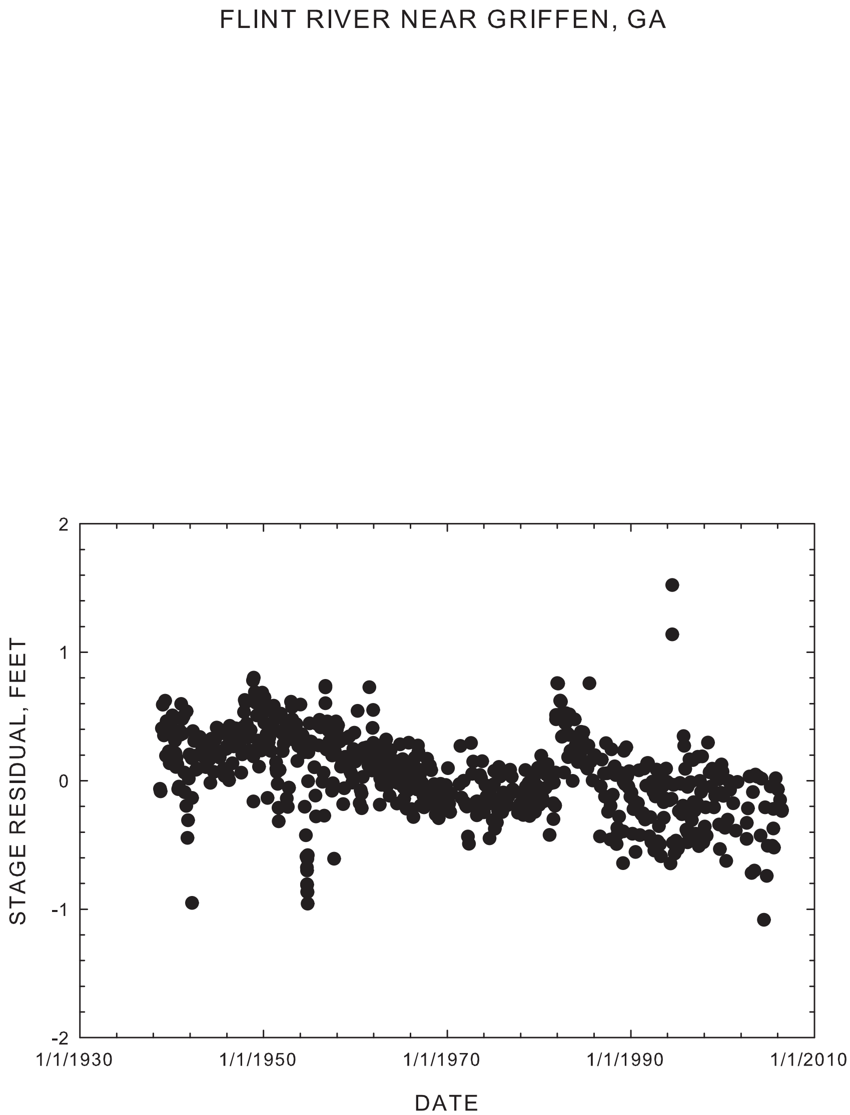

Figure 5.9: Residual analysis of inverse stage-discharge relation for Flint River near Griffin, GA (USGS station 02344500)

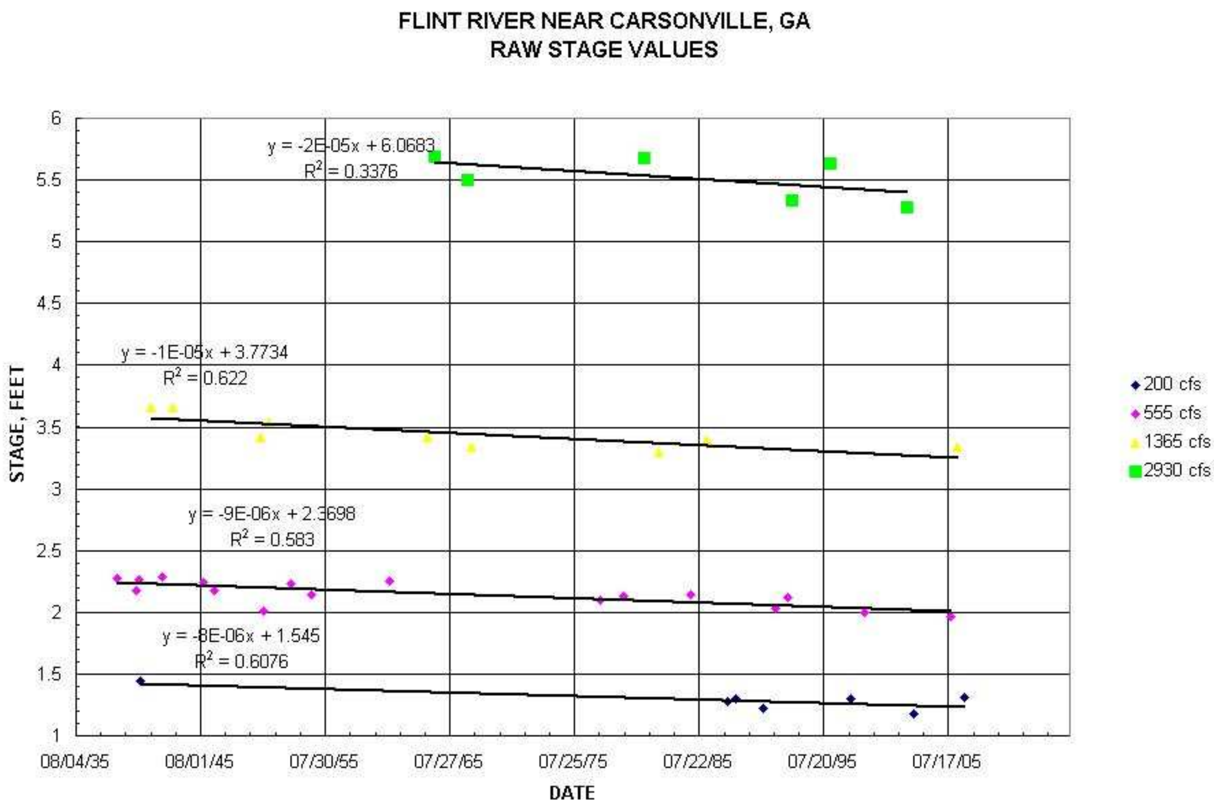

Figure 5.10: Analysis of raw stage data at constant discharge conditions for Flint River near Carsonville, GA (USGS station 02347500)

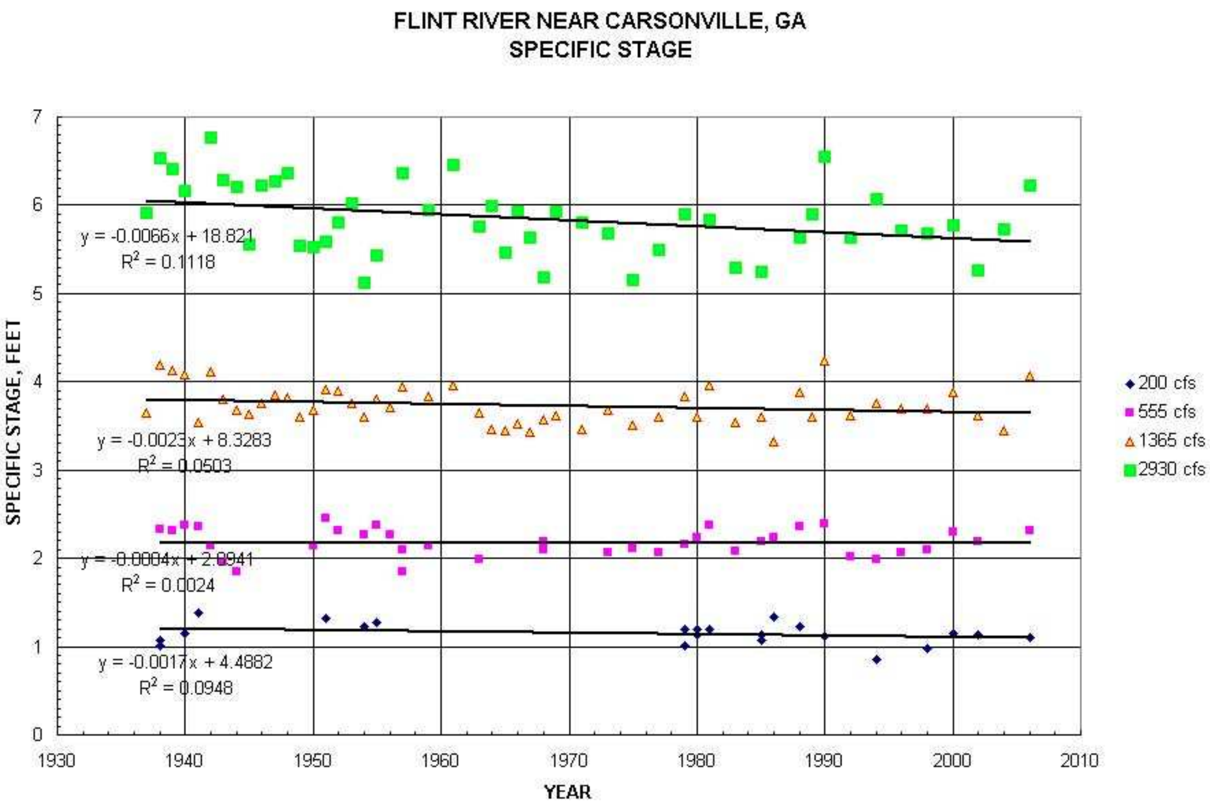

Figure 5.11: Specific stage analysis for Flint River near Carsonville, GA (USGS station 02347500)

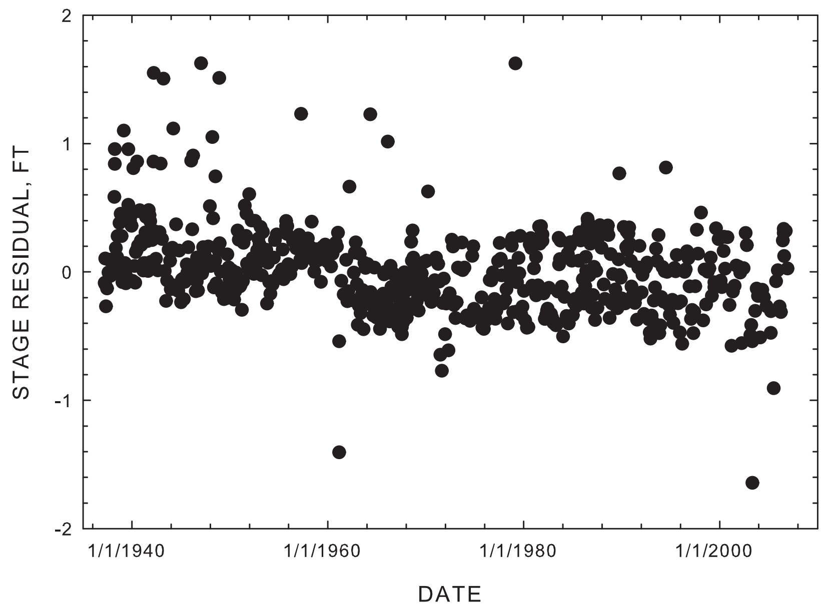

Figure 5.12: Residual analysis of inverse stage-discharge relation for Flint River near Carsonville, GA (USGS station 02347500)

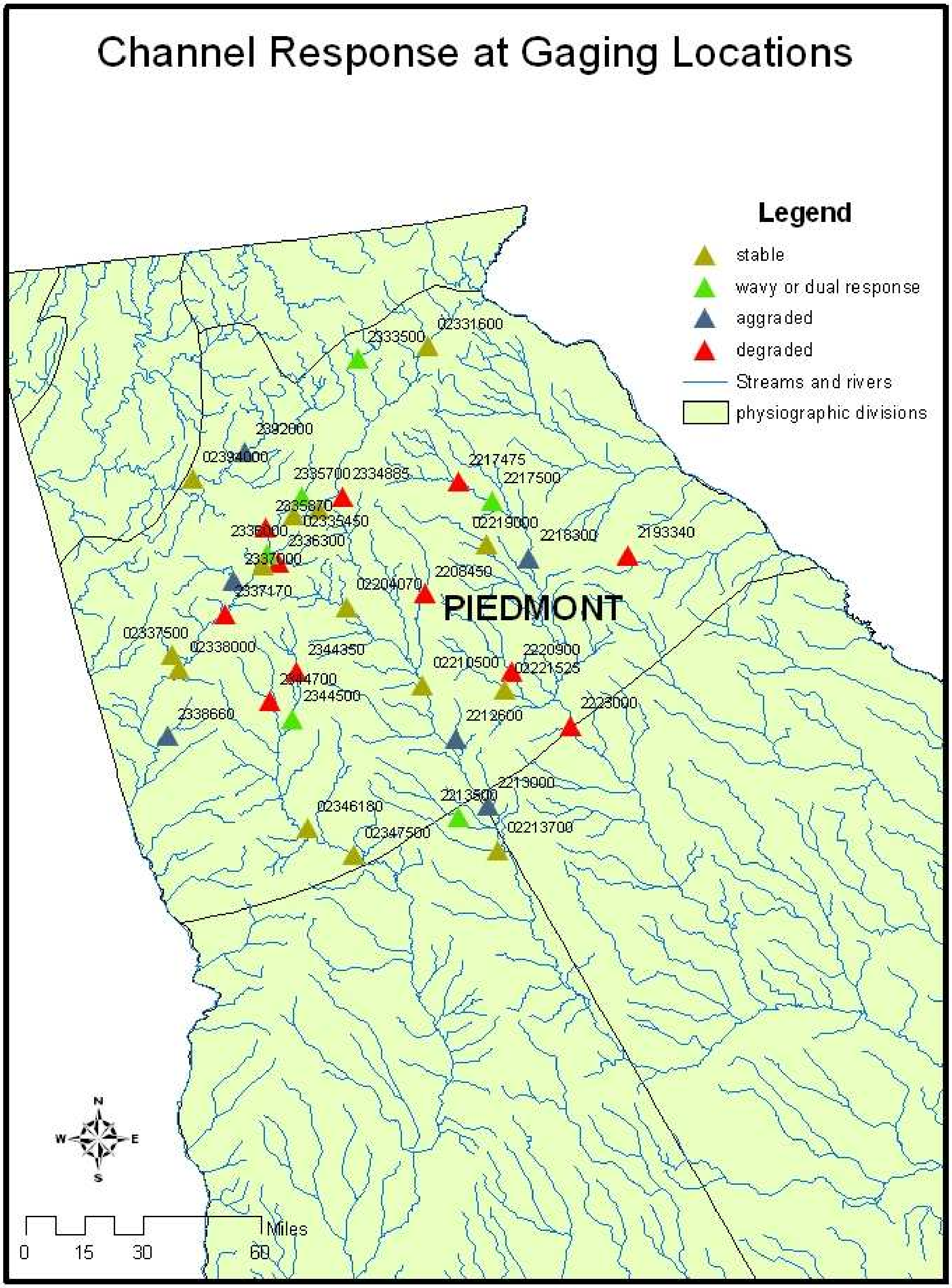

Figure 5.13: Spatial distribution of streamgages and the associated response inferred from residual analysis

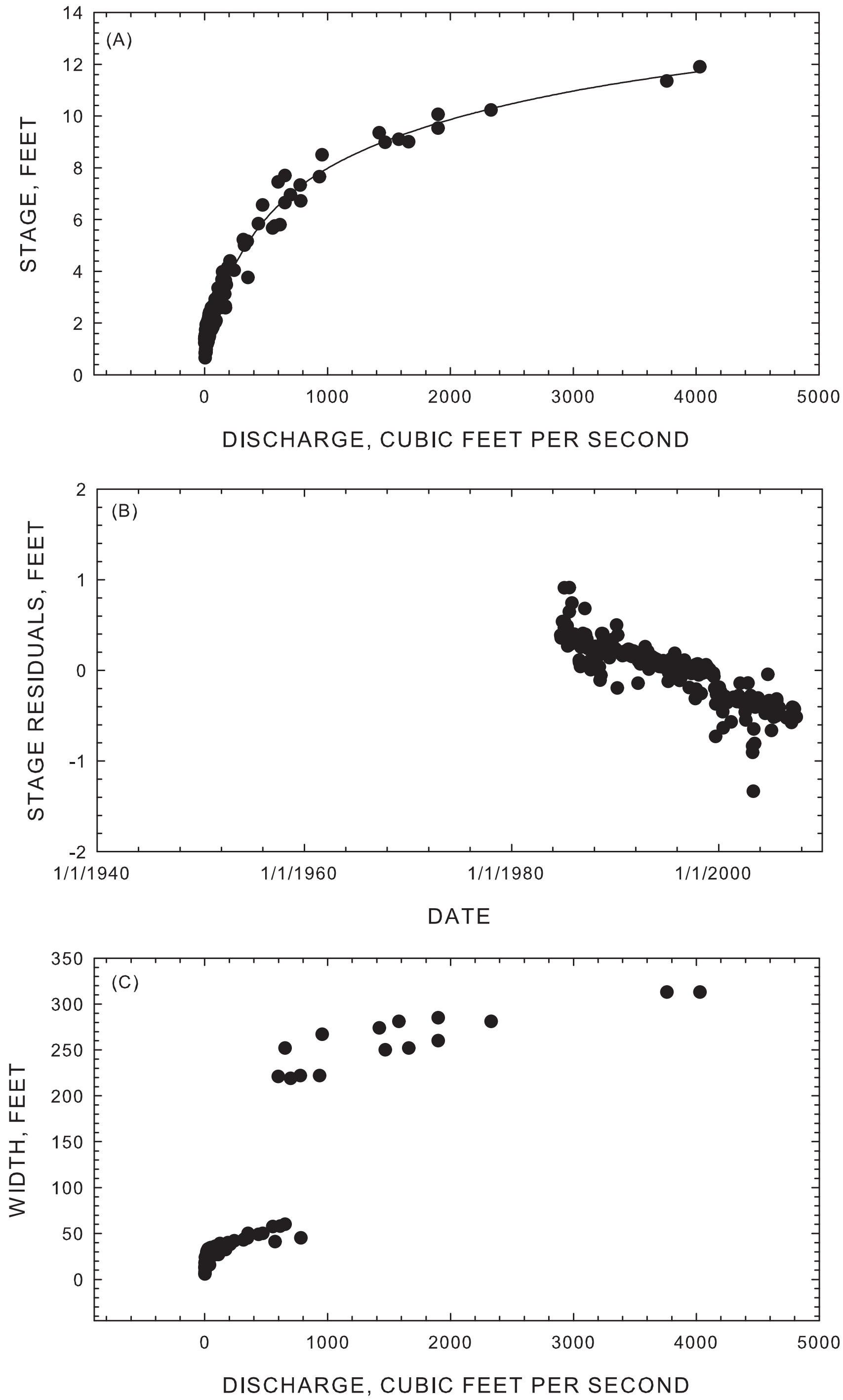

Figure 5.14: Geomorphic analysis of stream gage data for Suwanee Creek at Suwanee, GA (Station number: 02334885) (A) stage and discharge; (B) stage residual time series; (C) width and discharge

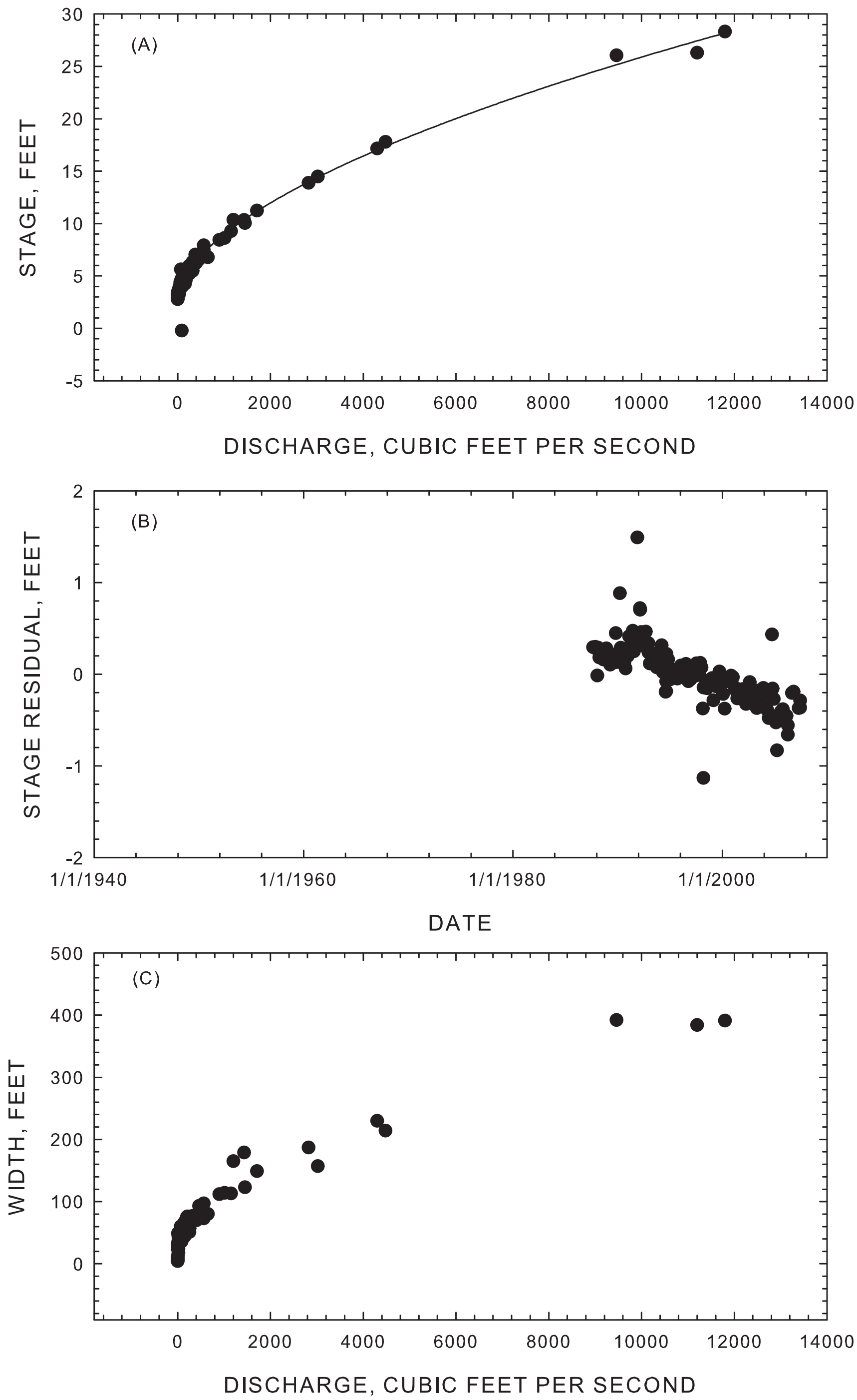

Figure 5.15: Geomorphic analysis of stream gage data for Little River near Eatonton (Station number: 0220900): (A) stage and discharge; (B) Time series of stage residuals; (C) width and discharge

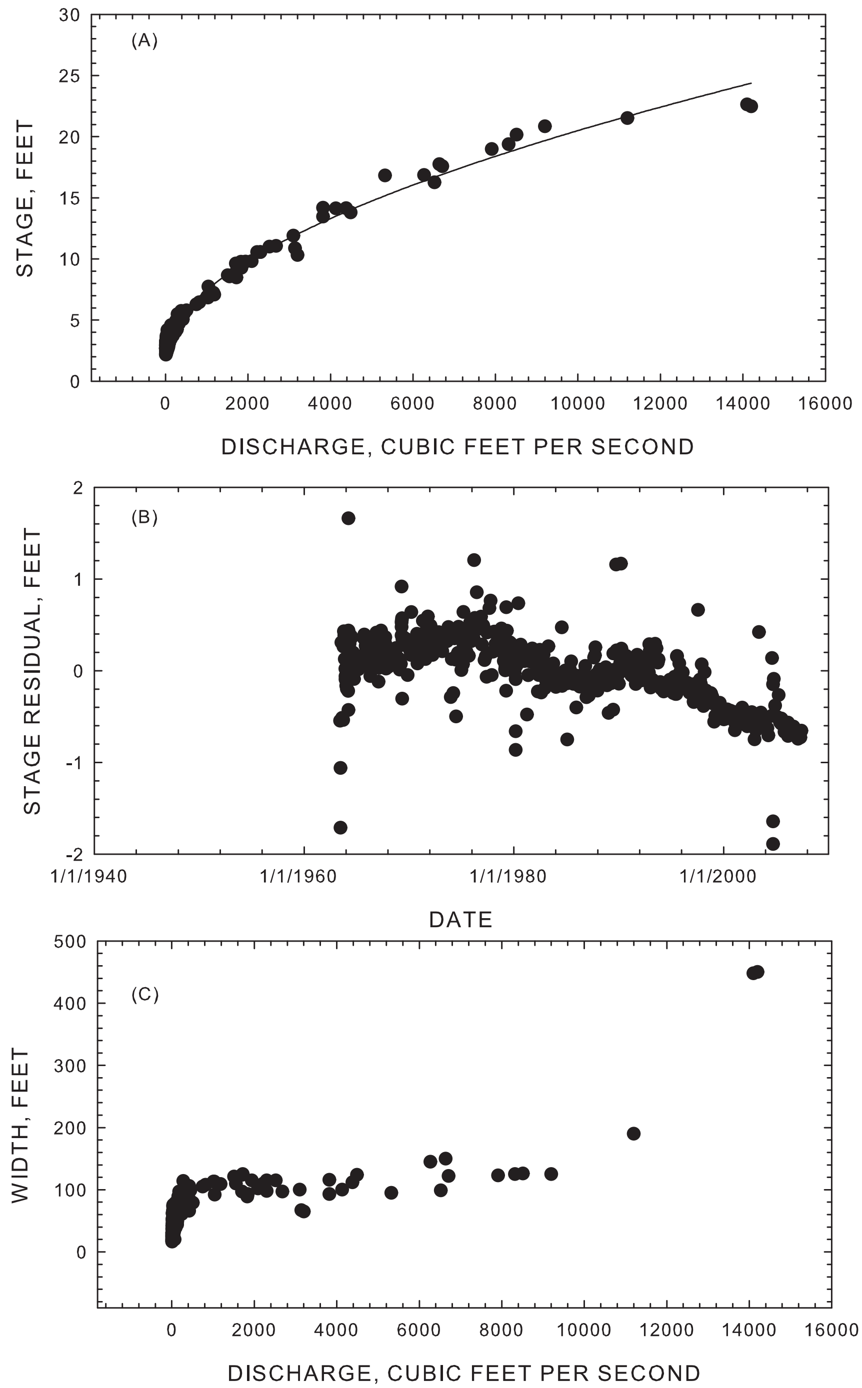

Figure 5.16: Geomorphic analysis of stream gage data for Peachtree Creek at Atlanta, GA (Station number: 02336300): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge

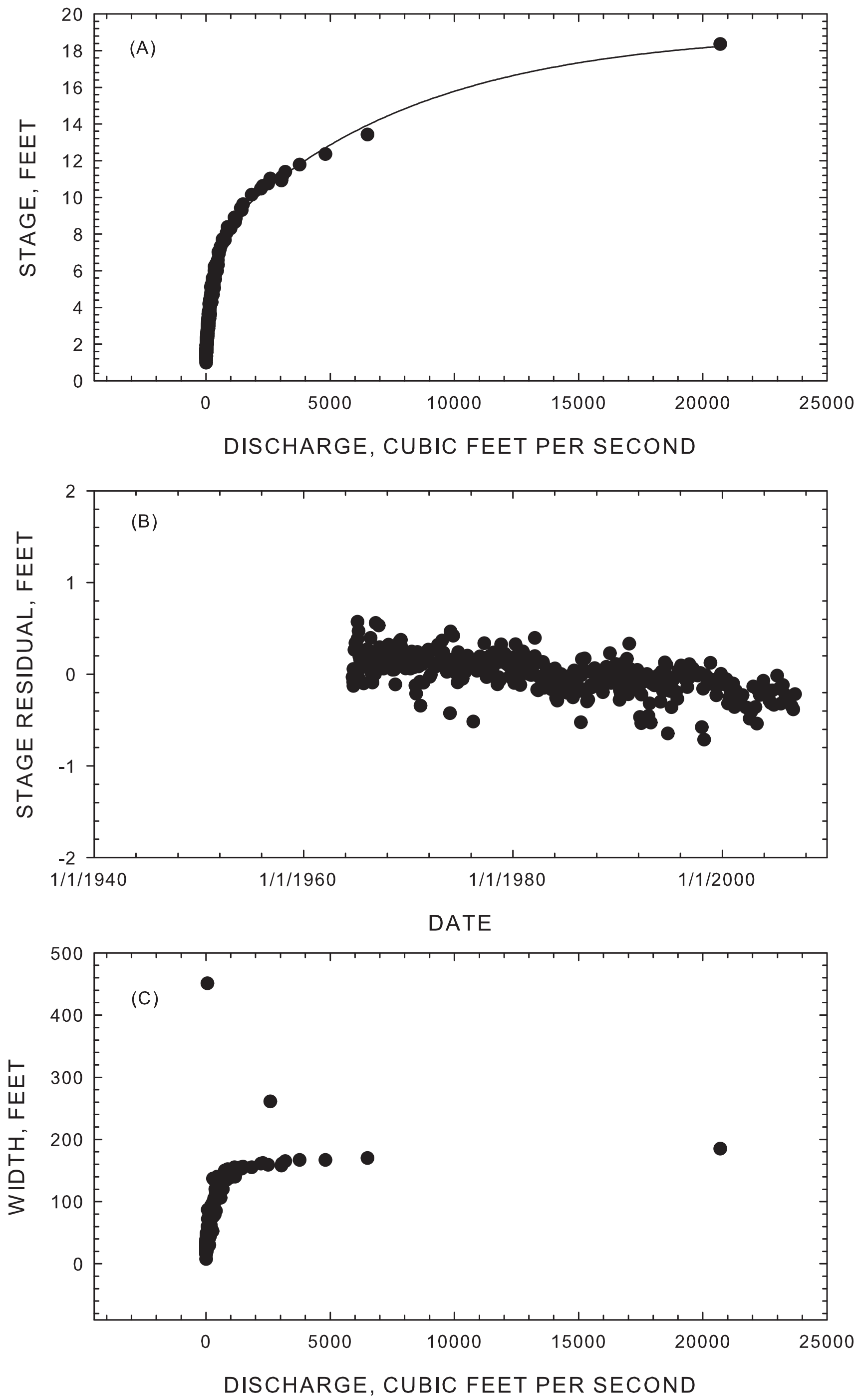

Figure 5.17: Geomorphic analysis of stream gage data for Line Creek near Senoia, GA (Station number: 02344700): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge

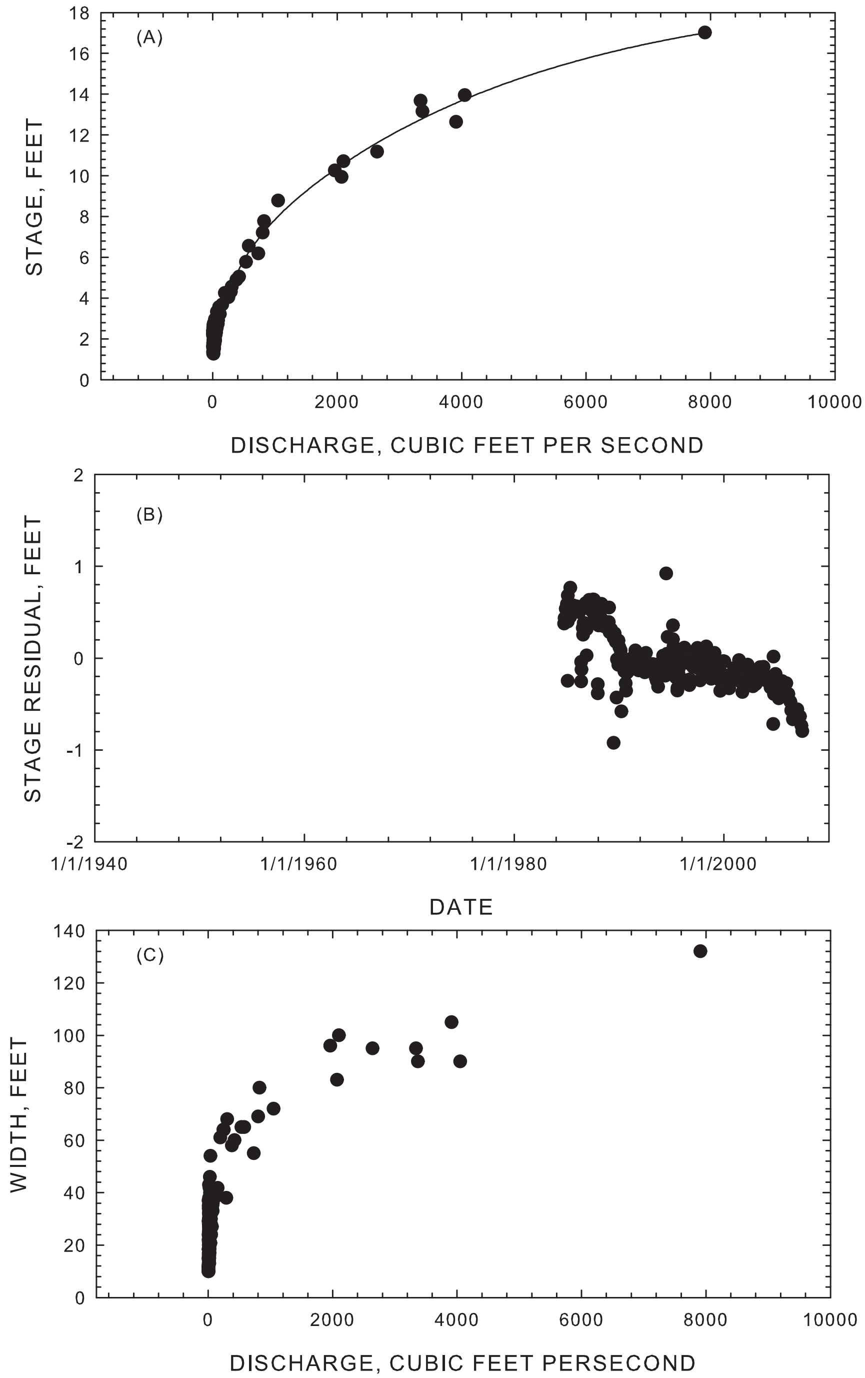

Figure 5.18: Geomorphic analysis of stream gage data for Sope Creek (Station number: 02335870): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge

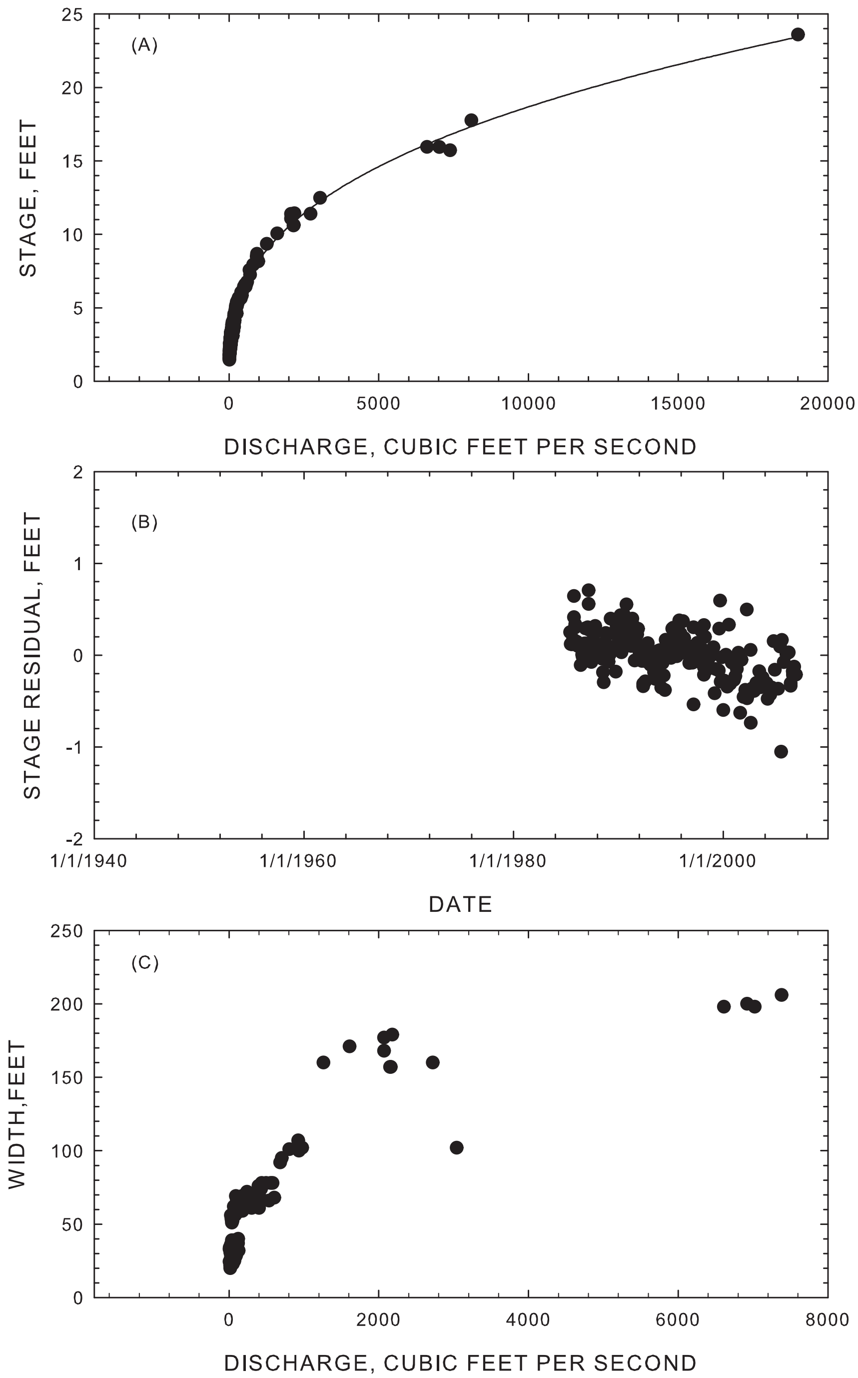

Figure 5.19: Geomorphic analysis of stream gage data for Flint River near Lovejoy, GA (Station number: 02344350): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge

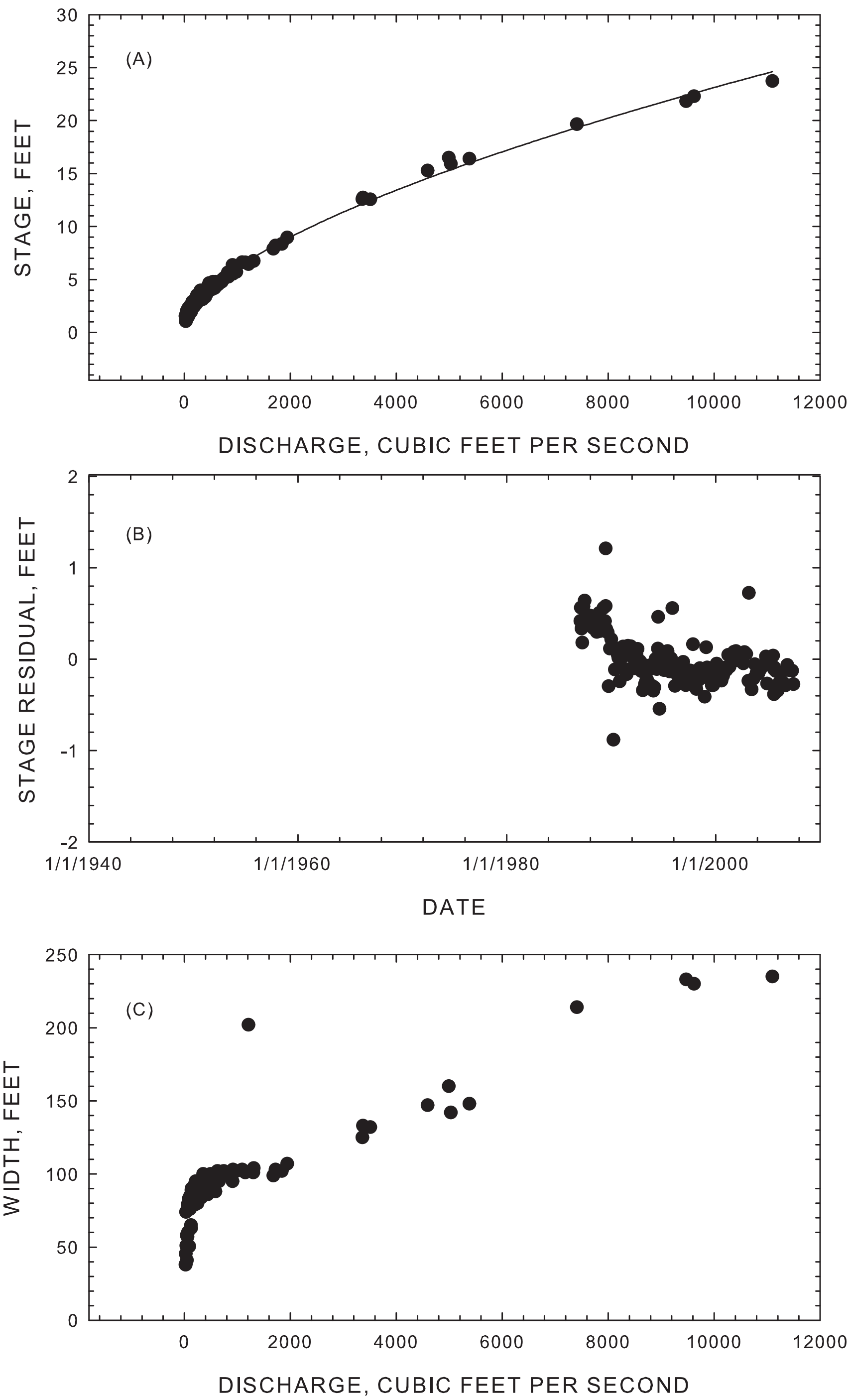

Figure 5.20: Geomorphic analysis of stream gage data for Middle Oconee River near Arcade, GA (Station number: 02217475): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge

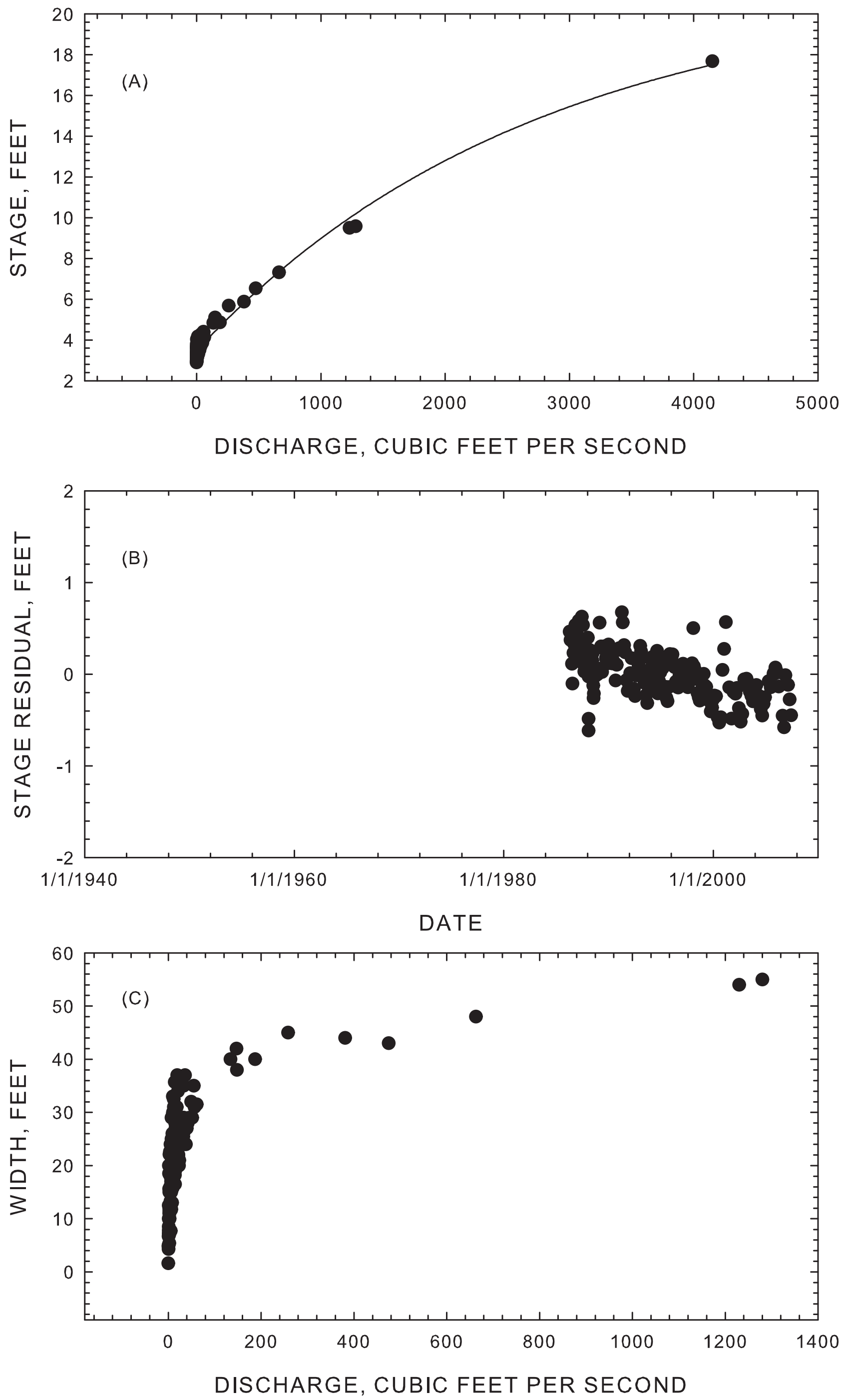

Figure 5.21: Geomorphic analysis of stream gage data for Kettle Creek near Washington, GA (Station number: 02193340): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge

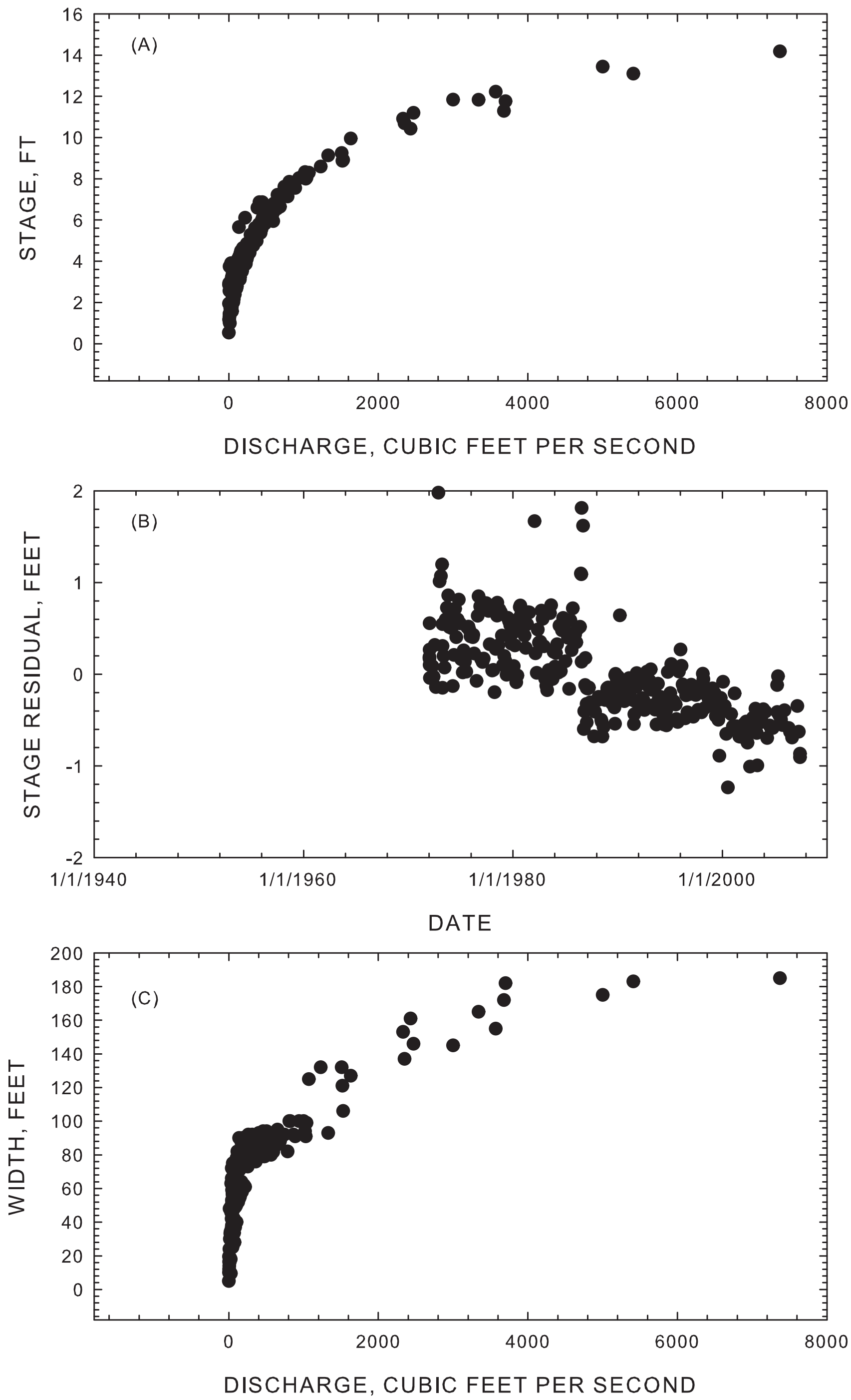

Figure 5.22: Geomorphic analysis of stream gage data for Alcovy River above Covington, GA (Station number: 02208450): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge

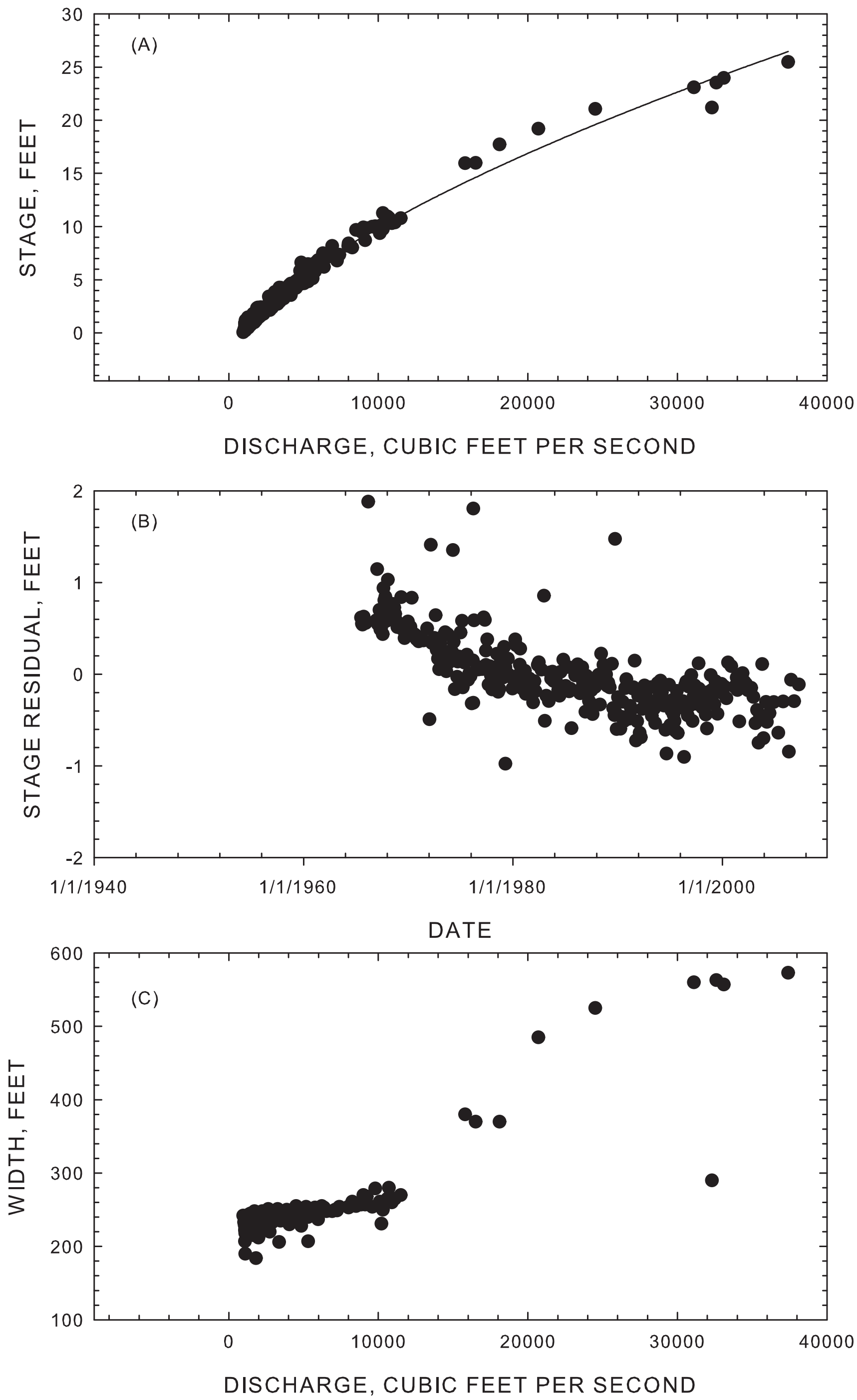

Figure 5.23: Geomorphic analysis of stream gage data for Chattahoochee River near Fairburn, GA (Station number: 02337170): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge

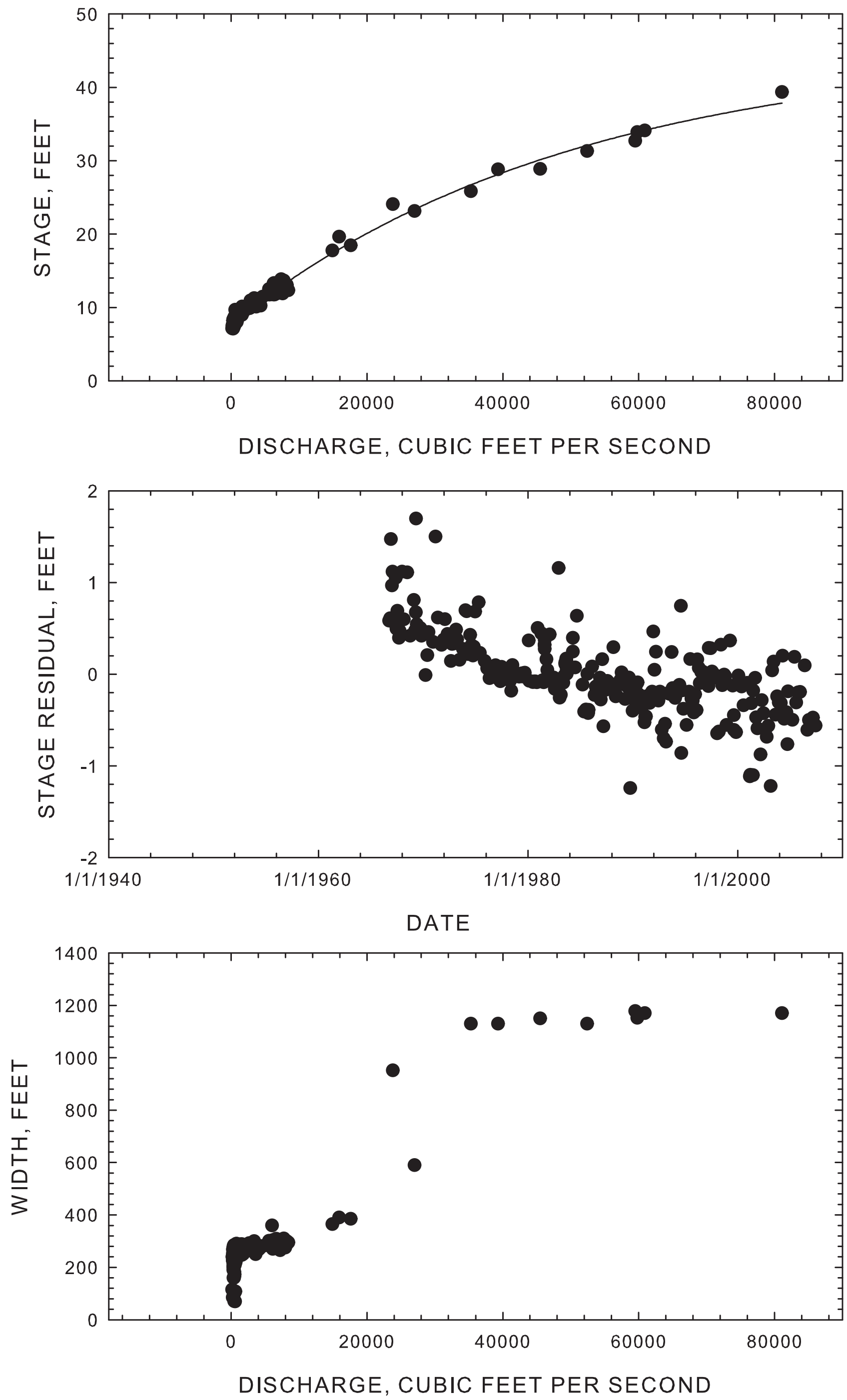

Figure 5.24: Geomorphic analysis of stream gage data for Oconee River at Milledgeville, GA (Station number: 02223000): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge

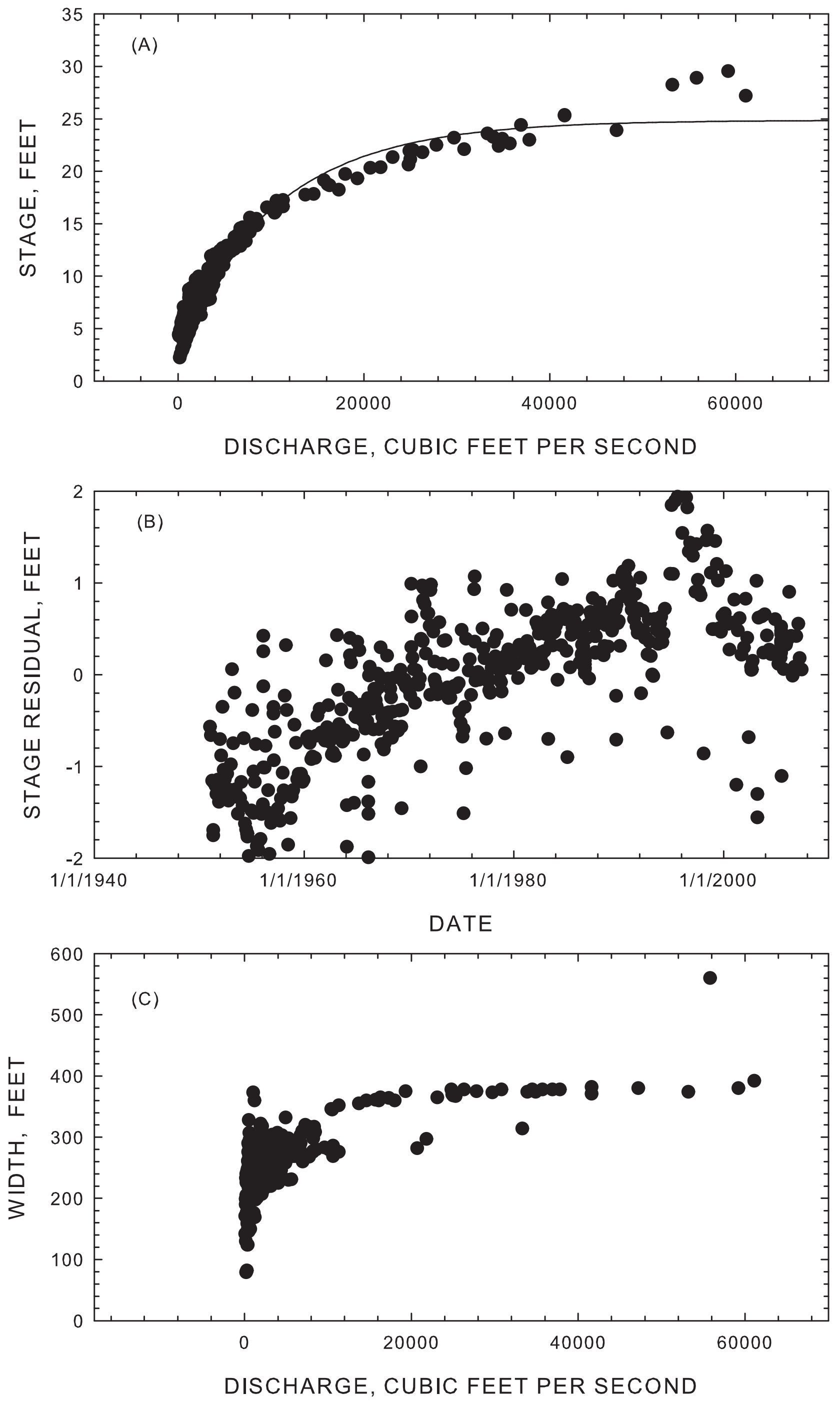

Figure 5.25: Geomorphic analysis of stream gage data for Ockmulgee River at Macon, GA (Station number: 02213000): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge

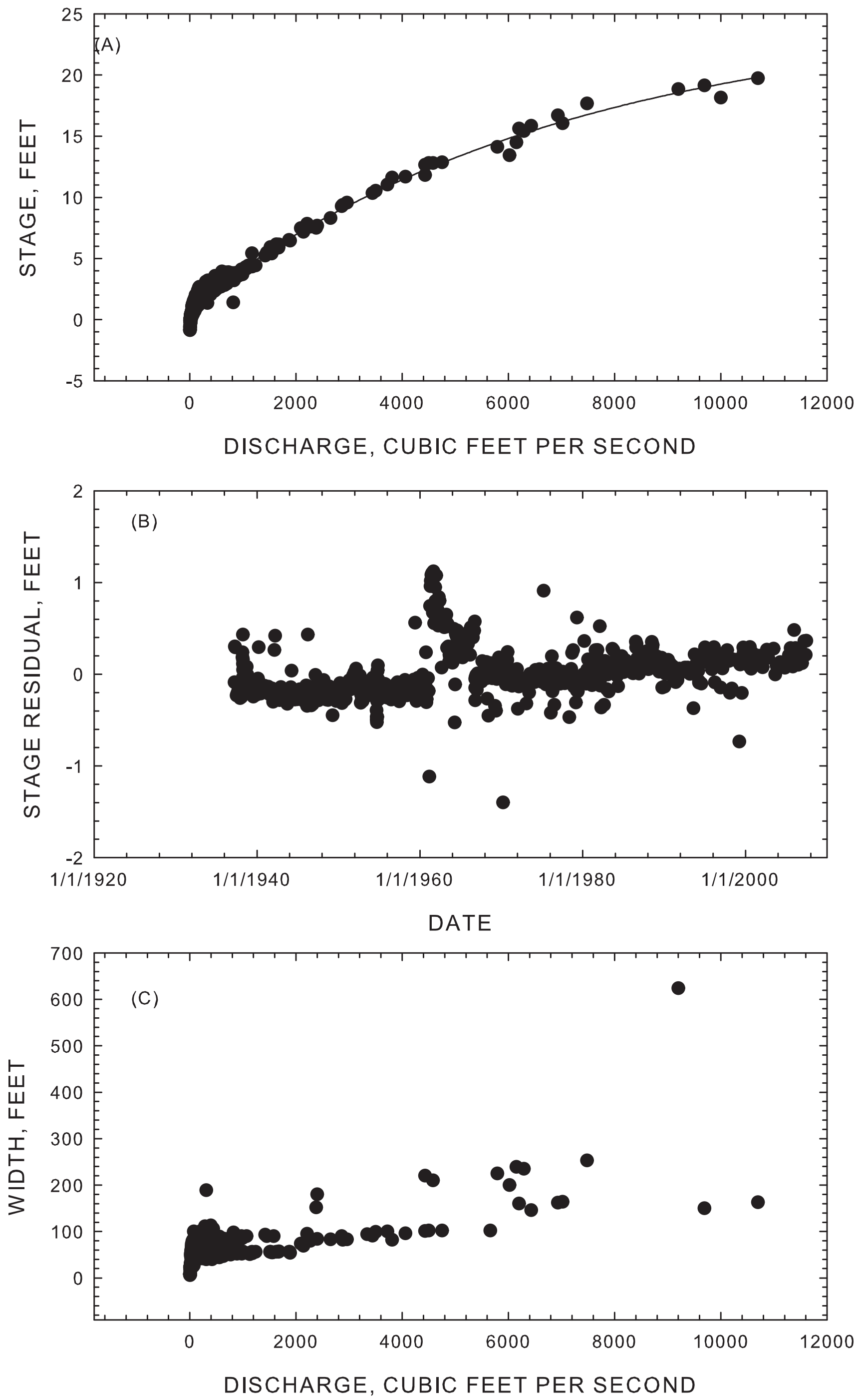

Figure 5.26: Geomorphic analysis of stream gage data for Sweetwater Creek near Austell, GA (Station number: 02337000): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge

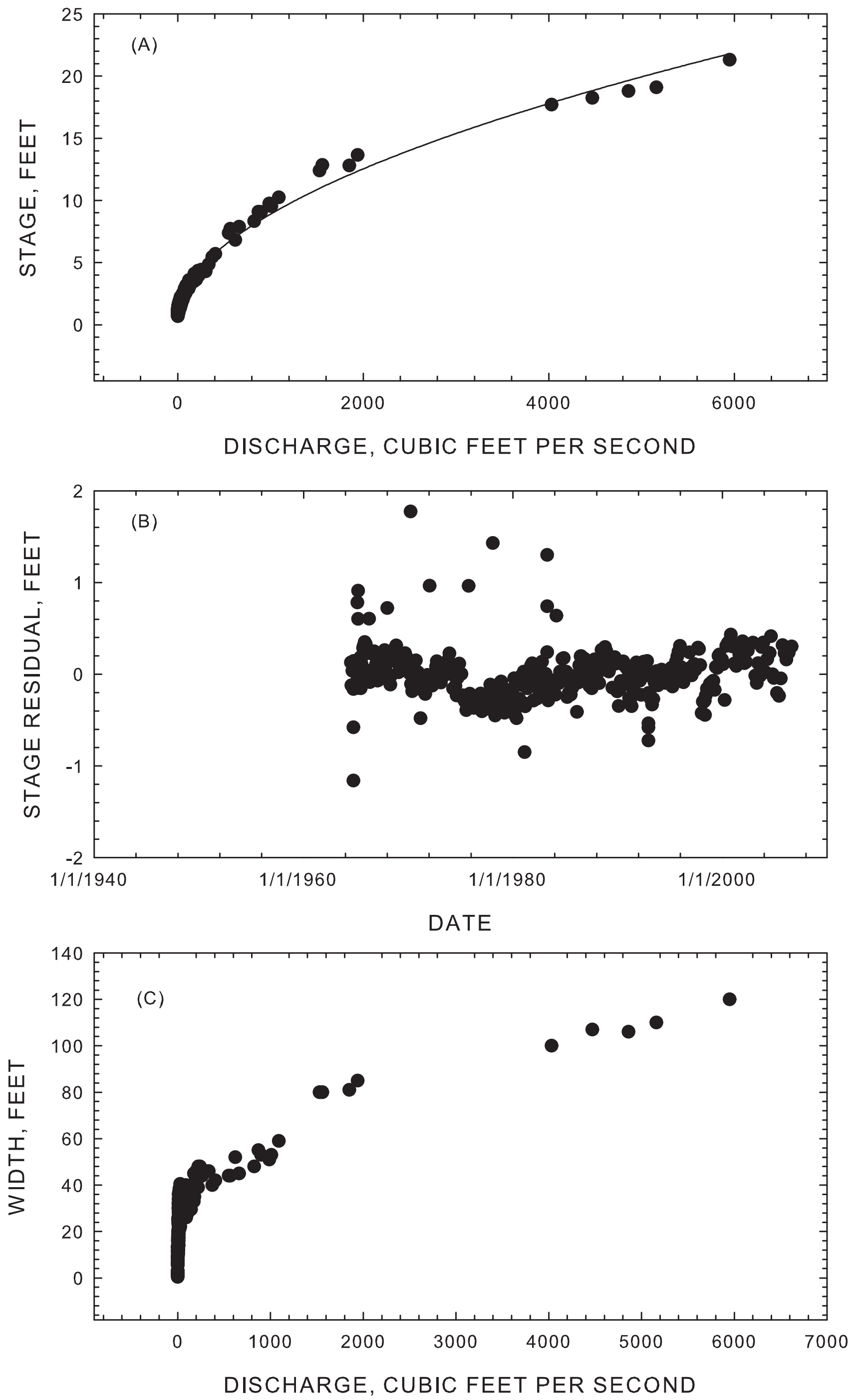

Figure 5.27: Geomorphic analysis of stream gage data for Falling Creek near Juliette, GA (Station number: 02212600): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge

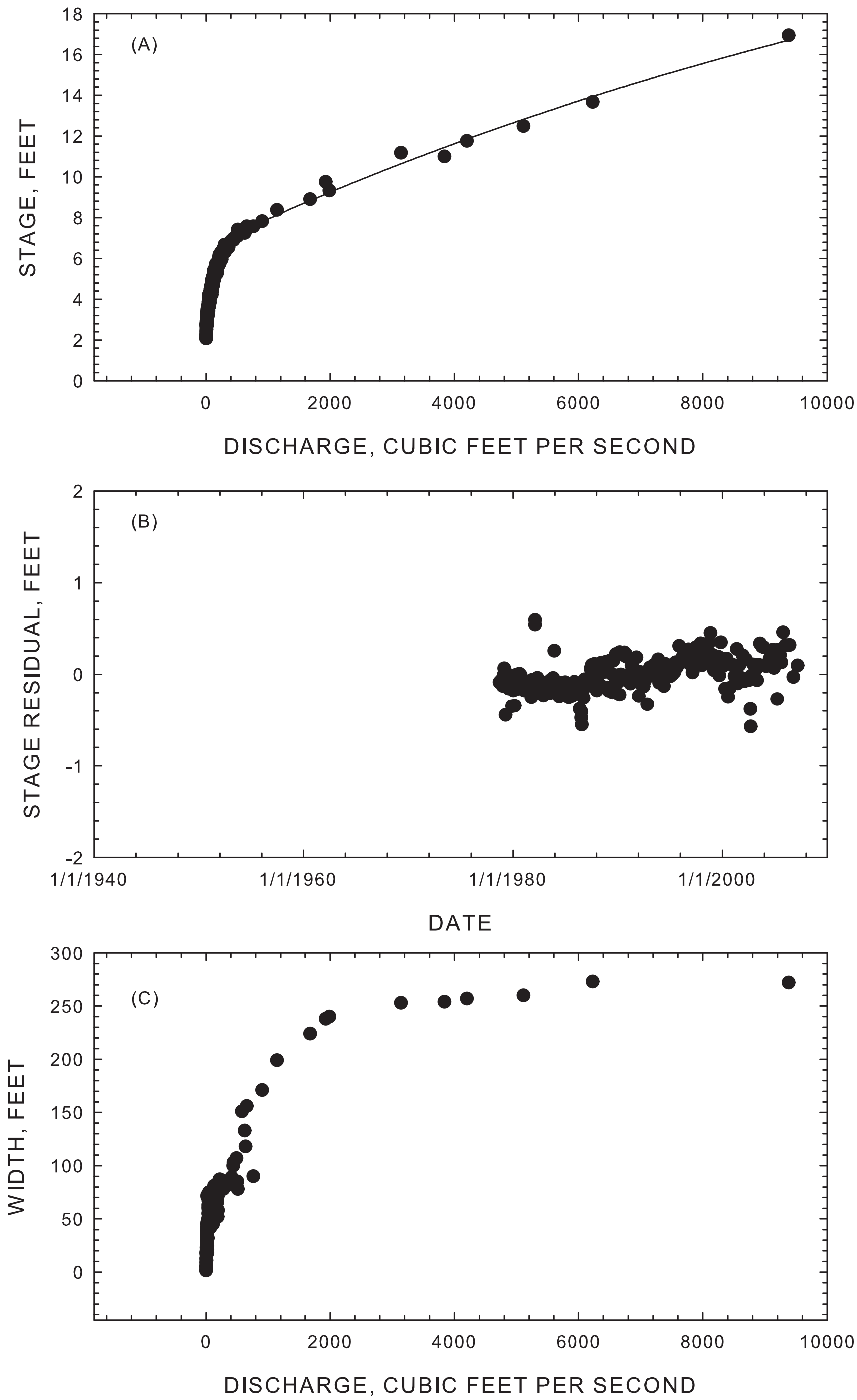

Figure 5.28: Geomorphic analysis of stream gage data for New River at GA 100, near Cornith, GA (Station number: 02338660): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge

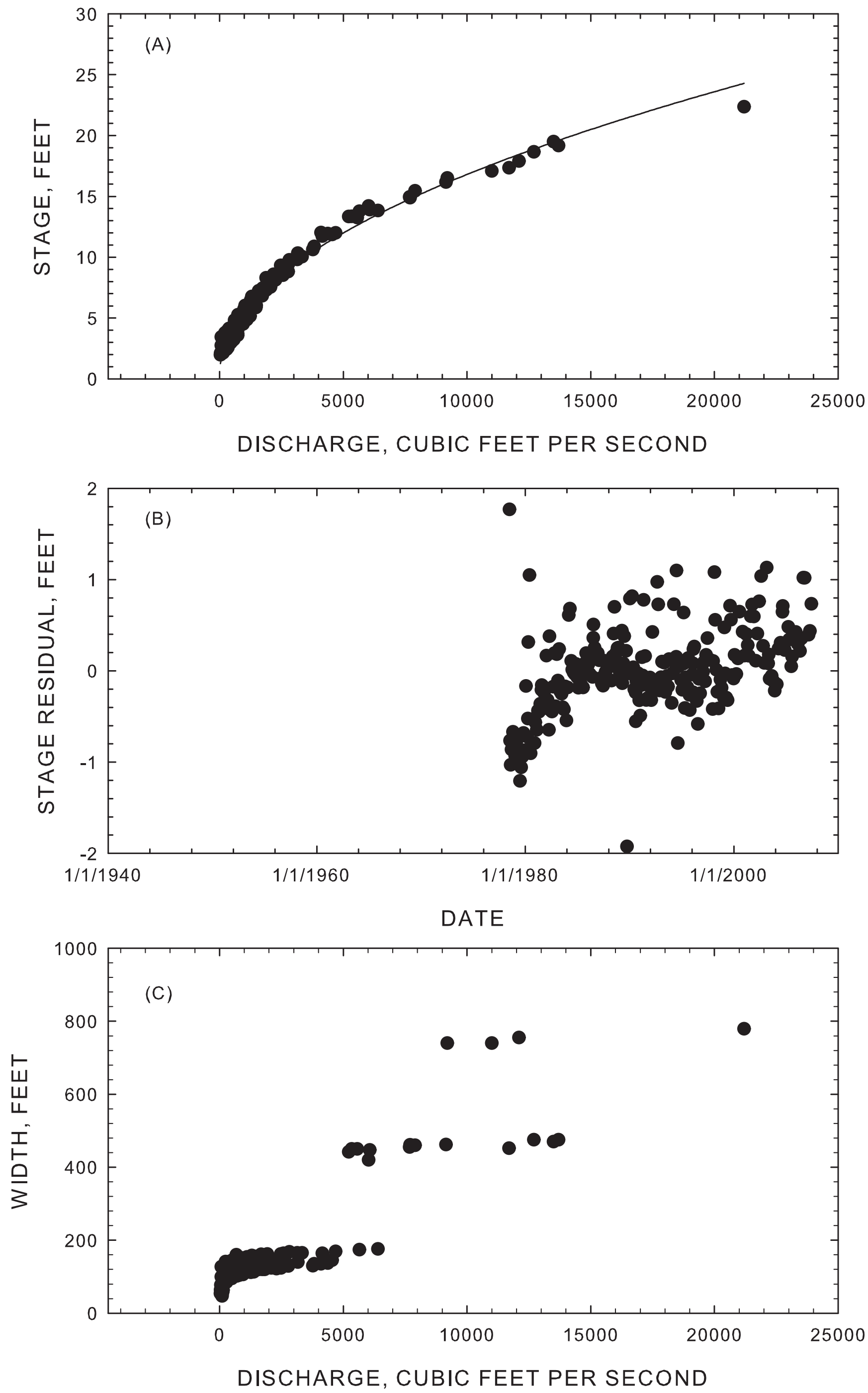

Figure 5.29: Geomorphic analysis of stream gage data for Oconee River near Penfield, GA (Station number: 02218300): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge

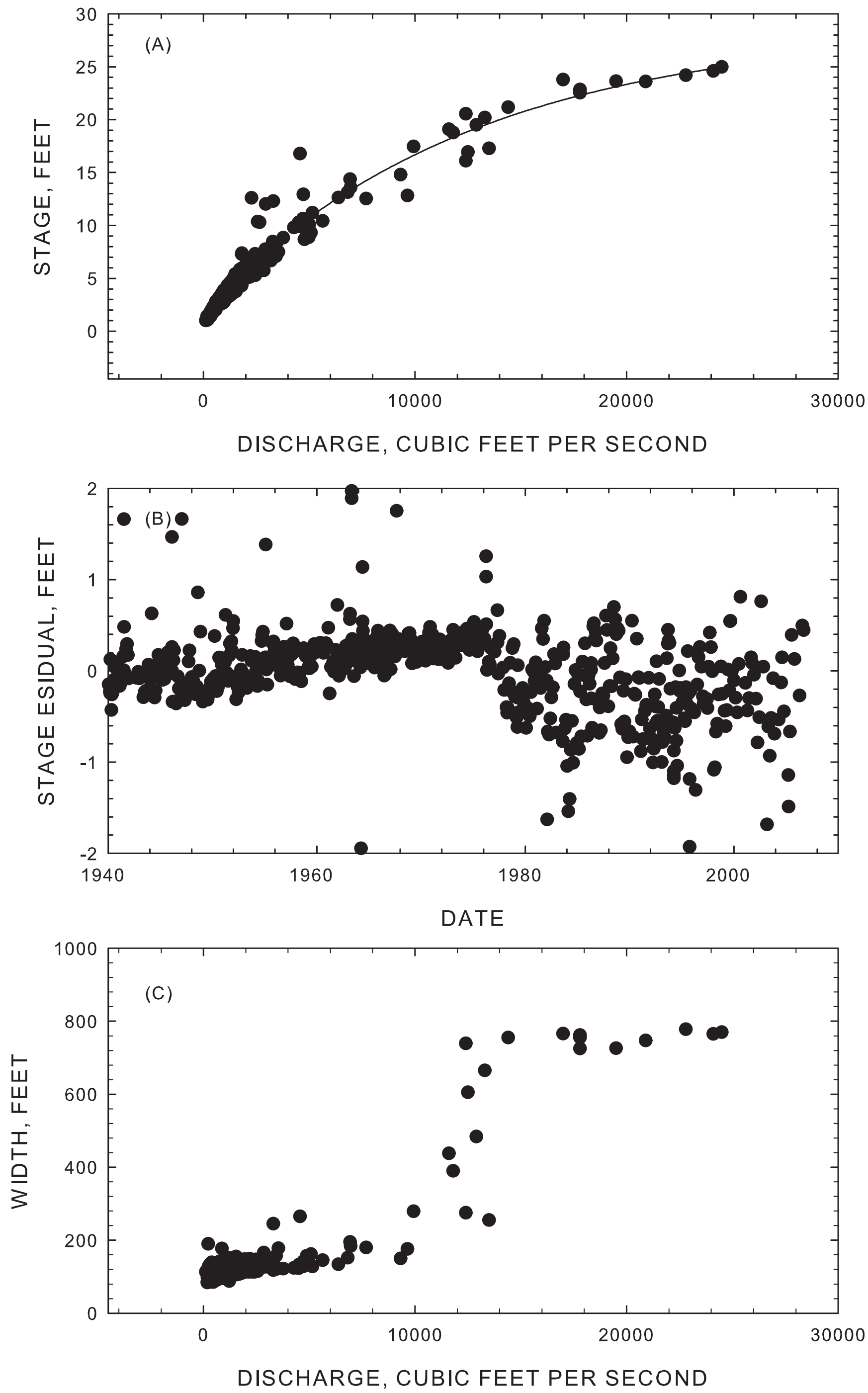

Figure 5.30: Geomorphic analysis of stream gage data for Etowah River at Canton, GA (Station number: 02392000): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge

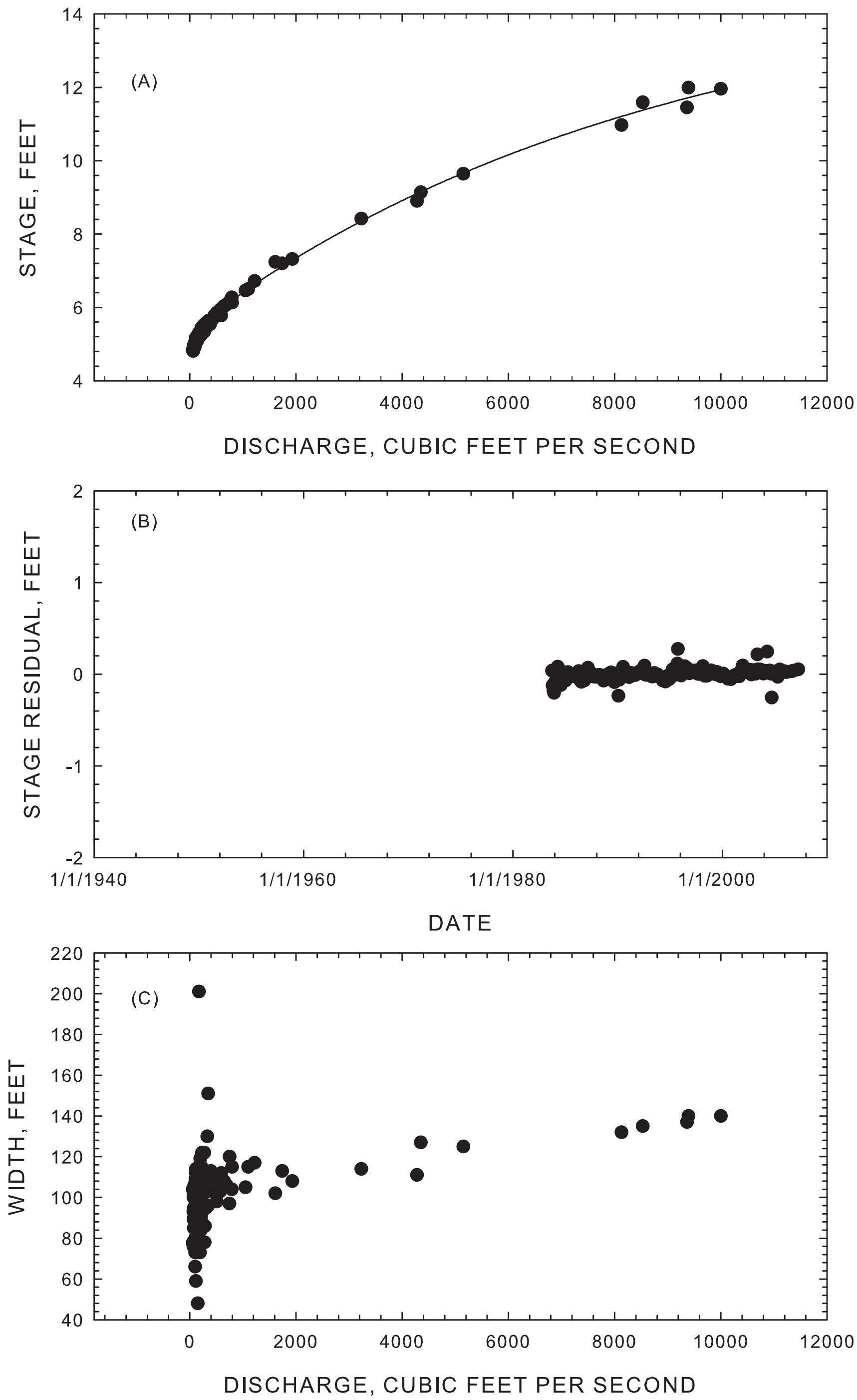

Figure 5.31: Geomorphic analysis of stream gage data for South River at Klondike Road, near Lithonia, GA (Station number: 02204070): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge

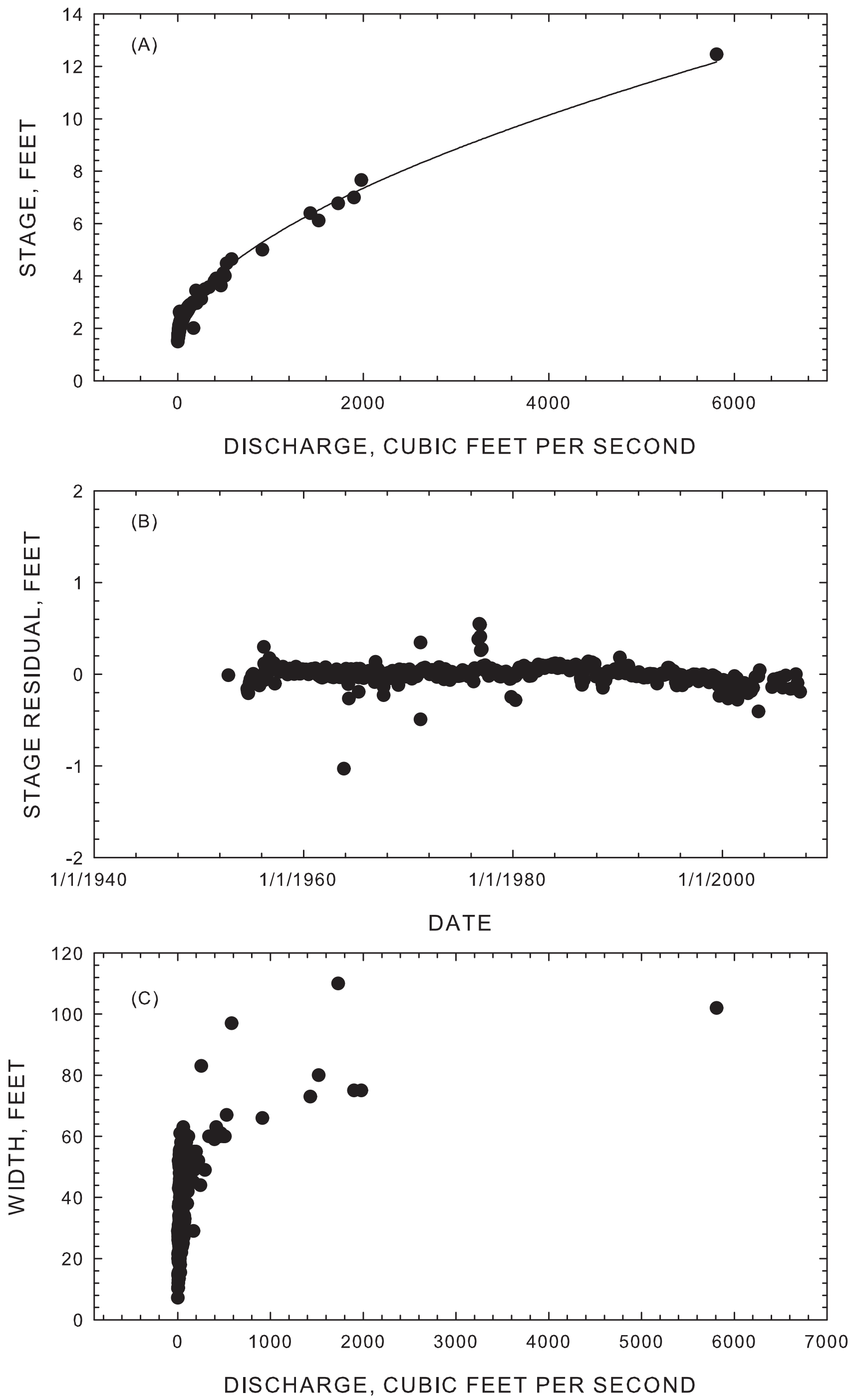

Figure 5.32: Geomorphic analysis of stream gage data for Snake Creek near Whitesburg, GA (Station number: 02337500): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge

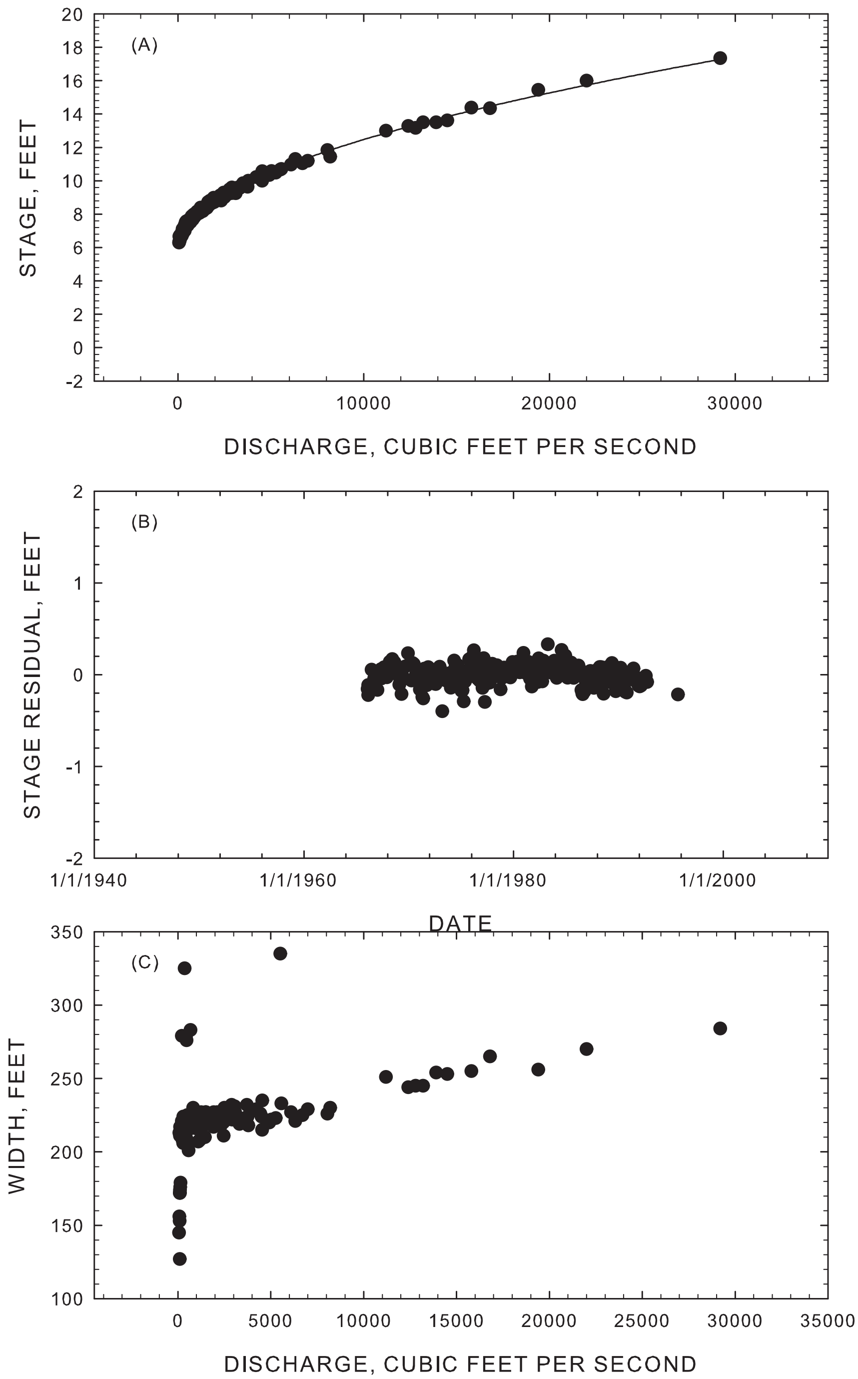

Figure 5.33: Geomorphic analysis of stream gage data for Flint River near Thomaston, GA (Station number: 02346180): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge

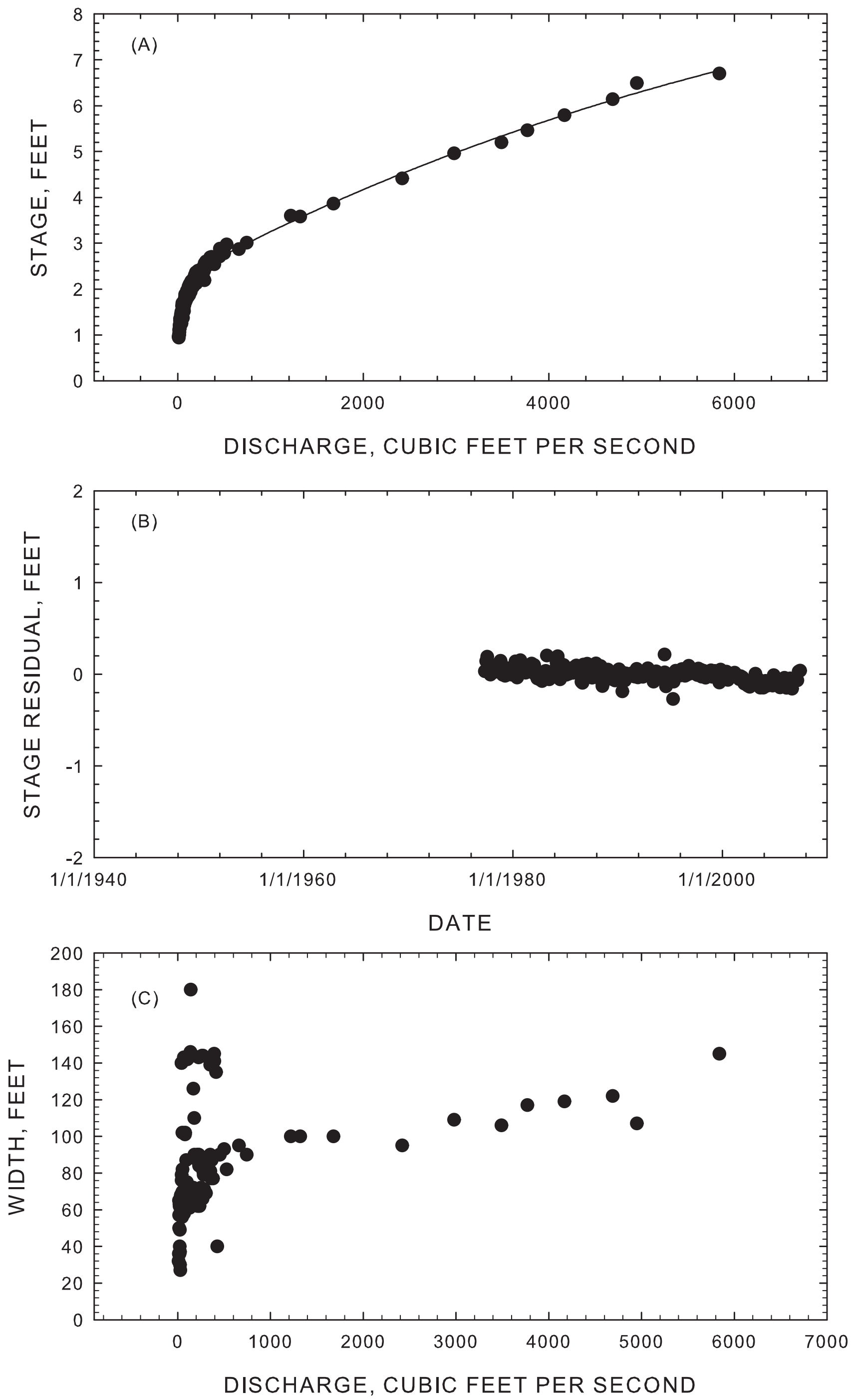

Figure 5.34: Geomorphic analysis of stream gage data for Apalachee River near Bostwick, GA (Station number: 02219000): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge

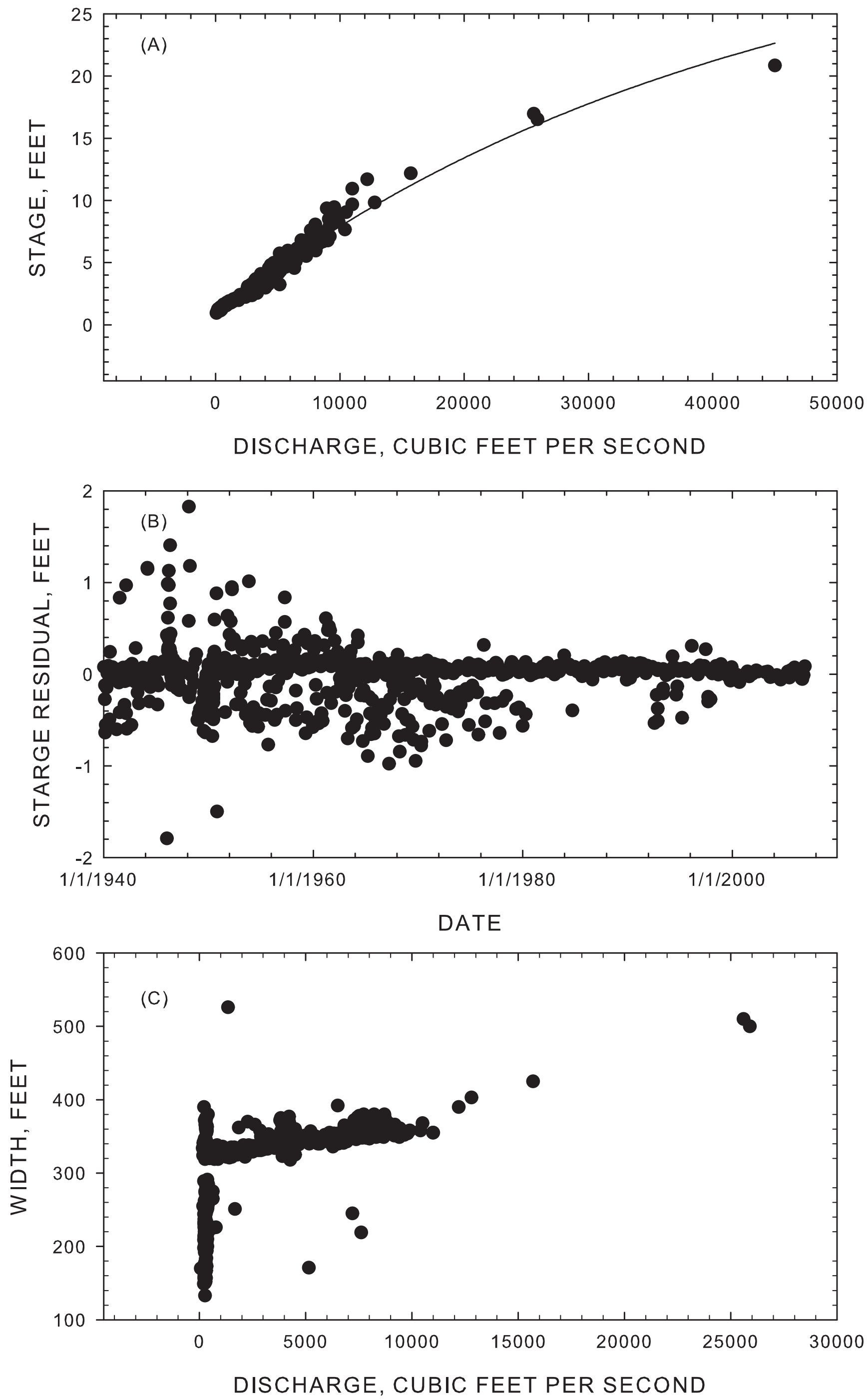

Figure 5.35: Geomorphic analysis of stream gage data for Etowah River at Allatoona Dam, above Cartersville, GA (Station number: 02394000): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge

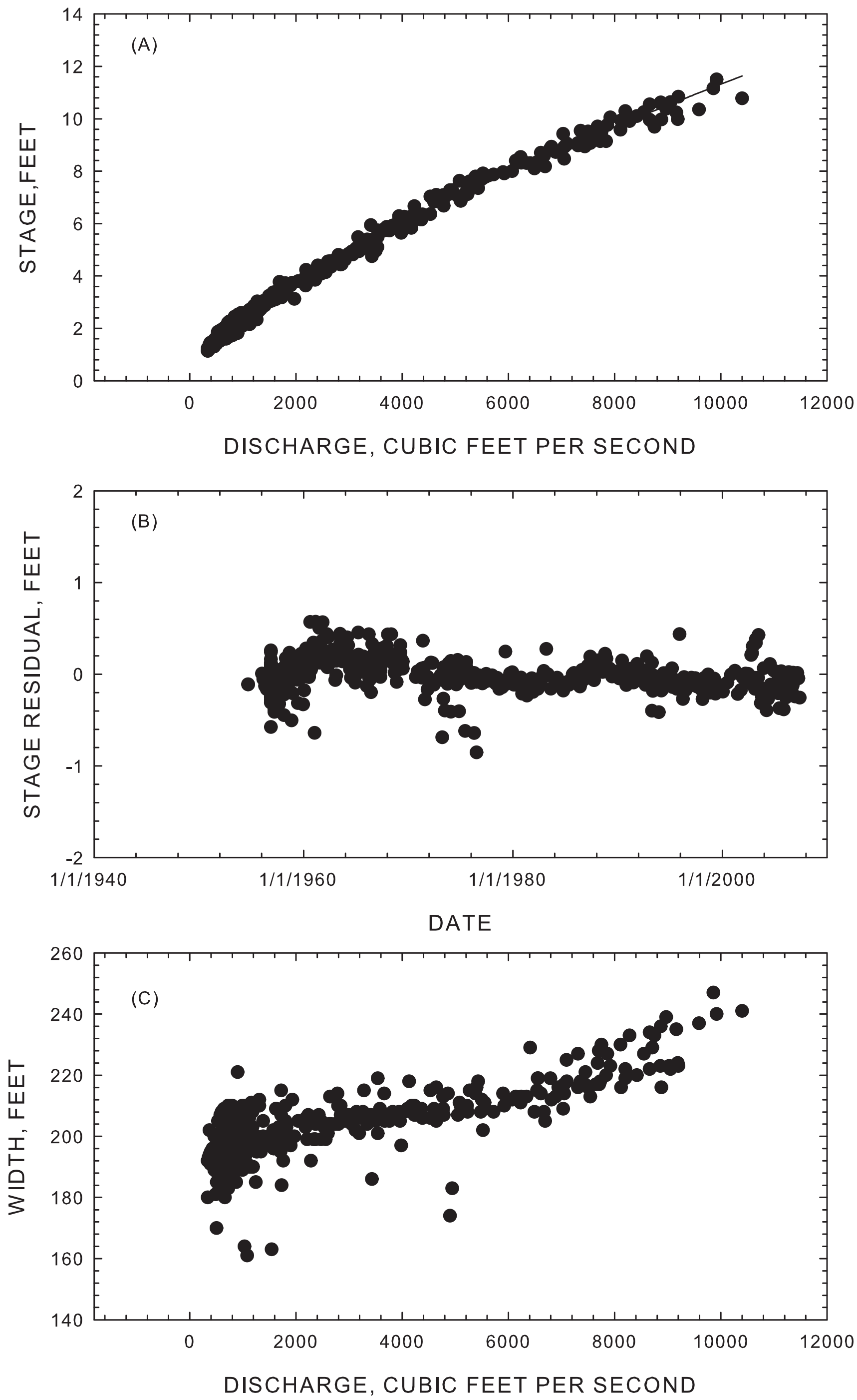

Figure 5.36: Geomorphic analysis of stream gage data for Chattahoochee River near Norcross, GA (Station number: 02335000): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge

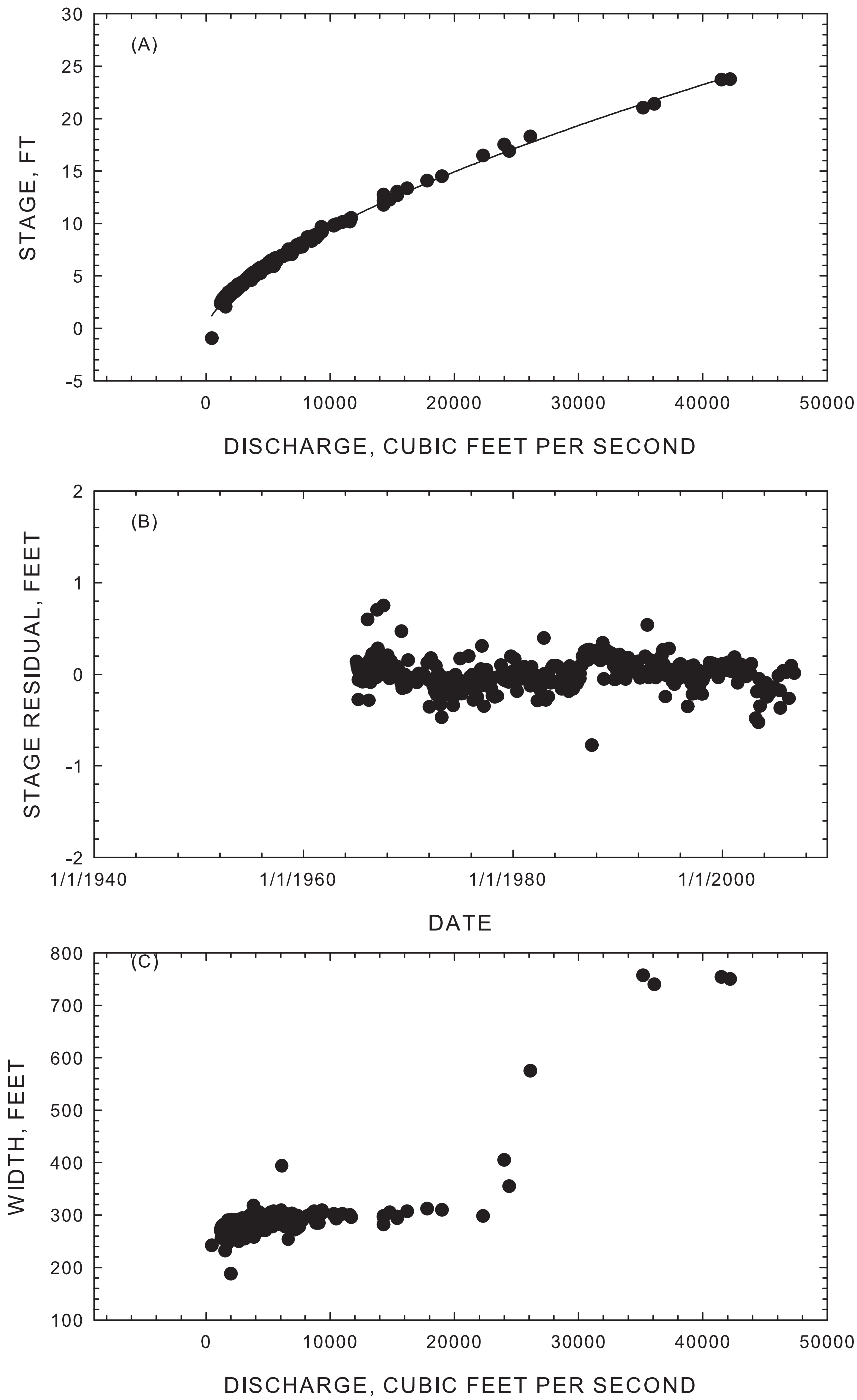

Figure 5.37: Geomorphic analysis of stream gage data for Chattahoochee River near Whitesburg, GA (Station number: 02338000): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge

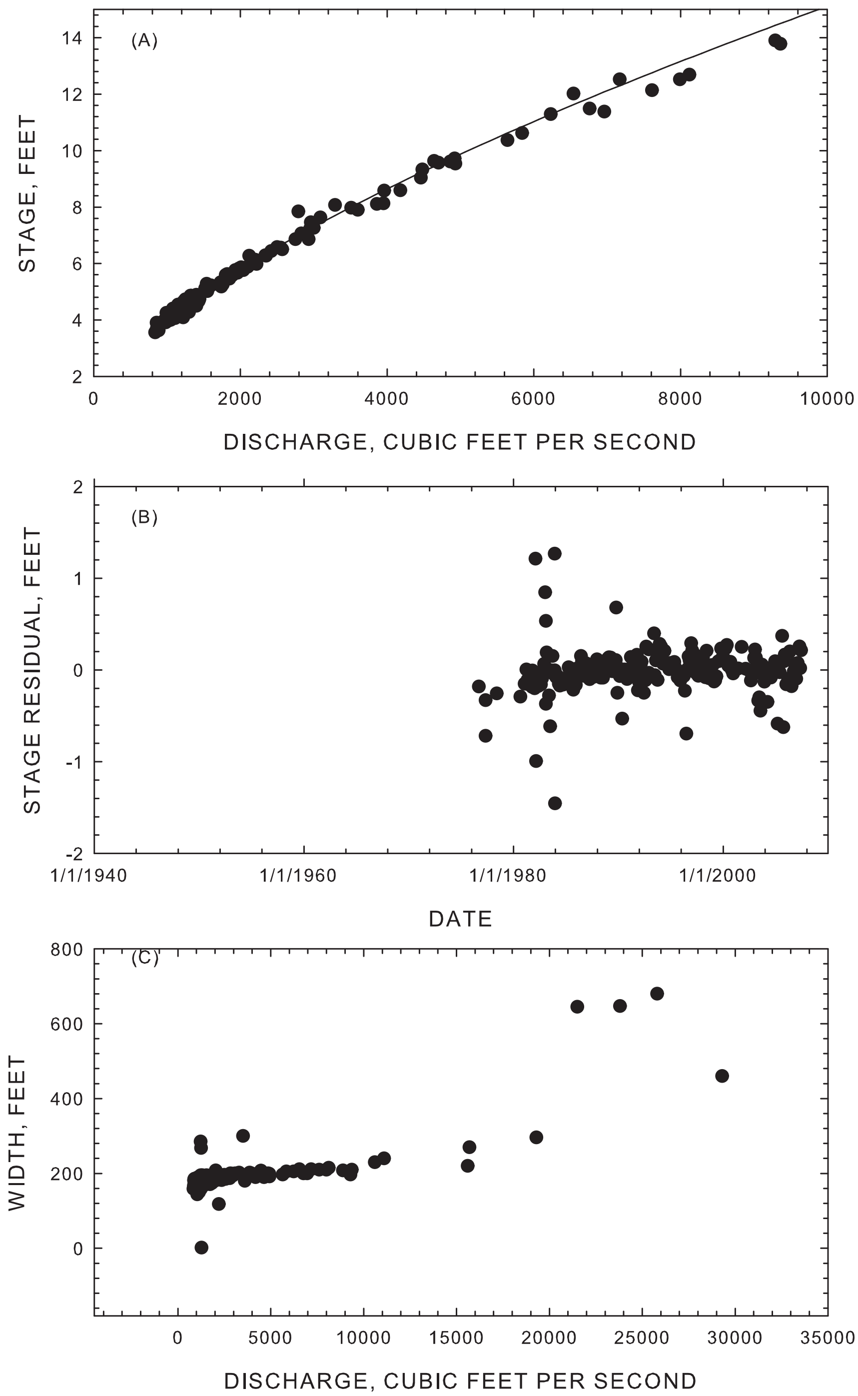

Figure 5.38: Geomorphic analysis of stream gage data for Chattahoochee River at GA 280, near Atlanta, GA (Station number: 02336490): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge

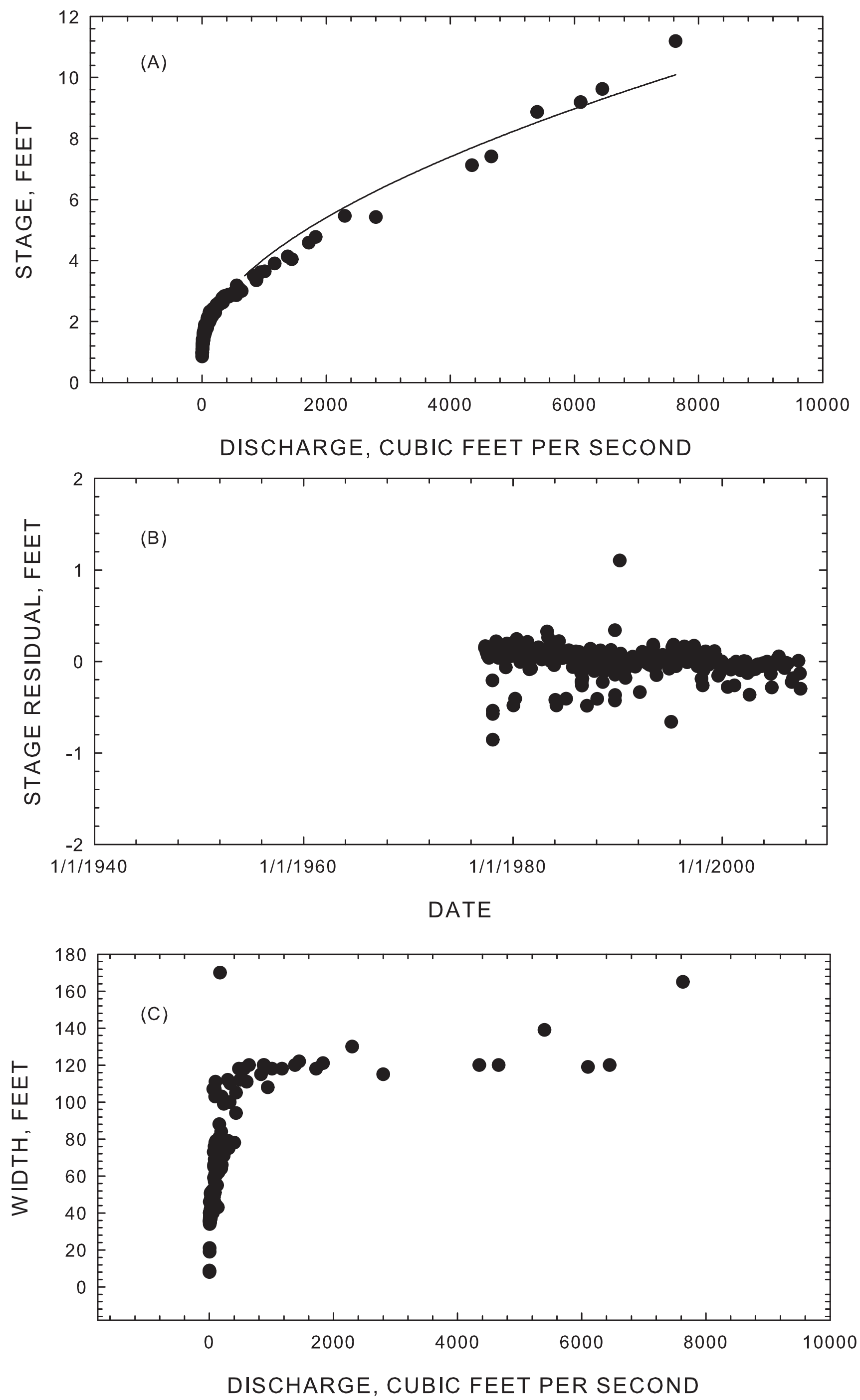

Figure 5.39: Geomorphic analysis of stream gage data for Murder Creek below Eatonton, GA (Station number: 02221525): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge

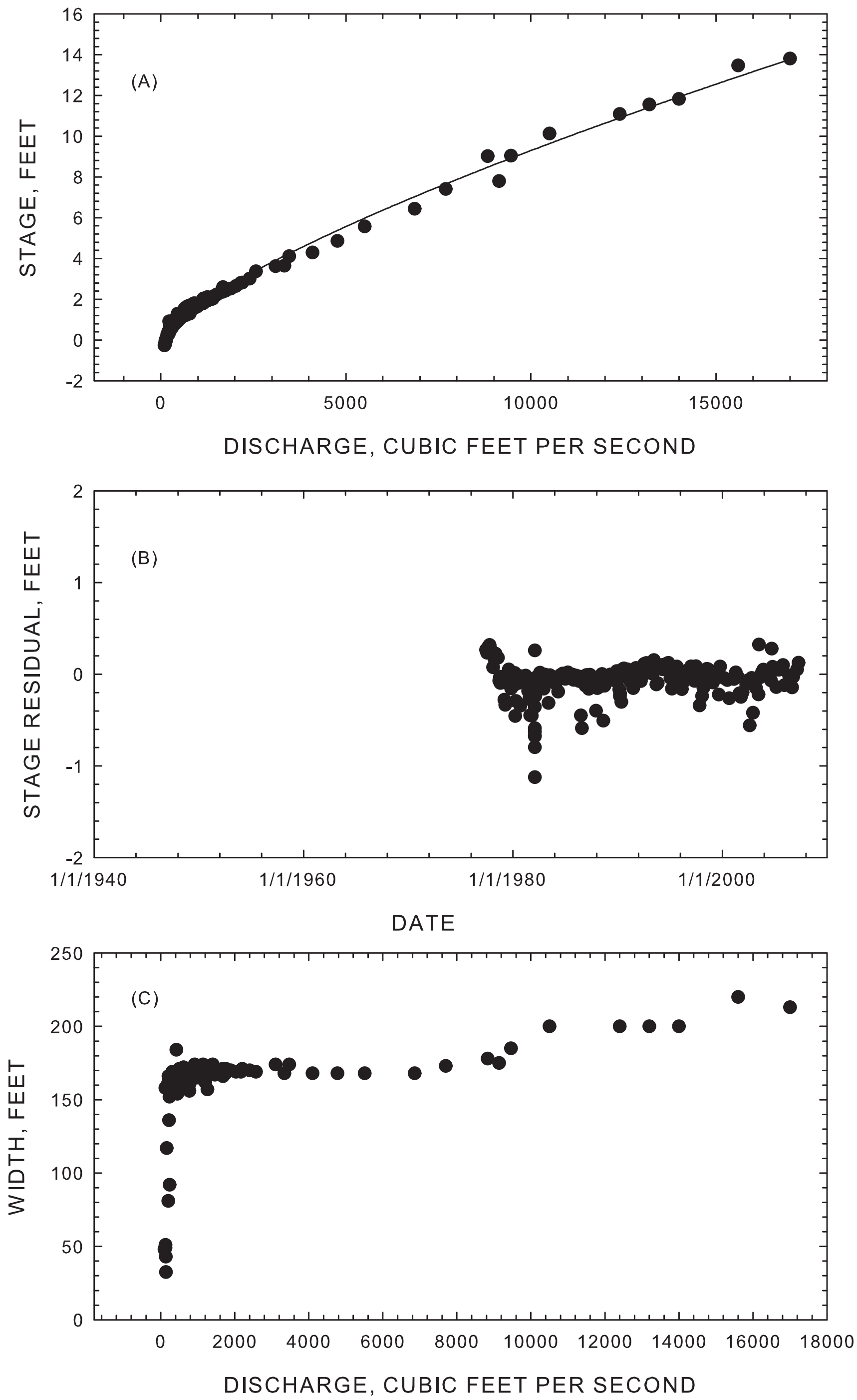

Figure 5.40: Geomorphic analysis of stream gage data for Chattahoochee River near Cornellia, GA (Station number: 02331600): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge

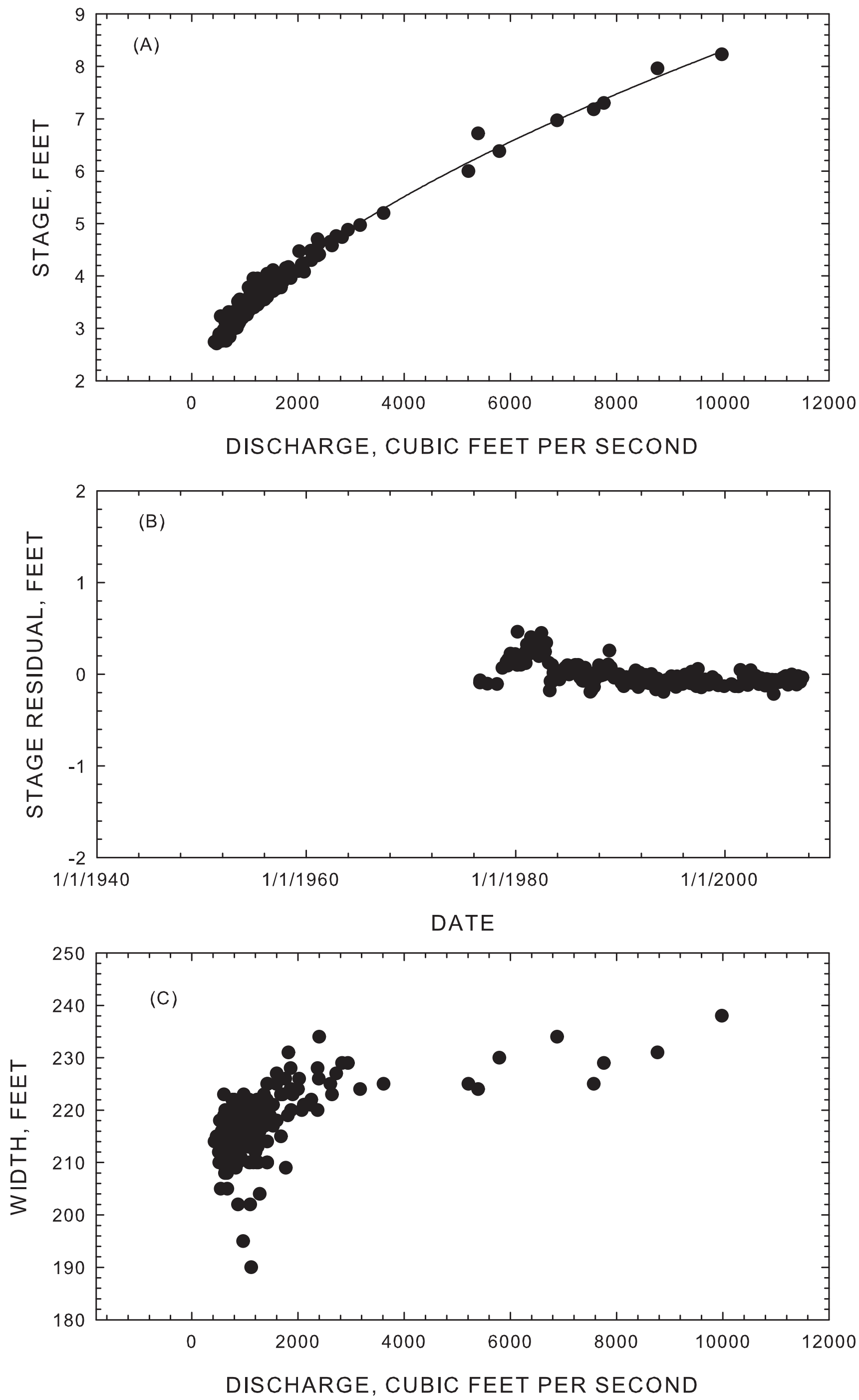

Figure 5.41: Geomorphic analysis of stream gage data for Chattahoochee River above Roswell, GA (Station number: 02335450): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge

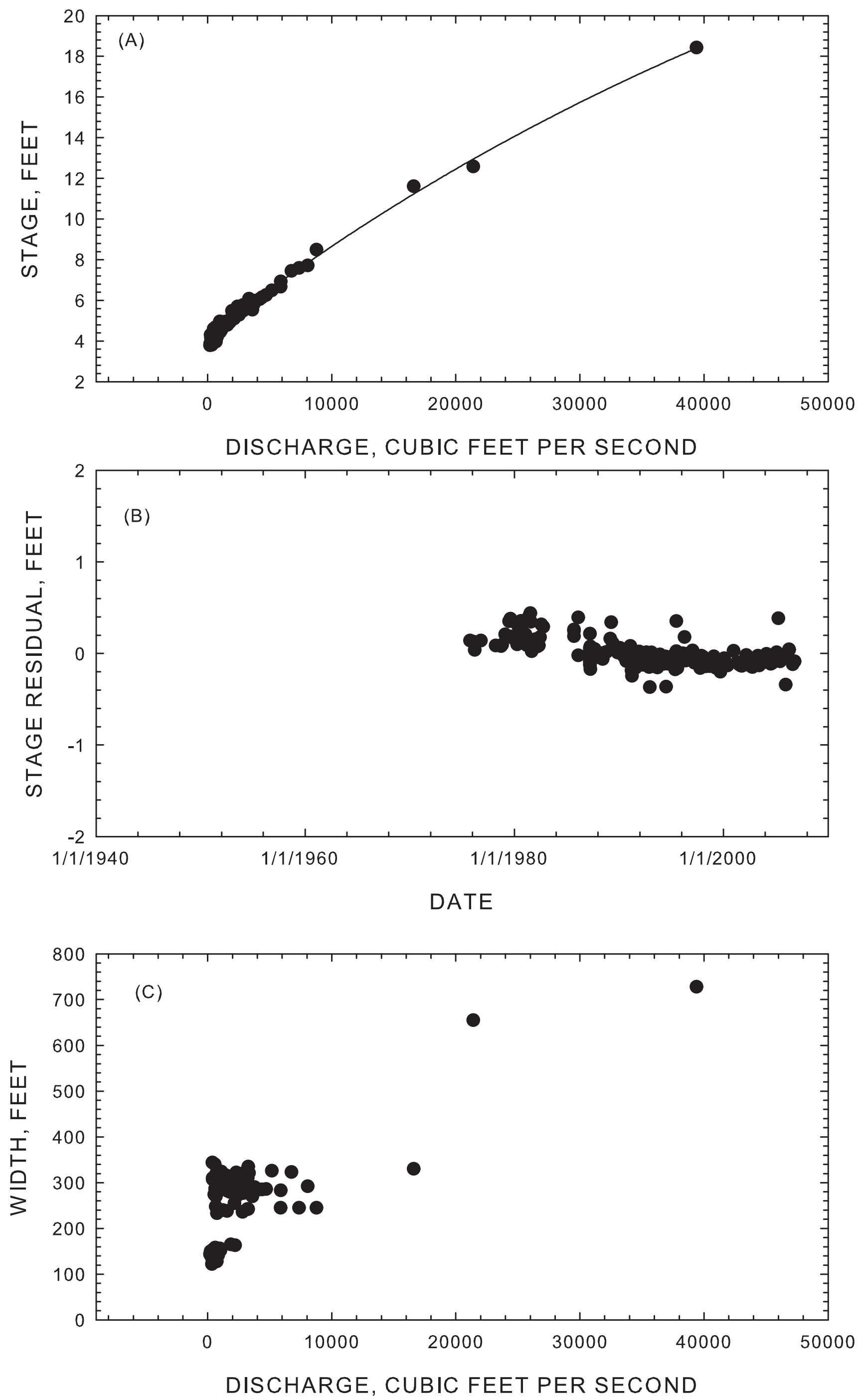

Figure 5.42: Geomorphic analysis of stream gage data for Ocmulgee River near Jackson, GA (Station number: 02210500): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge

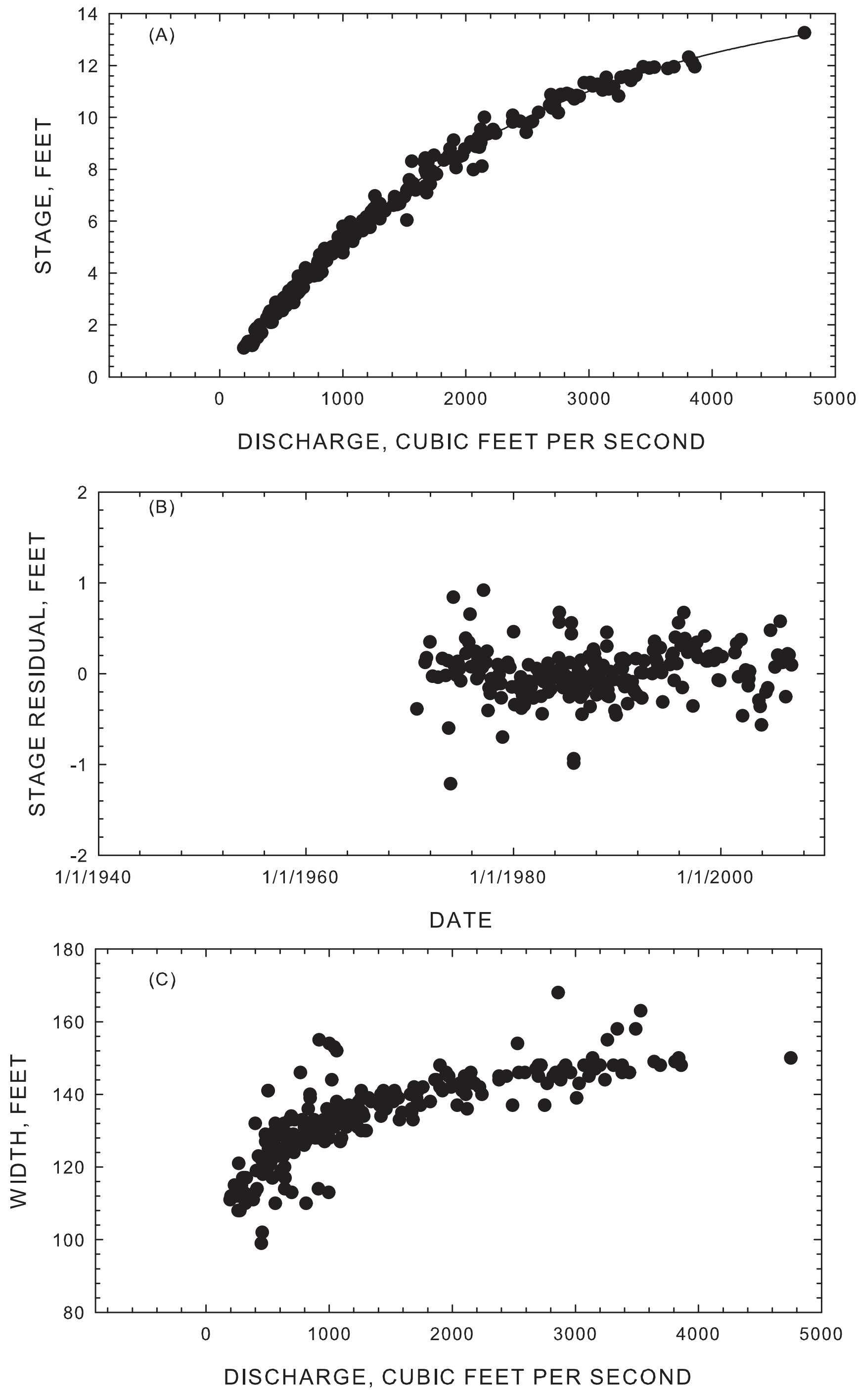

Figure 5.43: Geomorphic analysis of stream gage data for Ocmulgee River near Warner Robins, GA (Station number: 02213700): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge

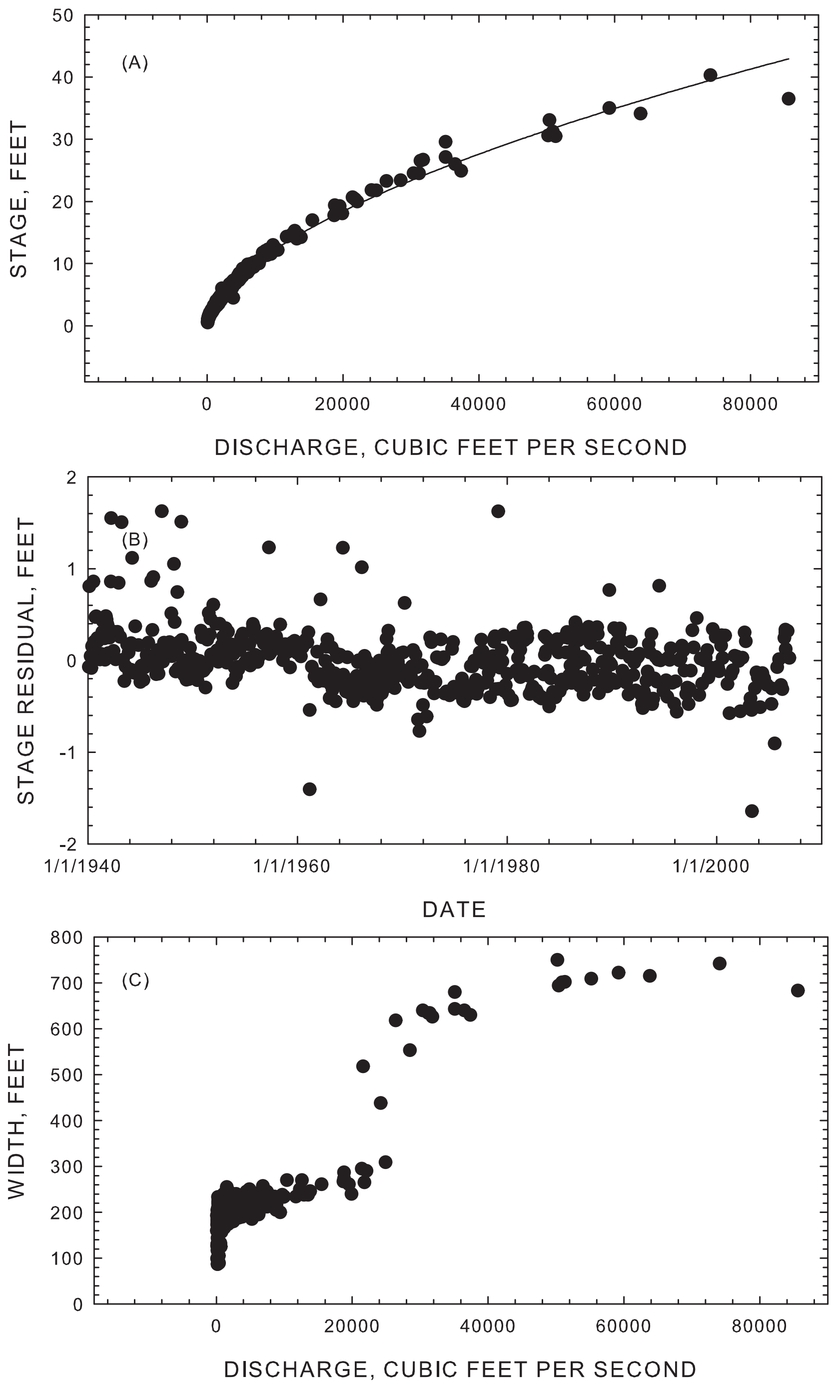

Figure 5.44: Geomorphic analysis of stream gage data for Flint River at US 19, near Carsonville, GA (Station number: 02347500): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge

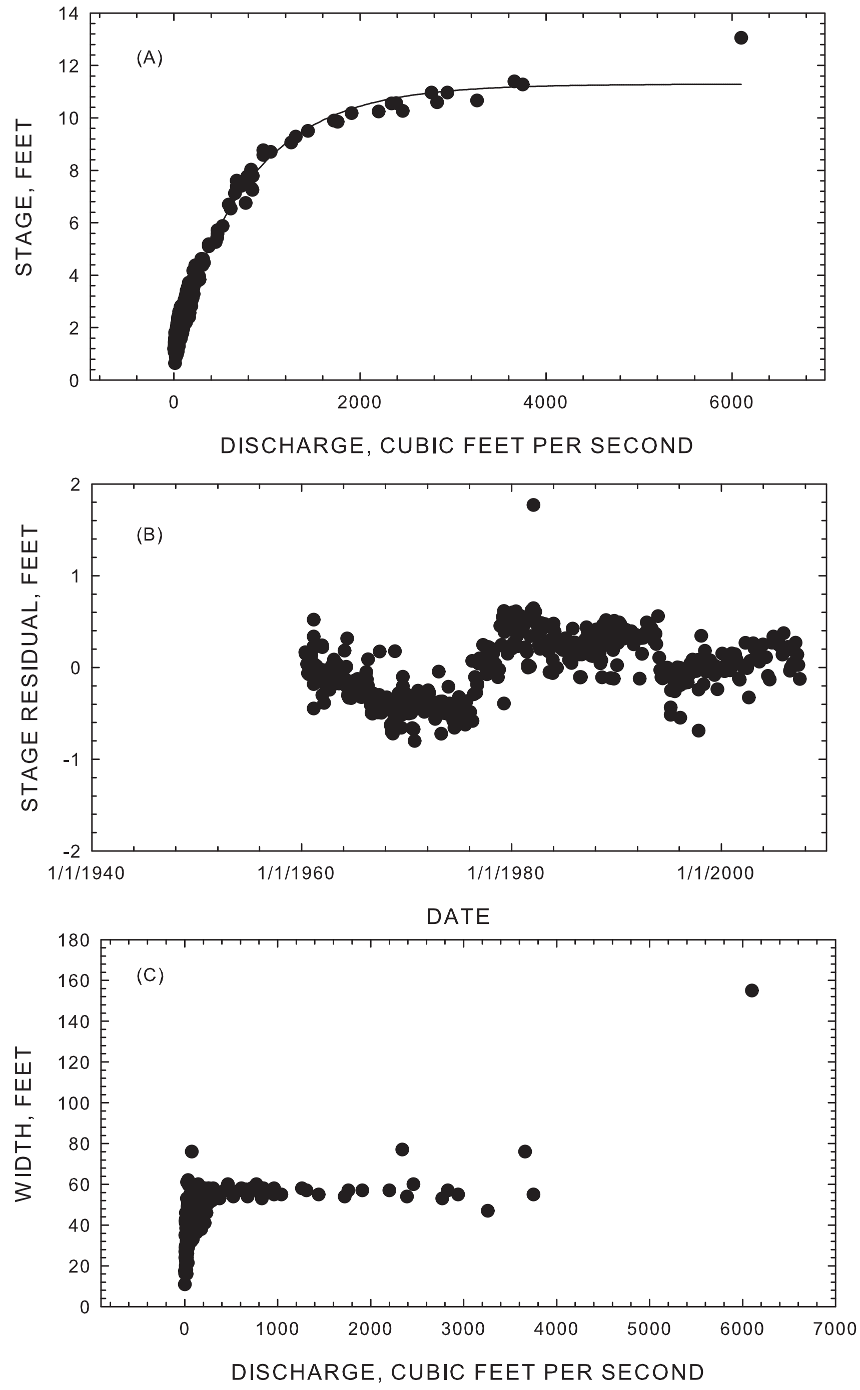

Figure 5.45: Geomorphic analysis of stream gage data for Big Creek near Alpharetta, GA (Station number: 02335700): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge

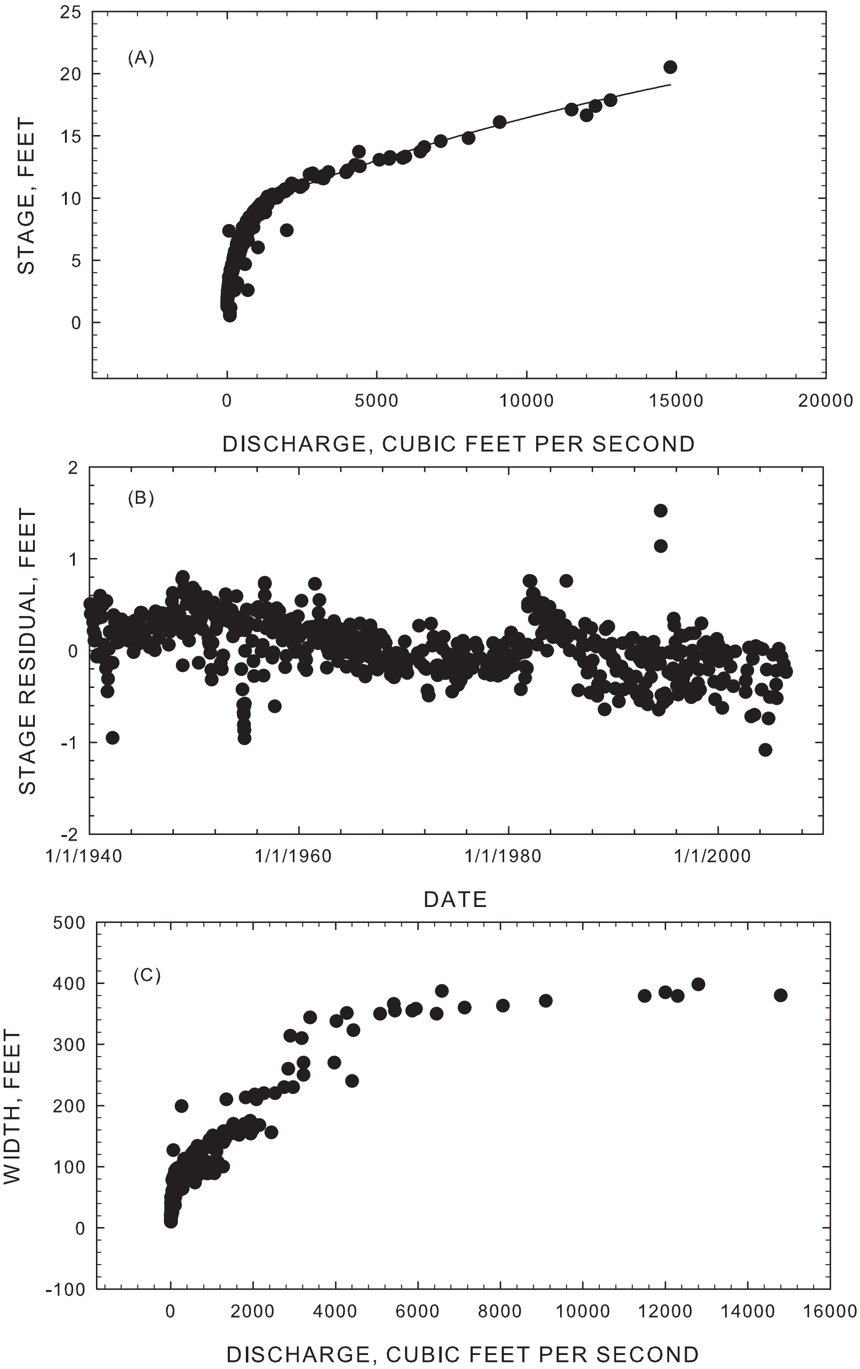

Figure 5.46: Geomorphic analysis of stream gage data for Flint River near Griffin, GA (Station number: 02344500): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge

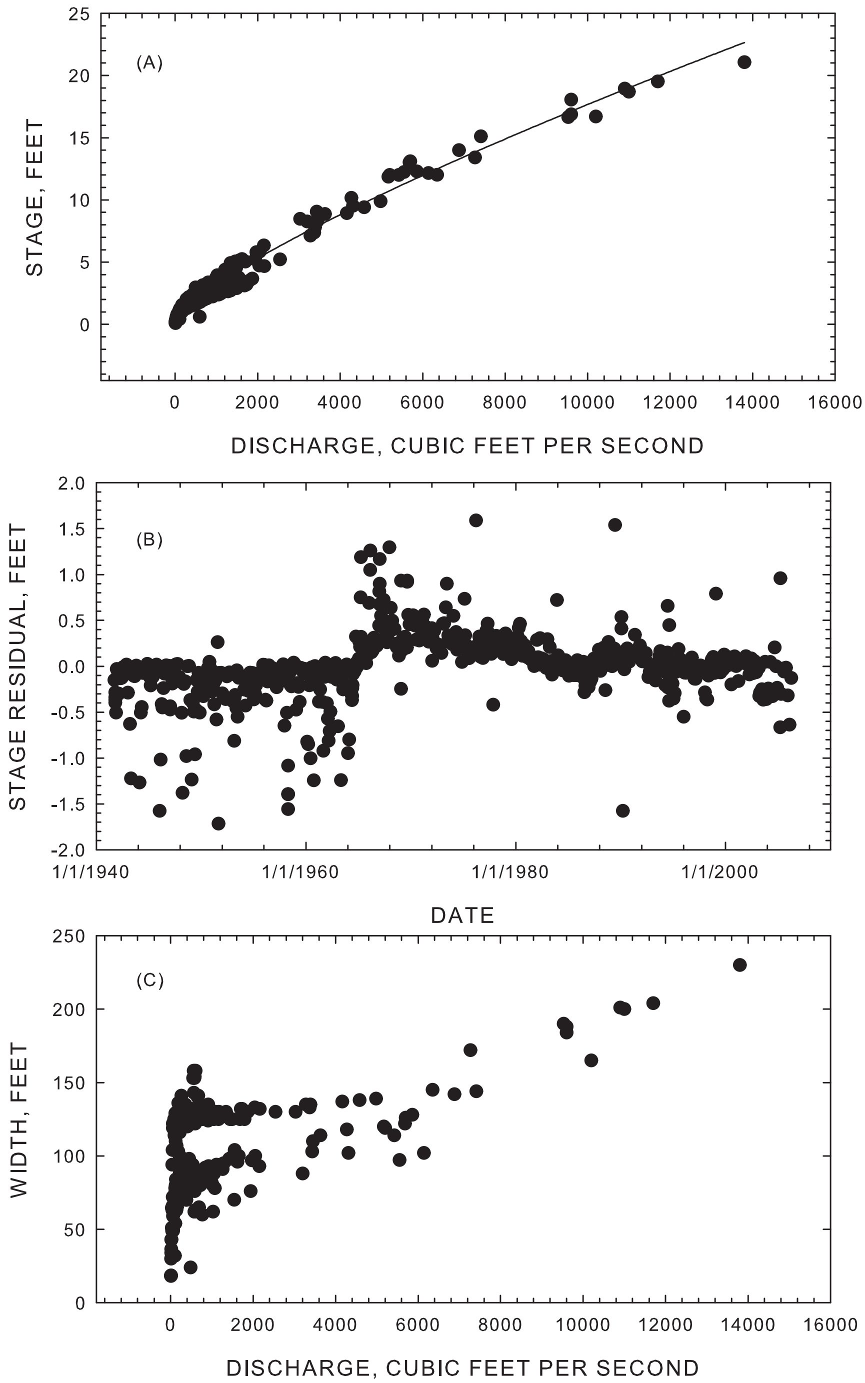

Figure 5.47: Geomorphic analysis of stream gage data for Middle Oconee River near Athens, GA (Station number: 02217500): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge

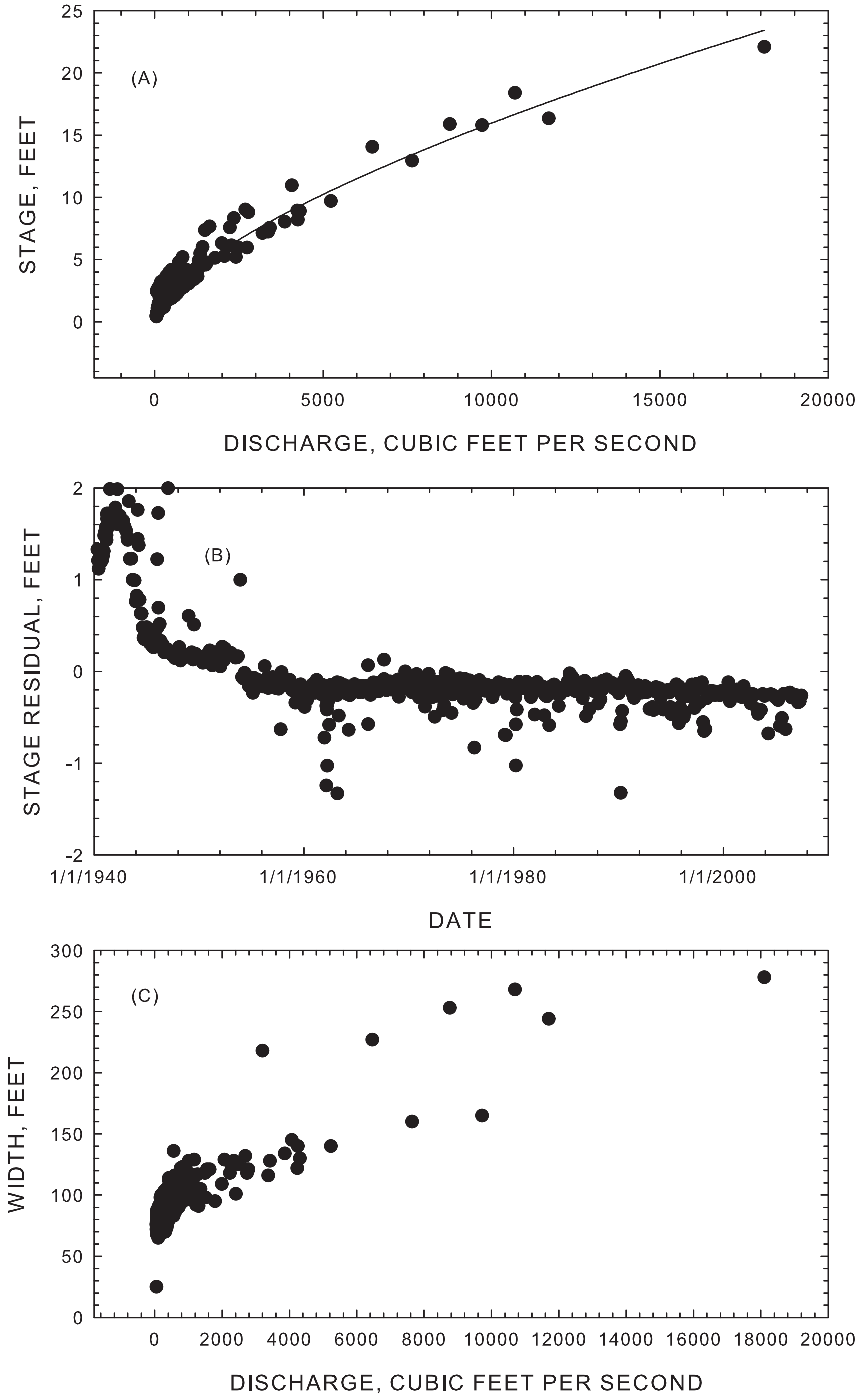

Figure 5.48: Geomorphic analysis of stream gage data for Chestatee River near Dahlonega, GA (Station number: 02333500): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge

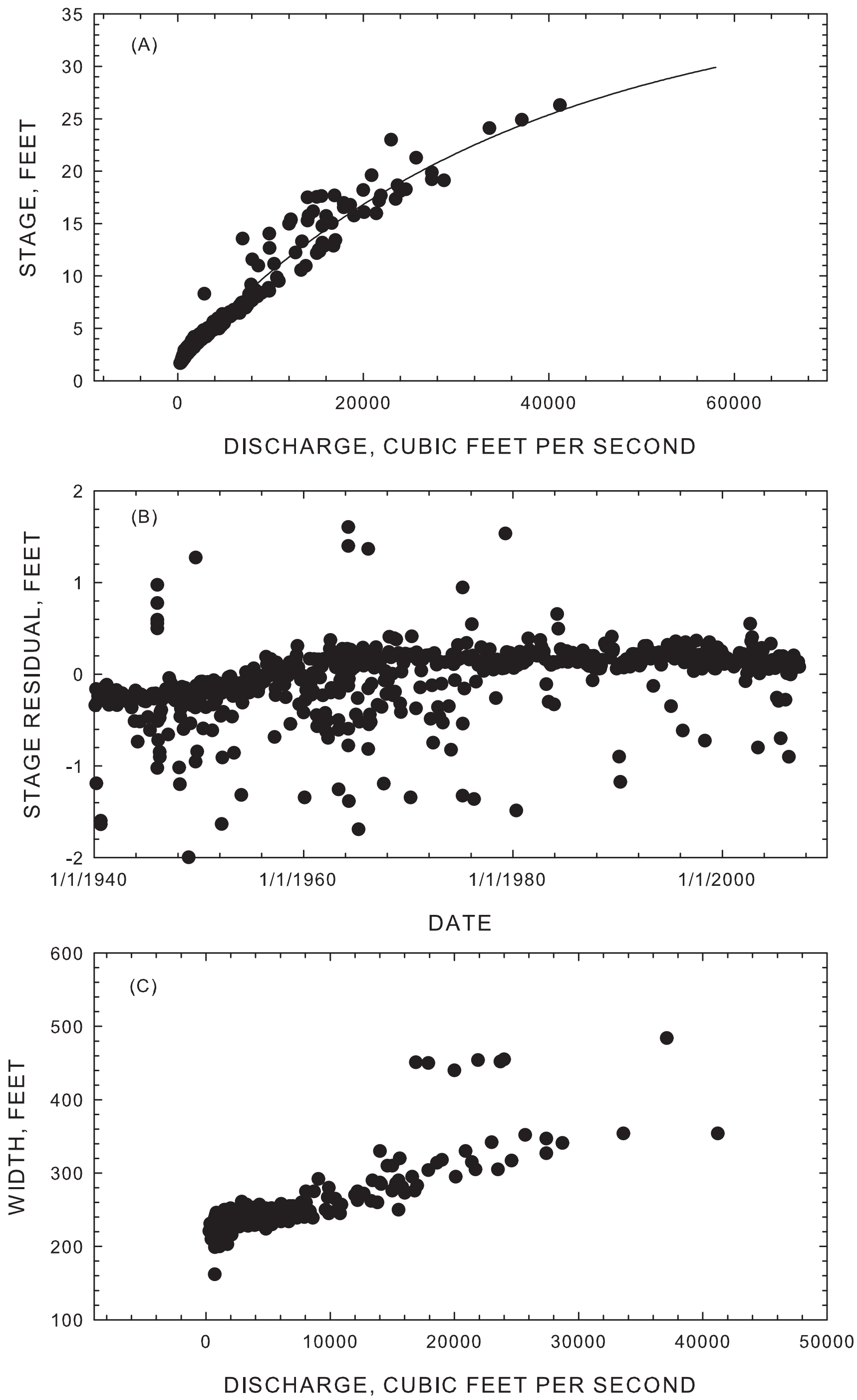

Figure 5.49: Geomorphic analysis of stream gage data for Chattahoochee River at Atlanta, GA (Station number: 02336000): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge

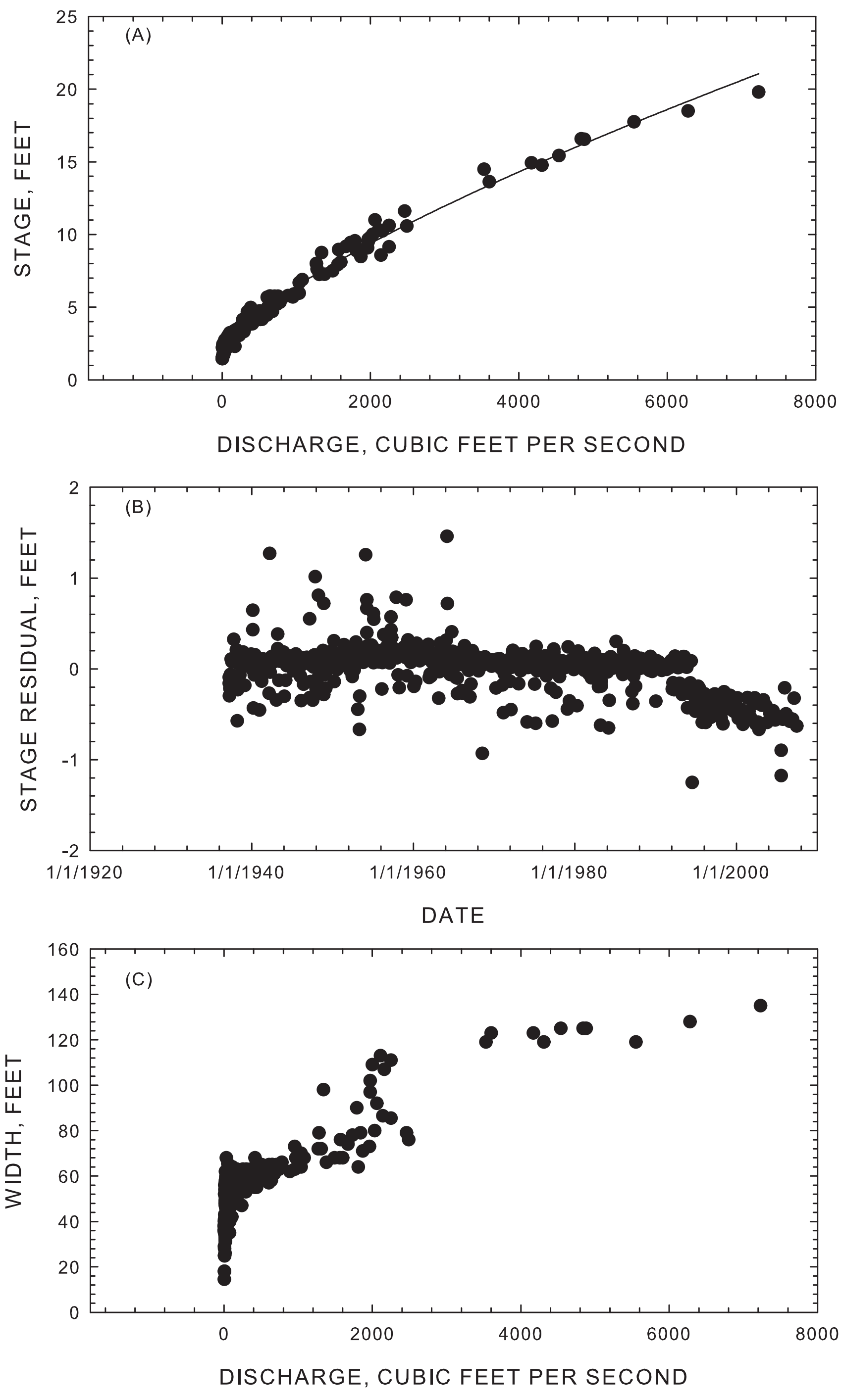

Figure 5.50: Geomorphic analysis of stream gage data for Tobesofkee Creek near Macon, GA (Station number: 02213500): (A) stage and discharge; (B) time series of stage residuals; (C) width and discharge

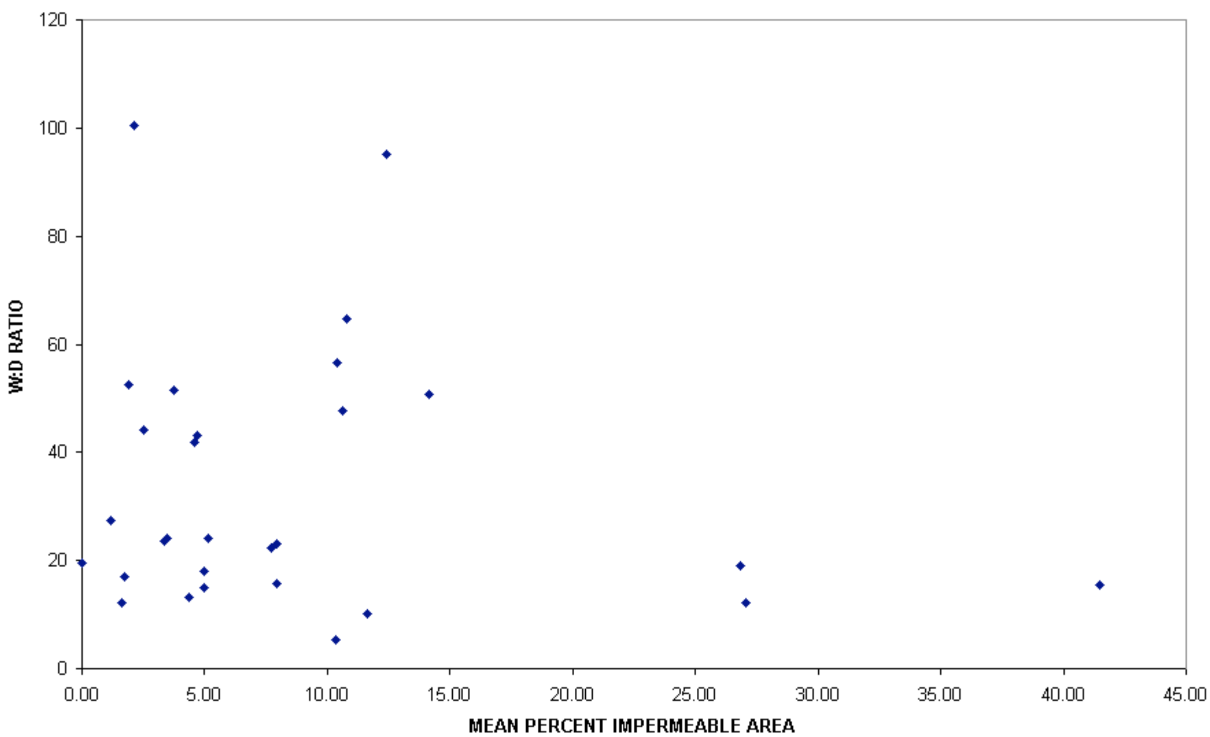

Figure 5.51: Relationship between width : depth ratio and impervious surface cover

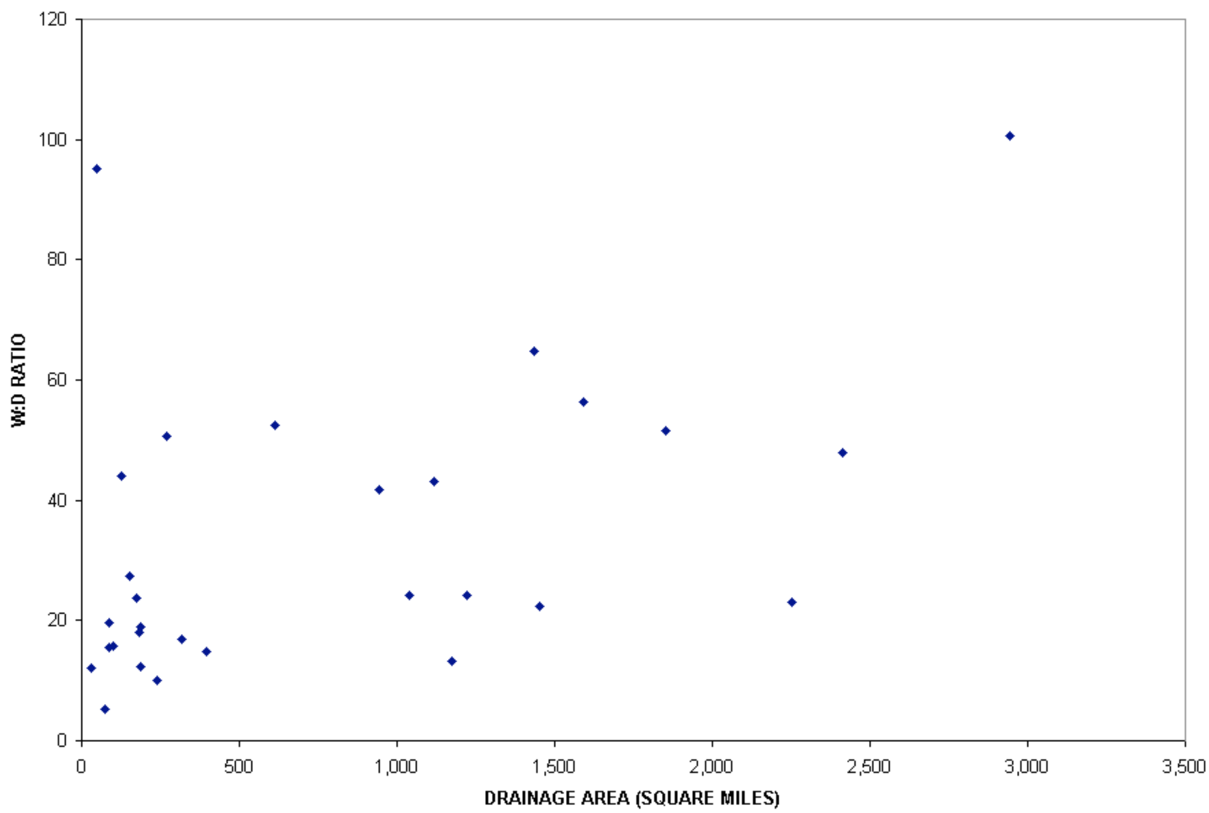

Figure 5.52: Relation between width : depth ratio and drainage area

Figure 5.53: Uppermost RGA location on the Flint River just above Flt0 both locations had the same response only Flt0 was more deeply incised

Figure 5.54: Lowermost site in the basin above Pine Mountain Ridge. This site had low well vegetated banks and appeared undisturbed

Figure 5.55: Representative reach for FLT1, illustration alternating bars and incipient meander.

Figure 5.56: Example of fluvial erosion that was present through most of the reach at Flt3.

Figure 5.57: Example mass wasting (right bank) and vegetation covered failed blocks that are now protecting bank toe.

Figure 5.58: Evidence of both mass wasting and fluvial erosion (left bank) approximately 1/4-mile upstream of gage.

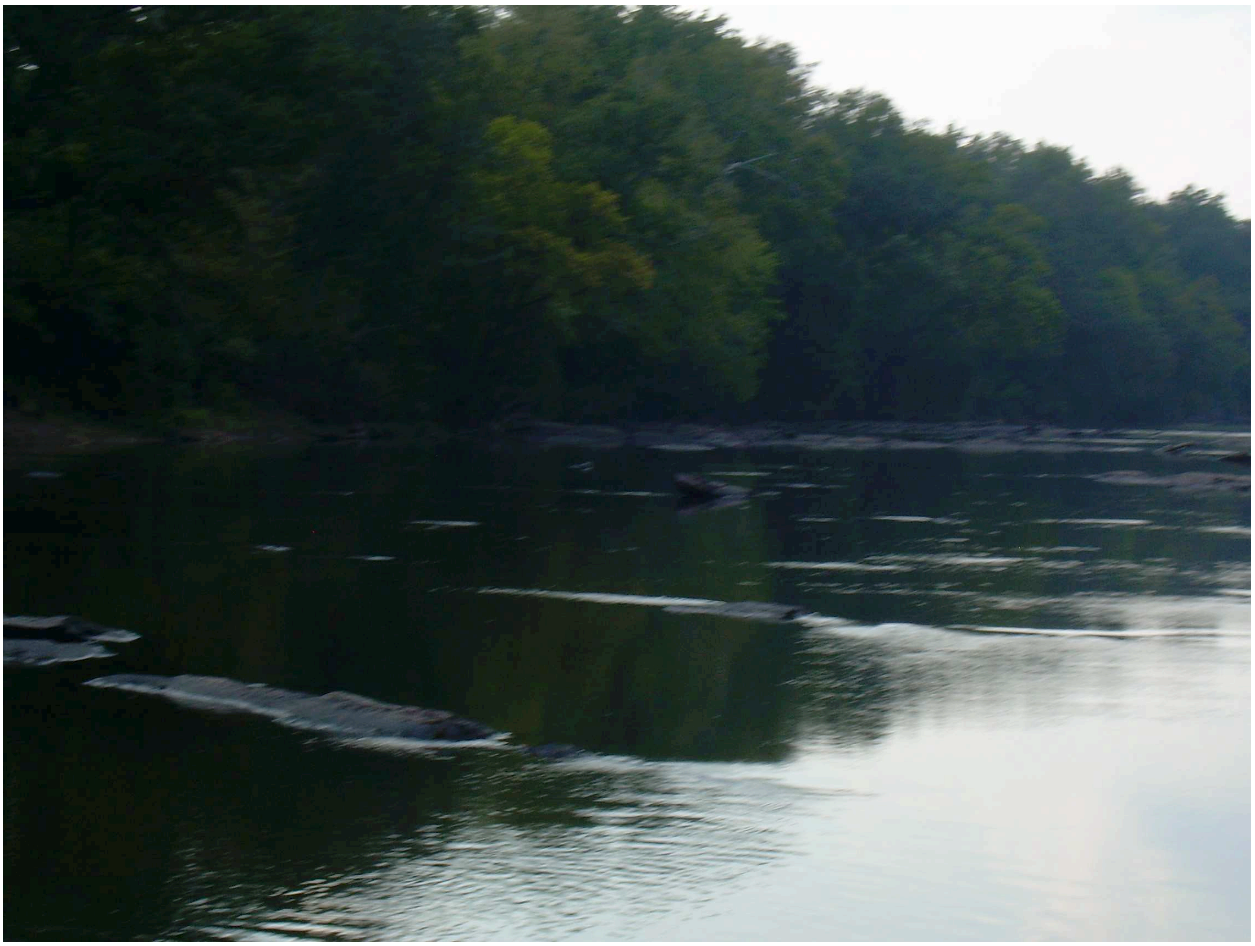

Figure 5.59: Example of bedrock control on bed level adjustment.

Figure 5.60: Example of mass wasting and fluvial erosion along a very slight outward bend of the Flint River below Pine Mountain Ridge.

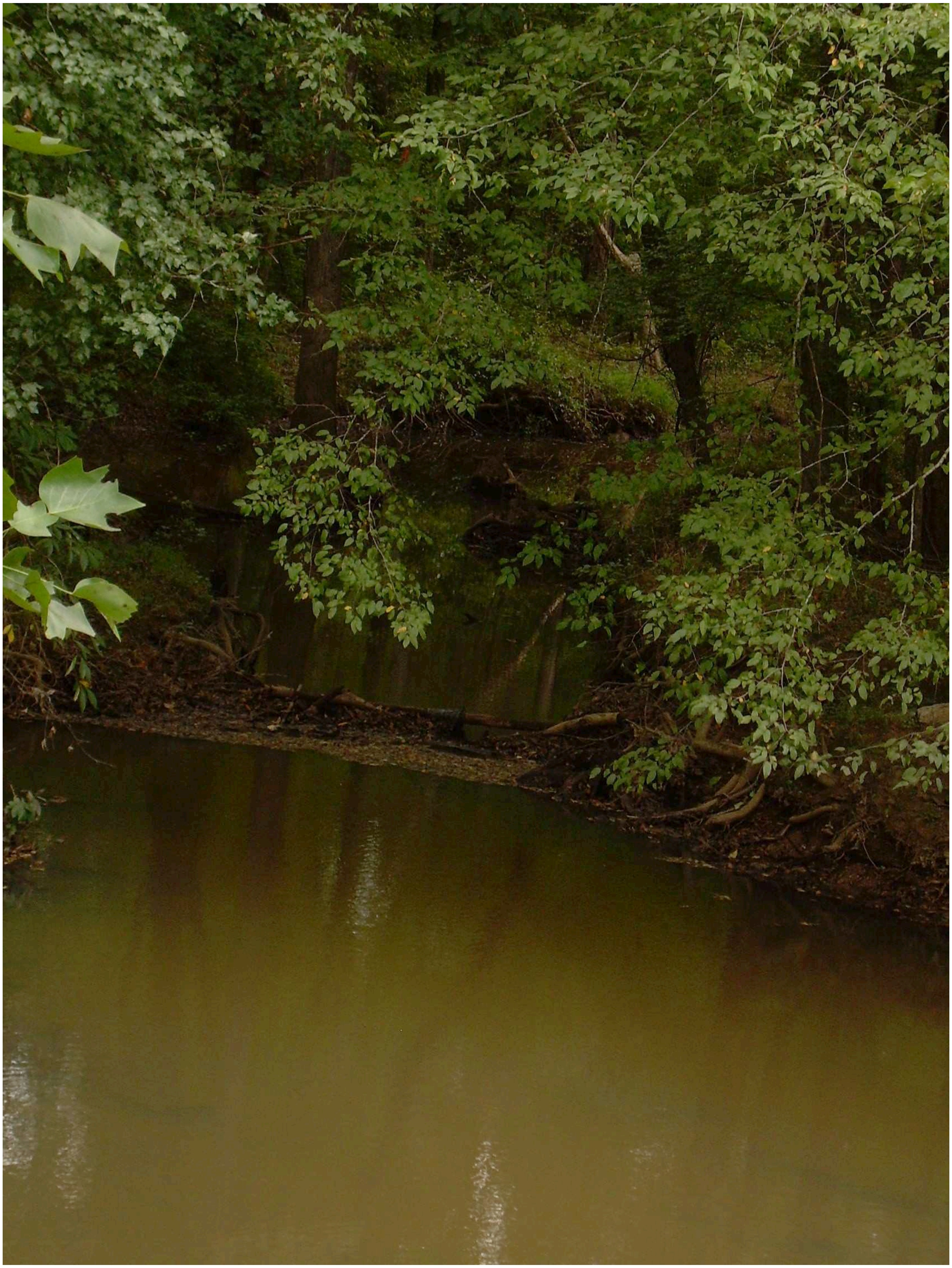

Figure 5.61: Channel downstream of pool exhibits minor fluvial erosion with low stable banks.

Figure 5.62: Representative reach at LINE2. Trees in stream are from mass wasting events.

Figure 5.63: Evidence of coarse bed downstream of small dam at LINE3 and apparent lateral stability of the reach.

Figure 5.64: Reach at LINE4 located upstream of the stream gage, experienced large amount of mass wasting. In the center of the photo is a vegetated bar apparently the result of a large amount of failed bank material.

Figure 5.65: Representative reach of PT1.

Figure 5.66: Representative reach of PT2. Only about 1/4-mile downstream from PT1 exhibits a more wetland character and appears undisturbed.

Figure 5.67: Location visited to perform RGA on Potato Creek where multiple channels were encountered. Vegetated area to the right had two smaller channels flowing through it.

Figure 5.68: Directly upstream of dam on Potato Creek, above location for RGA PT4.

Figure 5.69: Representative reach for RGA PT4 about 1/4-mile downstream of dam. Bar in the middle of the photo is dominated by cobbles and gravel.

Figure 5.70: Partially breach mill dam on Potato Creek approximately 1/4-mile above reach for RGA PT5.

Figure 5.71: Furthest downstream site on Potato Creek, stream is deeply entrenched. For reference, man in the stream is about six-feet tall.

Chapter 6

Discussion

6.1 Urban Gradient Analysis

The hypothesis for this portion of the study was that systematic trends would be observed in channel response (from residual plots) and in width:depth ratios (W:D) at the approximate bank full discharge (calculated as 2 yr recurrence interval flow from annual duration series) to varying amounts of impervious cover. These variables have been used in other studies with success (Wolman, 1967; Chin 2006). However no significant trends were observed in this study. The one, largely anecdotal, trend that was noticed is that many of the streams that did exhibit decreased water surface elevation (degradation) were in smaller more urbanized basins. In terms of the W:D ratio this could adjust in either direction depending on boundary material. In other words, it is possible that a channel will incise only and not adjust width which would result in a decreased W:D ratio. Some studies have found width (i.e. lateral adjustment) to be the dominant adjustment in urbanizing basin (Arnold, et.al, 1982; Gregory, et.al, 1992) whereas others have documented incision as the dominant mode of adjustment (Booth, 1990). Thus without detailed knowledge about boundary conditions for each gage location, W:D was not the best variable to analyze.

Without details of boundary conditions many controlling variables were missing from the dataset (e.g. soil type, gradient, lithology, as well as others). Other studies (Booth, 1990; Allen and Narramore, 1985) found these to be important variables, exerting a greater control over reach scale adjustments than broad scale impervious cover. The possibility also exist that the urban effects are less pronounced in the piedmont area due to the legacy of disturbances left from historical agriculture (Jackson, 2007 personal communication). For

LTS to be used reliably, many factors need to be controlled, for which existing data were not available.

The only land cover data available was from 2001 which could be somewhat misleading, considering the rapid growth that continued in metro Atlanta and surrounding areas through 2007. Another consideration is the idea of total impervious cover (TIC) versus effective impervious cover (EIC, Booth and Jackson, 1997). This concept addresses the concern that not all impervious cover has a direct impact on runoff generation to stream channels. Greater detail and updated land cover data may have improved this analysis.

6.2 Channel Adjustments in the Flint River and Tributaries

In the mainstem of the Flint River, channel adjustments were apparent from gage data and evidence of adjustment was obvious at many of the site where RGAs were conducted. RGAs performed in the vicinity of the gage locations generally supported results from gage data analysis. The Flint River at Lovejoy gage exhibited decreasing stage from the gage analysis and this was generally supported by the RGA, which observed bank toe erosion which usually occurs after a decrease in bed elevation. At Line Creek and Flint River near Griffin, the adjustments were apparent from gage data analysis. Both of the reaches are deep, sluggish, and very turbid so it was difficult to determine adjustments to the bed or bank toe; however width adjustments were apparent at both locations in the form of mass wasting scars, fallen trees, and exposed root wads. At the gage location furthest downstream, Flint River at Carsonville, data indicated relative stability. The RGA supported this with only a small portion of the reach exhibiting bank erosion and the bed composed largely of bedrock outcrops.

Channel adjustments did not follow the longitudinal sequence of evolutionary forms (Figure 6.1) noted by others (Simon, 1989; Bledsoe et. al, 2001). In other studies a primary knickpoint was identified from where disturbances originated and the evolutionary sequence was set in motion. The initial basis of channel evolution models is set on the premise that temporal and spatial adjustments are in response to a single base level lowering (Bledsoe et al, 2001). In reality this sequence could be altered because of multiple disturbances, upland land-use, or human interjection.

The initial hypothesis for this study was that channels in the Flint River basin would be adjusting in response to land use - urbanization, historical agriculture, or both. In terms of bed level adjustment, as viewed using gage data analysis, adjustments were occurring at low magnitude. Initially more merit was placed on the hypothesis of adjustments due to urbanization. This was largely because of the close proximity of the headwaters and upper reaches to the city of Atlanta and the substantial body of literature supporting the detrimental effects of urbanization on stream morphology (e.g. Wolman, 1964; Chin, 2006; Colisimo and Wilcock, 2008). After a firsthand account of much of the basin and somewhat outdated land cover maps (2001) the widespread urbanization is isolated to the very upper reaches, and only sparse amounts elsewhere (Figure 6.2).

The Flint River has an abundance of riparian wetlands. In some of these areas multiple channels were encountered. Knickpoints usually migrate upstream by headward erosion, when an area of multiple channels is encountered there is the possibility for energy dissipation. This could result in the stalling or halting of the knickpoint migration (Knighton, 1998). For this reason it is believed that observations from the Flint River are the result of local scale disturbances or possibly the result of lagged response from historical agriculture. Many areas that had a wetland character retained the appearance of undisturbed. However in most locations where the RGAs were performed consisting of a single channel, either fluvial erosion or mass wasting was encountered. One of the benefits of wetlands is their ability to retard flood waters and attenuate peak flows (Dodds, 2002) and by doing so reducing energy and shear stress. From field reconnaissance, it is believe the amount of wetlands present could attenuate much of the storm pulse delivered from upstream urbanized areas.

Following the initial hypothesis, that adjustments would be taking place primarily due to urbanization, two large tributaries of the upper Flint were selected to perform additional RGAs to test the effects of urbanization. Line Creek was selected as the urban basin having eight percent impervious cover, and Potato Creek as the rural, with just under three percent impervious cover. Although these basins are categorized based on which had the greatest urban cover, they are both relatively rural with the majority of the imperviousness located in their upper reaches. The results obtained from both basins highlight the effect of wetlands dissipating energy and retarding flood waters. Responses between basins were indistinguishable, with what appeared to be local scale disturbances responsible for observed morphological adjustments.

One difference between the basins that could have a substantial influence on water and sediment delivery is the presence of legacy mill dams and farm ponds on Potato Creek (Walter and Merritts, 2008). While performing RGAs on Potato Cr. two mill dams were encountered on the main channel. One was over 20 ft tall; the other was lower and had been damaged allowing water to flow over about one fourth of the channel bed. Below both dammed locations the stream bed was coarser than any of the other sites. The Potato Creek basin also has many small impoundments (flood control structures) on its tributaries and a few on the mainstem.

Line Creek was low gradient and wetland like at all locations except downstream of a small pond where it too had a much coarser bed composed largely of bedrock. The difference was primarily in bank height. Potato Cr. was a stage III at these locations and was entrenched, where as the Line Cr. Site had low banks and appeared to be an undisturbed, stage I. Further down Line Cr. in the vicinity of the stream gage the stream was deep and sluggish. This site exhibited the greatest instability in this basin. The dominant process throughout this reach was mass wasting.

In most of the locations both streams showed the same basic response; in the wetland areas, channels appeared relatively undisturbed. It was in the lower reaches of both where large amounts of wasting bank erosion were encountered. Downstream of small dams the response was similar as well with coarsening of the bed material encountered at both but morphological adjustments only obvious in Potato Creek. The presence of the dams alone helps support the hypothesis of multiple disturbances in the tributaries, as they would be an impediment to knickpoint advancement or large sediment waves moving downstream.

6.3 Hypothetical Scenarios for Multiple Disturbances

Hypothetical scenarios for multiple disturbances will begin by considering potential influences from historical agriculture and then contemporary factors that may have helped shaped the Flint River and be responsible for observed conditions. First, this area was subject to large scale deforestation for agriculture in the early 19th century. Accounts of this from Trimble (1974) report some streams channels completely filling with sediment and water would then flow onto the floodplain until there was sufficient energy to cut through the eroded sediment to once again form a channel. If this were the case in the Flint River, riparian wetlands that are quite prevalent could be a result of large scale valley aggradation. These wetlands could represent areas where there is a break in valley slope. If this were the case, where multiple channels are observed there could have not been a single path of least resistance when the stream began to once again cut through the deposited material. Multiple channels could then be the result, which were observed at a many locations.

If this mechanism were responsible for the current form of the Flint River I believe it could be viewed as its new state, similar to a press type disturbance (Lake, 2000). Due to the shallow slopes, it would take floods of great magnitude to erode and transport the sediment in wetland and floodplain storage. It also would take great energy for a knickpoint to migrate headward through a wetland area where multiple channels are present. As for the single thread channels that are not located immediately in contact with the wetlands, they could continue to adjust and follow a similar evolutionary sequence as that predicted by Simon (1989), however the predictability/extrapalability of other locations in the watershed may not hold true. If the channels are mass wasting and failed bank material is supplying sediment, channels will likely continue to widen until energy is dissipated in these reaches and aggradation will begin to occur, returning a new equilibrium condition.

The second scenario could be similar assuming that the wetlands are natural and have been present for thousands of years. If this were the case agriculture could still be a major factor. Streams draining agriculture fields could contribute multiple disturbances. Depending on spatial distribution of tributary junctions and local slopes the effects could be additive, leading to large slugs of sediment forming expansive deltaic deposits responsible for a gradient of sediment deposition extending outward from the now enlarged wetland areas. Sediment that is in storage (in floodplains and upstream channels) may or may not be available for transport depending on local slopes and magnitude of hydrometeorlogical events. If a case of this nature exists then it is likely that in the current climatic regime the Flint Basin would remain in a similar dynamic state, given near static land development scenarios.

Thirdly, assuming the riparian wetlands are natural, observed channel response from the Flint River could be due to contemporary local scale disturbances. For example, at the Love Joy gage there is a large water plant that more than likely contributed to some instability at least at the reach scale. In the vicinity of the Griffin gage is a large dairy farm immediately adjacent to the channel. Livestock access to streams are known (Trimble, 1994) to destabilize stream channels via direct trampling as well as soil compaction that increases surface runoff. Many of the areas where RGAs were performed had similar indicators of local disturbances (residential areas immediately on bank, drainage ditches directly to the channel, small pond and mill dams in the tributaries, as well as others). All of these are examples of local scale factors that could potentially cause a disturbance and channel instability. However, due to the intermittent nature of wetland occurrence it is not likely that these disturbances would migrate past these areas. As a result, it is believed that observed responses are most likely due to disturbances operating on local (reach or segment) scales.

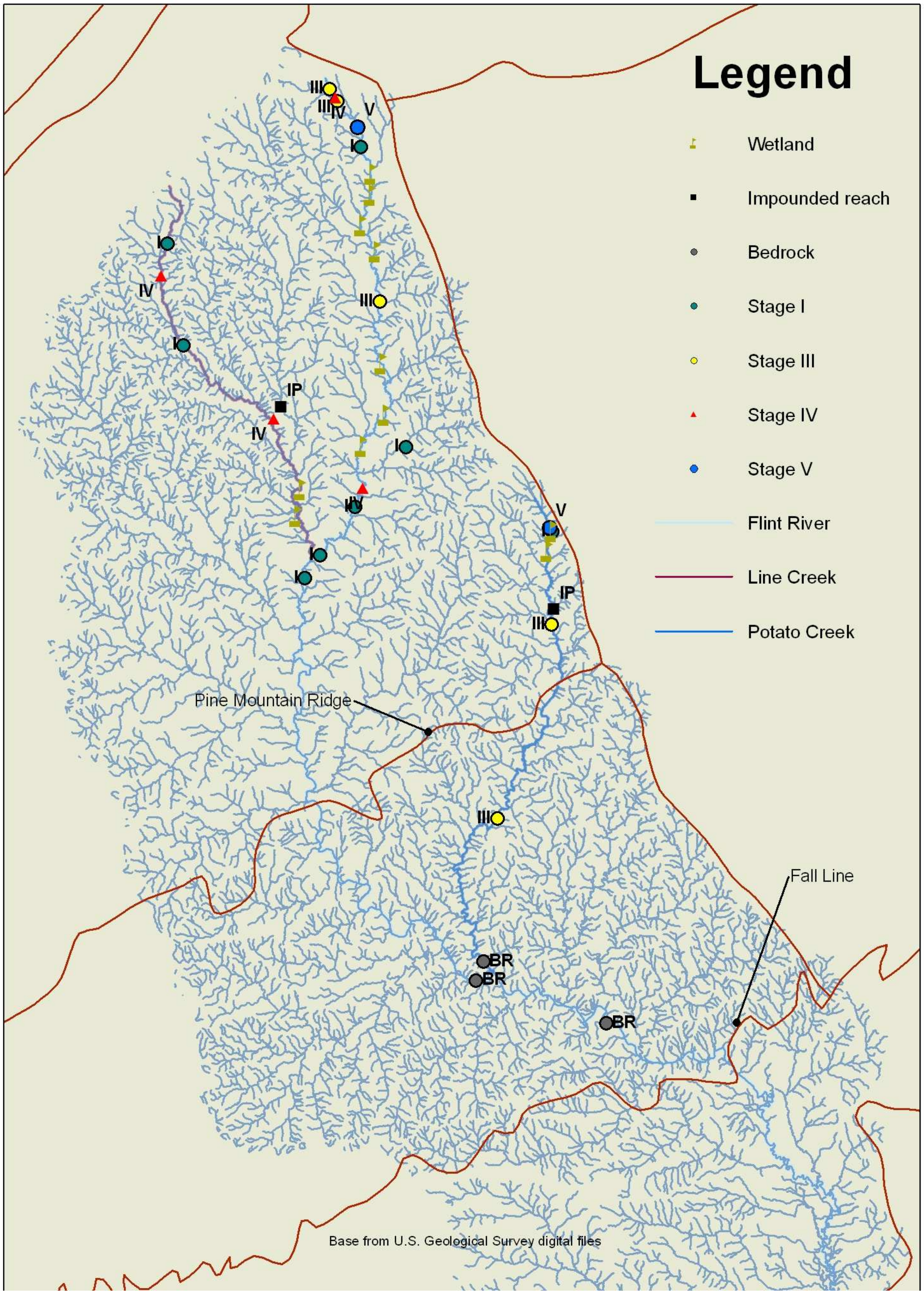

Figure 6.1: Location and observed response at RGA locations, green flags represent areas that are wetland like and/or have multiple channels, grey circles (BR) represents sites with substantial bedrock that may inhibit adjustments

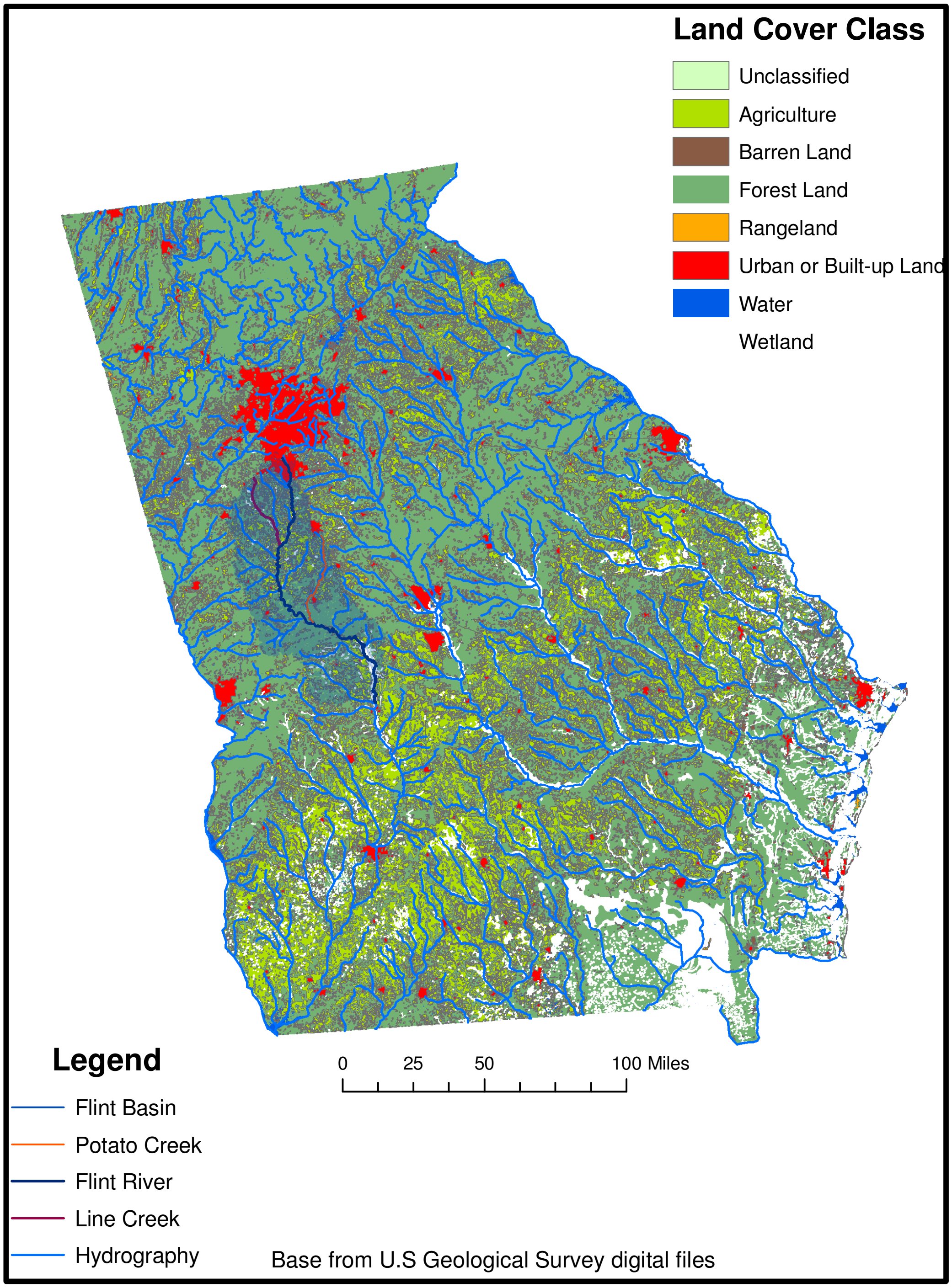

Figure 6.2: State of Georgia land cover classification as of 2001

Chapter 7

Conclusions

As demonstrated, the Flint River and its tributaries have been dynamic over the recorded period and do show some signs of adjusting to disturbances. Although the density of the gage network was not sufficient to alone make strong inferences; it supports the hypothesis that adjustments are occurring in the upper reaches. From gage data analysis it was determined that the station in the lower portion of the basin (02347500) has been relatively stable, demonstrating minor variability indicative of dynamic equilibrium. Gage data analysis at station 02344500 indicated a slight wavy pattern. In the upper reaches, at station 02344350 and 02344700, trends of slight degradation were occurring with a maximum magnitude of about one-half foot over the record. While adjustments were observed at the gage locations, they were discontinuous in between. Many of the locations visited for RGAs between gage locations appeared undisturbed and were often wetland like with multiple channels. It is unknown if observed responses are a result of external stressors such as urbanization, or if it is internal to the system, such as sporadic sediment movement through the basin resulting in aggradation and subsequent degradation.

These observations support that most adjustments appear to only operate on a local scale and appear discontinuous. However this is not to infer that local scale disturbances could not influence ecological integrity. Rather that channel adjustments do not appear to be related to a single event and do not appear to migrate over large areas. The abundant wetlands in the basin may provide a mechanism of self preservation against wide spread physical adjustments all the while protecting water quality and ecological function. However if land development continues a threshold may be exceeded in which the wetlands become overwhelmed and cannot dissipate sufficient energy to prevent wide scale channel adjustments. Thus it is imperative to recognize and protect those areas that are least disturbed, to maintain both ecological and societal functions.

Chapter 8

References

Aiken, C. S. (1998). The Cotton Plantation South since the Civil War 1st ed. Johns Hopkins University Press (1998).

Alberti, M., Booth, D., Hill, K., Coburn, B., Avolio, C., Coe, S. and Spirandelli, D. (2007). The impact of urban patterns on aquatic ecosystems: An empirical analysis in puget lowland sub-basins. Landscape and Urban Planning 80(4): 345-361.

Allen, P. and Narramore, R. (1985). Bedrock controls on stream channel enlargement with urbanization, North Central Texas. Water Resources Bulletin. 21(6): 1037-1048.

Ambers, R. K. R., Druckenbrod, D. L. and Ambers, C. P. (2006). Geomorphic response to historical agriculture at Monument Hill in the Blue Ridge Foothills of Central Virginia. CATENA 65(1): 49-60.

Arnold CL, Boison PJ, Patton PC. (1982). Sawmill Brook: an example of rapid geomorphic change related to urbanization. Journal of Geology 90: 155166.

Beechie, T. J., Pollock, M. M., and Baker, S. (2008). Channel incision, evolution and potential recovery in the Walla Walla and Tucannon River Basins, Northwestern USA. Earth Surface Processes and Landforms 33(5): 784-800.

Bledsoe, B.P., Watson, C. C., and Biedenharn, B. D (2002). Quantification of incised channel evolution and equilibrium. Journal of the American Water Resources Association 38(3): 861-870.

Blench, T., (1969). Mobile-Bed Fluviology: A Regime Theory Treatment of Canals and Rivers for Engineers and Hydrologists, University of Alberta Press, Edmonton (1969).

Booth, D.B., (1990). Stream channel incision following drainage basin urbanization. Water Resources Bulletin. 26(3): 407-417.

Booth, D. B., (1991). Urbanization and the Natural Drainage System-Impacts, Solutions and Prognoses. Northwest Environmental Jl. 7(1):93-118.

Booth, D. B. and Jackson, C. R., (1997). Urbanization of Aquatic Systems - Degradation Thresholds, Stormwater Detention, and the Limits of Mitigation. Journal of the American Water Resources Association 33(5):1077-1090.

Bouvier, L. and Mccloe-Stein, S. NPG Special Report Georgia's Dilemma: The unintended consequences of population growth. http://www.npg.org/ga_poll/georgia.html

Brown, R.H. (2002). The Greening of Georgia: the improvement of the environment in the twentieth century. Mercer University Press (pp.362).

Brunsden, D. and Thornes, J. B. (1979). Landscape sensitivity and change. Transactions of the Institute of British Geographers 4(4): 463-484.

Burns, D., Vitvar, T., McDonnell, J., Hassett, J., Duncan, J. and Kendall, C. (2005). Effects of suburban development on runoff generation in the Croton River Basin, New York, USA. Journal of Hydrology 311(1-4): 266-281.

Chin, A. (2006). Urban transformation of river landscapes in a global context. Geomorphology 79(3-4): 460-487.

Colosimo, M. F. and Wilcock P. R. (2007). Alluvial sedimentation and erosion in an urbanizing watershed, gwynns falls, maryland. JAWRA Journal of the American Water Resources Association 43(2): 499-521.

Cooksey E. B. (2006) Meriwether County. New Georgia Encyclopedia. Retrieved March 11, 2007:
http://www.georgiaencyclopedia.org/nge/Article.jsp?id=h-2366&sug=y

Cowell, M.C., (1998). Historical change in vegetation and disturbance on the Georgia piedmont. Am. Midl. Nat. 140: 7889.

Daniels, J. M. and Knox, J. C., (2005). Alluvial stratigraphic evidence for channel incision during the Medieval Warm Period, Central Great Plains, USA. The Holocene, v. 15, p. 736-747.

Davis, W.M., 1902. Base Level, Grade, and Peneplain: Geophysical Essays, XVIII, pp. 381-412, Ginn, Boston.

Dodds, W. K., (2002). Freshwater Ecology: Concepts and Environmental Applications. Academic Press 2002.

Georgia Department of Agriculture. Georgia: Historical and Industrial. Atlanta, GA: Franklin Printing and Publishing Company, 1901.

Georgia Geologic Survey. Water Powers of Georgia. Atlanta, GA: Franklin Printing and Publishing Company,1896.

Giesen J.C. (2004). Cotton. New Georgia Encyclopedia. Accessed February 6, 2007:
http://www.georgiaencyclopedia.org/nge/Article.jsp?id=h-2087&hl=y

Georgia Land Use Trends, (1998). Land cover of the upper Flint watershed: Natural Resources Spatial Analysis Laboratory, Institute of Ecology, Athens, Ga.,

accessed August 19, 2007:
http://narsal.ecology.uga.edu/glut.html

Gregory, K. J., (2006). The human role in changing river channels. Geomorphology 79 (3-4): 172-191; 37th Binghamton Geomorphology Symposium - The Human Role in Changing Fluvial Systems.

Gregory, K. J. and Brookes, A. (1983). Hydrogeomorphology downstream from bridges. Applied Geography 3(2): 145-159.

Gregory, K.J., Davis, R.J., Downs, P.W., (1992). Identification of river channel change to due to urbanization. Applied Geography 12: 299318.

Hanley, T. (2006). Piedmont Geologic Province, New Georgia Encyclopedia accessed online 3-12-2009 at: http://www.georgiaencyclopedia.org/nge/Article.jsp?id=h-1162&hl=y

Hack, J.T. 1960. Interpretation of erosional topography in humid temperate regions. American Journal of Science, Bradley Volume 258-A: 8097.

Harper, F.(Ed.). 1998. The Travels of William Bartram: Naturalist Edition, University of Georgia Press. 824 pp.

Harvey, A. M. (2007). Geomorphic instability and change-introduction: Implications of temporal and spatial scales. Geomorphology 84(3-4): 153-158.

Horowitz, R.J., Johnson, T. and Hession, W. C. (2001). Fish communities along an urban gradient: Influences of riparian vegetation. World Water Congress 2001, ASCE.

Hughes, W.B., Freeman, M.C., Gregory, M.B., and Peterson, J.T., 2007, Water availability for ecological needs in the upper Flint River Basin, Georgia - A USGS Science Thrust project: Proceedings of the 2007 Georgia Water

Resources Conference, March 27-29, 2007, Athens, Georgia, accessed online at http://cms.ce.gatech.edu/gwri/uploads/proceedings/2007/6.6.1.pdf

Jacobson, R. B. 1995. Spatial controls on patterns of land use induced stream disturbances at the drainage-basin scale an example for gravel-bed streams in the Ozark Plateaus, Missouri. In: J.E Costa, A.J. Miller, K.W. Potter, and P. R. Wilcock, eds. Natural and Anthropogenic Influences in Fluvial Geomorphology. American Geophysical Union Monograph 89: pp. 219-239

Jackson, C.R., Martin, J.K., Leigh, D.S., and West, L.T., (2005). A Southeastern Piedmont Watershed Sediment Budget; Evidence for a Multi-Millennial Agricultural Legacy. J. Soil Water Cons. 60(6):298-310.

James, L. A. (1991). Incision and morphologic evolution of an alluvial channel recovering from hydraulic mining sediment. Geological Society of America Bulletin: 723-736.

James, L. A. and Marcus, W. A. (2006). The human role in changing fluvial systems: Retrospect, inventory and prospect. Geomorphology 79(3-4): 152-171.

Jiongxin, X. (1997). Study of sedimentation zones in a large sand-bed braided river: An example from the hanjiang river of china. Geomorphology 21(2): 153-165

Johnson, R. M.,Warburton, J., Mills, A. J., (2008). Hillslope-channel sediment transfer in a slope failure event: Wet Swine Gill, Lake District, northern England Source: Earth surface processes and landforms vol:33 iss:3 pg:394 -413

Juracek, K. E. and Fitzpatrick, F.A. (2009). Geomorphic applications of stream-gage information. River Research and Applications. v.25, p.329-347

Kang, R. S. and Marston, R. A. (2006). Geomorphic effects of rural-to-urban land use conversion on three streams in the central Redbed Plains of Oklahoma. Geomorphology 79(3-4): 488-506.

Kaufmann, P. R., Faustini, J. M., Larsen, D. P. and Shirazi, M. A. (2008). A roughness-corrected index of relative bed stability for regional stream surveys. Geomorphology 99(1-4): 150-170. Knighton, D.1998, Fluvial Forms and Processes: A new perspective. Oxford University Press, New York 1998, pp.168

Knox, J.C., (1977). Human impacts on Wisconsin stream channels. Annals of the Association of American Geographers 67, pp. 323-342.

Knox, J.C., (1983). Responses of river systems to Holocene climates. In: Wright Jr., H.E. Editor, 1983. Late Quaternary Environments of the United States Vol. 2 The Holocene. University of Minnesota Press, Minneapolis, pp. 26-41.

Knox, J. C. (2001). Agricultural influence on landscape sensitivity in the Upper Mississippi River Valley. CATENA 42(2-4): 193-224.

Kondolf, G.M. (1997). Hungry water: Effects of dams and gravel mining on river channels. Environmental Management. Vol. 21(4): 533-551.

Kuhnle, R., Simon, A., (2000). Evaluation of Sediment Transport Data for Clean Sediment TMDL's. National Sedimentation Laboratory Report 17, Oxford, MS. 65 pp.

Kundell, J. E., White, F. C., and Graham, J. (1982). Prime farmland in Georgia. Athens, Ga, Institute of Government, University of Georgia.

Lake, P. S. (2000). Disturbance, patchiness, and diversity in streams. Journal of the North American Benthological Society 19(4): 573-592.

Langbein, W. B., and Leopold, L. B. 1964. Quasiequilibrium States in Channel Morphology. American Journal of Science 262:782-794.

Lane, E.W., (1955). The importance of fluvial morphology in hydraulic engineering, Proceedings of the American Society of Civil Engineers 81 (1955), pp. 1-17

Leopold, L.B. and Maddock, T. Jr. 1953.The hydraulic geometry of stream channels and some physiographic implications, US Geol. Survey Prof. Paper 252 (1953).

Leopold, L. B., and Langbein, W. B. 1962. The Concept of Entropy in Landscape Evolution. United States Geological Survey Professional Paper 500- A. Washington, D.C.: U.S. Government Printing Office.

Mackin, J. H. (1948). Concept of a graded river, Bulletin of the Geological Society of America, 59:463-511.

Magilligan, F. J. and Stamp, M.A., (1997). Historical Land-Cover Changes and Hydrogeomorphic Adjustment in a Small Georgia Watershed, Annals of the Association of American Geographers, Vol. 87, No. 4. (Dec., 1997), pp. 614-635.

Mazeika, S., Sullivan, P., Watzin, M. and Hession, W. (2004). Understanding stream geomorphic state in relation to ecological integrity: Evidence using habitat assessments and macroinvertebrates. Environmental Management 34(5): 669-683.

Newson, M. D. and Newson, C. L. (2000). Geomorphology, ecology and river channel habitat: Mesoscale approaches to basin-scale challenges. Progress in Physical Geography 24(2): 1195-217.

Niezgoda, S. L. and Johnson, P. A. (2005). Improving the urban stream restoration effort: Identifying critical form and processes relationships. Environmental Management 35(5): 579-592. NPG special report, Georgiafs Dilemma: The unintended consequence of population growth Accessed December 29, 2007: http://www.npg.org/ga_poll/georgia.html

Ourso, R.T. and Frenzel, S.A., (2003). Identification of linear and threshold responses in streams along a gradient of urbanization in Anchorage, Alaska: Hydrobiologia 501: 117-131

Park, C.C., (1977). Man-induced changes in stream channel capacity. In: K. J. Gregory ed. River Channel Changes. Wiley, New York

Parsons, M. and Thoms, M. C. (2007). Hierarchical patterns of physical-biological associations in river ecosystems. Geomorphology 89(1-2): 127-146.

Paul, M. J. and Meyer, J. L. (2001). Streams in the urban landscape. Annual Review of Ecology & Systematics 32: 333-333.

Pinter, N., 2005. Policy Forum: Floodplain encroachment since the 1993 flood. Science, 308: 207-208.

Pinter, N., and R.A. Heine, 2005. Hydrodynamic and morphodynamic response to river engineering documented by fixed-discharge analysis, Lower Missouri River, USA. Journal of Hydrology, 302: 70-91.

Poff, N. L., Bledsoe, B. P. and Cuhaciyan, C. O. (2006). Hydrologic variation with land use across the contiguous united states: Geomorphic and ecological consequences for stream ecosystems. Geomorphology 79(3-4): 264-285. Rasmussen, T. C., (2003). The Water Cycle in Georgia. New Georgia Encyclopedia. Retrieved 4-30-2008 at:
http://www.georgiaencyclopedia.org/nge/Article.jsp?id=h-947&hl=y

Richard, G. A., Julien, P. Y. and Baird, D. C. (2005). Statistical analysis of lateral migration of the Rio Grande, New Mexico. Geomorphology 71(1-2): 139-155.

Rostlund, E., (1957). The Myth of a Natural Prairie Belt in Alabama: An Interpretation of Historical Records. Annals of the Association of American Geographers 47:392-411.

Schumm, S.A. (1977). The Fluvial System. Wiley, New York (1977).

Schumm, S.A., Harvey, M.D. and Watson, C.C., (1984). Incised Channels: Morphology dynamics and control: Water Resources Pub., Littleton, CO. 200 p.

Schumm, S.A., (1991). To Interpret the Earth: Ten Ways to be Wrong, Cambridge: Cambridge University Press, pp. 133

Shields Jr, F. D., Cooper, C. M., and Knight, S. S., (1993). Initial habitat response to incised channel rehabilitation. Aquatic Conservation: Marine and Freshwater Ecosystems 3(2): 93-103.

Simon, A. (1989). A model of channel response in disturbed alluvial channels. Earth Surface Processes and Landforms 14(1):11-26.

Simon, A. and Hupp, C.R., (1986). Channel evolution in modified Tennessee channels. In: Proceedings of the Fourth Interagency Sedimentation Conference, March 1986 vol. 2, Subcommittee on Sedimentation, Las Vegas, NV, pp. 5:71-82.

Simon, A. and Rinaldi, M. (2006). Disturbance, stream incision, and channel evolution: The roles of excess transport capacity and boundary materials in controlling channel response. Geomorphology 79(3-4):361-383.

Sloan, J., Miller, J.R., Lancaster, N. (2001). Response and recovery of the Eel River, California, and its tributaries to floods in 1955, 1964, and 1997. Geomorphology 36(3-4):129-154.

Smelser, M. G. and Schmidt J. C. (1998). An assessment methodology for determining historical changes in mountain streams. General Technical Report RMRS-GTR-6. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. pp. 29

Smith, R. D., Sidle, R. C., Porter, P. E., Noel, J. R., (1993). Effects of experimental removal of woody debris on the channel morphology of a forest gravel bed stream. Journal of Hydrology vol:152 iss:1-4 pg:153 -178

Stanly Consultants, (1979). Alternative Uses for the Upper Flint River Basin: Prepared for Army Corps of Engineers

Strahler, A.N., (1956). The nature of induced erosion and aggradation. In W. L. Thomas (Ed.), Man's Role in Changing the Face of the Earth. University of Chicago Press, Chicago, 621-638.

Strohbehn, R. (1986). An economic analysis of USDA erosion control programs: A new perspective. Agricultural economic report no. 560. Economic Research Services (DOA), Washington, D. C.: 88p.-88p.

Sullivan, S., Watzin, M., and Hession, W., (2006). Influence of stream geomorphic condition on fish communities in Vermont, U.S.A. Freshwater Biology, 51(10), 1811-1826.

Sutherland, A.B., Meyer, J. L., and Gardiner, E. P. (2002). Effects of land cover on sediment regime and fish assemblage structure in four southern Appalachian streams. Freshwater Biology 47: 1791-1805.

Thorn, C.E. and Welford, M.R. 1994. The Equilibrium Concept in Geomorphology. Annals of the Association of American Geographers, 84(4), p. 666-696.

Trimble, S.W., (1974). Man-Induced Soil Erosion on the Southern Piedmont 1700-1970 Soil Conservation Society of America, Ankeny, Iowa, - swcs.org

Trimble, S. W., (1994). Erosional effects of cattle on streambanks in Tennessee, U.S.A. Earth Surface Processes and Landforms 19(5): 451-464.

Trimble, S.W. and Brown, R. H., (2003). Soil erosion, New Georgia Encyclopedia. Retrieved August 23, 2008: http://www.georgiaencyclopedia.org/nge/Article.jsp?id=h-942&sug=y

Urban, M. C., Skelly, D. K., Burchsted, D., Price, W., and Lowry, S. (2006). Stream communities across a rural-urban landscape gradient. Diversity and Distributions. 12:337-350.

Walter, R. C. and Merritts, D. J., (2008). Natural streams and the legacy of water powered mills. Science vol. 319 p. 299-304

Waters, T. F. (1995). Sediment in stream: Sources, biological effects, and controls. American Fisheries Society Monograph 7.

Watson, C. C., Biedenharn, B. D., and Bledsoe, B.P., (2002). Use of incised channel evolution models in understanding rehabilitation alternatives. Journal of the American Water Resources Association 38(1): 151-160.

Williams, G.P. and Wolman, M.G., (1984). Downstream effects of dams on Alluvial rivers, Professional Paper vol. 1286, US Geological Survey, Washington D.C. (1984).

Wilson, K.V., Jr., and Turnipseed, D.P., (1994). Geomorphic response to channel modifications of Skuna River at the State Highway 9 crossing at Bruce, Calhoun County, Mississippi: U.S. Geological Survey Water-Resources Investigations Report 94-4000, 43 p.

Wolman, M.G., (1967). A cycle of sedimentation and erosion in urban river channels: Geografiska Annaler, v. 49A, no. 2-4, p. 385-395

Yarnell, S. M., Mount, J. F. and Larsen, E. W. (2006). The influence of relative sediment supply on riverine habitat heterogeneity. Geomorphology 80(3-4): 310-324.

Appendix A

Draft Manuscript - Evaluating Channel Adjustments Using Stream Gage Data: A Hierarchical Modeling Approach

EVALUATING CHANNEL ADJUSTMENTS USING STREAM GAGE DATA: A HIERARCHICAL MODELING APPROACH

Jeffrey W. Riley and James T. Peterson

ABSTRACT

Data from stream gages in the Upper Flint River basin, Georgia, USA allowed us to evaluate channel adjustments over periods of 21 – 78 years. Initial adjustments were inferred from changes in water surface elevation by analyzing the time series of residuals from the stage discharge relationship. Hierarchical linear models were then constructed to test hypotheses regarding channel adjustments in relation to different urban growth scenarios as well as the time since a high discharge event (two-year return interval). Results indicate that increases in short-term urban growth had a negative effect on the time slope of the residuals (bed level). The time since a high discharge event was positively related to the residual time slope (bed level) indicating an aggrading trend with less frequent high flow events. When these variables are viewed as interacting, short-term urban growth had the greatest effect on bed level when it had been three years or more since a high discharge event. This could be the result of fine sediment accumulating during the low discharge periods in between large flushing flows. The primary objective of this study was to illustrate a novel statistical technique; because stream gages were not randomly selected the results are generally site specific.

KEY WORDS: Akaike information criteria (AIC); channel change; disturbance; fluvial geomorphology; hierarchical linear model; stream gage

INTRODUCTION

Streams channels often change form in response to alterations in water or sediment delivery (Wolman, 1967; Booth and Jackson, 1997). This can be viewed using the concept of stream power proportionality $Q_bD50 \propto QS$; where Qb = bedload discharge, d50 = median grain diameter, Q = water discharge, and S = energy slope (Lane, 1955). The relationship between sediment supply and transport capacity will be altered and may result in channel adjustments if any one of the variables adjusts substantially. Most often adjustments will occur non-uniformly; in both time and space (Hoyle et. al, 2008). Local conditions and magnitude and frequency of the disturbance will dictate the pattern of adjustments, as will distance from the area of maximum disturbance (Simon, 1989). Adjustments may be present as both vertical (bed level) and lateral adjustments; these processes are not mutually exclusive and in alluvial settings, often operate in tandem or as a response to the other. For example, the channel evolution model as proposed by Simon and Hupp (1986) and Simon (1989) begins when a stream channel is subject to bed level lowering. This leads to degradation of the channel bed. Basal erosion occurs at the bank toe during normal flow levels which can result in destabilization of the banks by undercutting. Once the force of gravity overcomes the resistant force of the bank material, mass wasting will occur. This leads to channel widening and possible downstream aggradation (Schumm, 1984; Simon, 1989). Regardless of the cause of disturbance or mode of adjustment undesirable consequences often result.

The balance between water and sediment delivery in streams may be disturbed by natural and anthropogenic factors. Climatic fluctuations can alter precipitation patterns, changing the balance between sediment and transport capacity. These changes, however, generally occur over large time scales (Knighton, 1998). At shorter time scales (10^1 – 10^2 years), anthropogenic alterations to the landscape, such as stream impoundment and urbanization, generally have the greatest influence on stream channel change (Knighton, 1998). The effects of river impoundment on the morphology of downstream channels can often be considered the most extensive case in terms of altering ratio of sediment to transport capacity (e.g., Williams and Wolman, 1984; Kondolf, 1997). As water enters the reservoir, velocity and sediment transport capacity is decreased and sediment settles out, so when water is released from the dam it has excess energy and may erode the channel bed, banks, or both (Grant et al, 2003).

The influence of urbanization is more complex and generally consists of two different stages that vary with time. During the building or urban development phase, sediment supply is usually increased without a proportional increase in transport capacity that often leads to aggradation of the channel bed (Wolman, 1967). After the building is completed and sediment sources have been reduced through increased vegetative and impervious surface cover, transport capacity often exceeds sediment supply and may initiate bed and/or bank erosion. Whether it is the channel bed or banks that erode will depend largely on material composition (Simon and Renaldi, 2006). For example, bed degradation will dominate when channel bed is sand and the banks are cohesive due to the lower critical shear stress of the sand, whereas bank erosion will dominate once the sand is evacuated and the bed is armored. The most prevalent influence of urbanization on channel adjustment is the effect of impervious surfaces. Increased impervious surfaces can increase the magnitude and frequency of peak flows resulting in channel enlargement as the channel adjusts to convey the new “norm” discharge (Niezgoda and Johnson, 2005).

Stream channel adjustments have many practical implications for both humans and aquatic biota. Stream channel adjustments have reportedly undermined engineered structures, such as bridges and roadways (Landers and Mueller, 1996; Wilson and Turnipseed, 1994). Increased flood peaks have also been documented from aggrading channel beds resulting in damage to valuable agricultural land areas (Eash, 1996). Stream-dwelling biota also can be negatively affected by channel adjustments.

The structure of biotic communities is strongly influenced by the types and amounts of instream habitats (Schlosser 1982; Peterson and Rabeni 2001, Newson and Newson, 2000), which are largely controlled by the morphology of the stream channel (Leopold et al. 1964; Yarnell, 2006). Channel aggradation can negatively affect stream fishes and benthic macrointerveterbates by excess sediment deposition (Waters, 1995) resulting in decreased pool volume whereas increased scouring may cause bed armoring, reducing suitable habitat for benthic macroinvertabrates and spawning areas for fishes (Mazeika et al., 2004;Sullivan et al., 2006). Both forms of adjustment can decrease habitat complexity leading to a loss of biodiversity, and a community structure dominated by tolerant and generalist species (Scott and Helfman, 2001). Lateral adjustments to the stream channel (widening) can result in decreased habitat volume during low water, which can increase water temperature and decrease dissolved oxygen, increasing the stress to fishes and invertebrates (Maul, 2004). Because stream channel adjustment can affect humans and aquatic biota, suggests that both resource managers and engineers would benefit from a greater understanding of the factors influencing channel adjustments. Furthermore if the causes of channel adjustment can be identified, suitable measures can be taken to lessen or reverse problems associated with channel adjustments.

Several approaches have been used to evaluate the type and degree of channel adjustment. The usefulness of the approach depends largely on the research question and at what spatial and temporal scale inferences are desired. Field surveys, such as surveying cross sectional form or longitudinal profiles, offer the most detailed method but are also the most time consuming. Field studies are advantageous because specific locations can be selected for assessments. Bed level adjustments as well as width adjustments can be quantified when detailed surveys are conducted. However, data need to be collected over a sufficient period to detect trends in adjustments. If the focus of a study were at large spatial scales (watershed), intensive field surveys also could be cost-prohibitive with the costs dependent on the spatial extent of the study (i.e., number of study location) and the sampling effort of a specific location (e.g., the number of cross sectional profiles measured at a study location). In contrast, aerial photograph analysis allows for greater spatial and (sometimes) temporal coverage, but is most useful for determining lateral adjustments in larger rivers (20-200 m wide, Gilvear and Bryant, 2003). This method is often limited by the scale and resolution of the photo as well as interference from riparian vegetation, which may obscure channel margins. Aerial photos generally cannot address bed level adjustments unless they can be inferred from bar formation or evolution through time. Winterbottom and Gilvear, (1997) developed a technique that used image enhancement to relate the grey tone to water depth, in shallow clear rivers. If a stream gage, or some measurement of water surface elevation, were located in the photographed reach it may be possible to determine mean streambed elevation over the period of photos. However aerial photographs are most useful for studying channel adjustment in areas of open channels that do not have thick riparian vegetation, where lateral adjustments are the main concern.

Often stream gaging measurements provide the only source of consistent stream cross sectional data (Juracek and Fitzpatrick, 2009). In this study area, measurements have been taken between six and twelve times a year to update discharge rating curves. Depending on the stream stage at the time of measurement streams may be either waded or measurements may be made from a bridge. Often when measurements are made while wading; different cross sections are measured, this can complicate interpreting channel adjustments. These cross-sectional measurement data then can be used to evaluate changes in the stream channel by creating empirical models that relate discharge to other morphological parameters in basins (Blench, 1966; Pinter and Heine, 2005). Depending on the length of record, historical conditions also can be assessed to determine when and possibly where a disturbance may have occurred that caused a channel adjustment. Advantages of using stream gage data include; consistent quality controlled methods were used to collect the data, at active gaging locations there is temporal continuity of the data, and data cover a range of discharge conditions. Analysis of gage data allows both bed level and width adjustments to be evaluated; however width adjustments must be evaluated from a consistent cross section. Depending on the distribution of gages in a watershed, the spatial dynamics of adjustments can be examined. For example, Jacobson, (1995) used stream gage data, summarized as mean streambed elevations, to document the passage and translation of sediment waves through basins in the Ozarks. Temporal trends can also be determined, given a sufficient record, from individual gages. Thus, analyses of stream gage data are among the most cost effective means for evaluating channel adjustments occurring over relatively large spatial extents.

Several methods have been developed to evaluate channel adjustments from stream gage data, with the most common using water surface elevation (i.e., the stream stage) to infer changes in bed-level. Stream channel adjustments are often estimated using either the relationship between stage and discharge or the difference in mean depth of water from the water surface elevation (Pinter and Heine, 2005; Smelser and Schmidt, 1998). For example, mean streambed elevation (MSBE) is estimated by subtracting the mean depth from water surface elevation at a given cross section. Channel adjustments are then inferred by examining a time-series of MSBE at a given gage. If data are available from multiple gages in a basin, channel adjustments can be assessed temporally and spatially (Jacobson, 1995; Smelser and Schmidt, 1998). Specific gage technique can also be used to estimate channel adjustments at gages, here annual rating type curves are fit to discharge and other morphological parameters (ex, cross sectional area, width, velocity) for constant discharge conditions (blench, 1966; Pinter and Heine, 2005). This allows morphological adjustments at specific discharges to be estimated. One key assumption of specific gage technique, however, is that a consistent cross section must be used to measure variables other than stage. Another technique for evaluating channel adjustment with stream gage data that has received less attention is analysis of residuals from the inverse relationship between discharge and morphological variables (James 1991). This technique is similar to specific gage but instead fits a function to the entire period of record, rather than annually, and then analyzes the residuals over time. This method allows adjustments to be viewed independent of discharge.

All of the methods described above have been used to estimate channel adjustments, and these estimates are often related directly or indirectly to potential disturbances. For example, Du (2008) evaluated channel adjustments due to channelization and the effects of impoundment using specific gage technique and aerial photos. This study was similar to that of Pinter and Heine, (2005) who assessed channel adjustment on the Missouri River in response to engineering activities (ex. wing dams and levees). Fewer studies have used gage data to examine the effect of land use, such as James (1991); who used residual analysis to determine channel incision rates resulting from gold mining induced sedimentation.

Although these approaches have proved useful, they do not directly incorporate (model) the effect of variable(s) thought responsible for the perturbation. All rely on bivariate relationships with an independent and dependent variable that do not consider the variable responsible for the disturbance. If changes to stream channels could be modeled as a function of potentially important factors (e.g., land use change), it could lead to increased understanding of the processes and ability to predict changes. Here, we present a technique that model trends in channel adjustments, inferred from water surface elevation, and directly relate the trends in channel adjustment to land use change and high discharge events.

The objectives of this study were twofold: 1. to present a hierarchical modeling approach (Bryk and Raudenbush, 1992) to evaluate channel adjustments using stream gage data and, 2. to demonstrate this approach by evaluating the relationship between channel adjustments and land use change and frequency of high flow events.

Although our primary objective is to present a novel analytical technique, we enter this analysis hypothesizing that an increase in urban land cover will be negatively related to water surface elevation (indicating bed degradation). Also the frequency of bankfull events will also have an effect, potentially in either direction, depending on time since the last large sediment-transport event. We also hypothesize that an interaction of increased urban cover and greater frequency of bankfull events will have an effect on the trend in water surface elevation, with a greater possibility of bed degradation.

Study Area

The Upper Flint River basin (USGS Hydrologic # 03130005) is located almost entirely in the Piedmont physiographic province of Georgia, USA, with only a small portion in the Coastal Plain province (Figure 1). The Flint River drains an area of 6812 km^2 beginning in a heavily urbanized area in South Atlanta. As of 2005, land cover in the basin was 52% forest, 18% agriculture, 11% urban, 9% forested wetland, and sparse amounts of others (Georgia Land Use Trends, 2005). The majority of urban land use is concentrated in the northern portion of the basin. The Piedmont Region of Georgia as well as the Flint River Basin has a legacy of erosion and subsequent sedimentation as a result of historic agricultural practices. Much of the land was cleared for cultivation, with the arrival European settlers in the early 19th century. This led to increased hillslope erosion and valley aggradation. Trimble (1974) estimated that the entire Georgia Piedmont lost about 19.05 cm of topsoil from 1700- 1970 of which a large portion remains channel and floodplain storage. Around the mid 20th century much of the abandoned fields were reverting to forests and beginning to stabilize. Now the Upper Flint River Basin is currently undergoing substantial urban development as the Atlanta metropolitan region expands. Much of the headwaters of the basin have been urbanized for about four decades but it continues to spread southward through the basin (Hughes et al, 2007). Riparian wetlands are abundant in the upper portion of the basin. Bed material is dominated by sand in meandering reaches and a mixture of sand and finer material in wetland areas. After the Flint flows past the Griffin stream gage (Figure 2) bedrock outcrops become more numerous. There is an area below here known as the Pine Mountain Ridge where the river looses much of is alluvial character and is under grater bedrock and valley control. Past this section the channel widens back out and regains much its alluvial meandering form. Three of the stream gages used in this study are located in the upper portion of the basin where boundaries are readily adjustable. The forth gage (02347500) is below the Pine mountain area but has only limited amounts of bedrock, mostly overlain with sand. Thus if channel adjustments are occurring it should be feasible to detect them at all the gaging locations.

Data Sets Used

Stream gaging data collected by the U. S. Geological Survey (USGS) were used in this analysis. Eleven active real-time stream gages are located in the basin, both on tributaries and the mainstem Flint River with some gage records as long as 90 years. Because we wanted to evaluate channel adjustments occurring over relatively long time spans, we used data from four stream gages (Table 1) that had at least 20 years of record. This allowed us to evaluate slower processes or potentially lagged responses. Data from these sites were obtained using the National water information system (NWIS) at water.usgs.gov. Measurements were made at each gage between six and twelve times a year to update discharge rating curves for these gaging stations. However, multiple measurements may have been made in a single day if sites were visited during a flood event. Where gages had been relocated, data were edited to reflect the current datum of the stream gage.

Stream aggradation or degradation were potentially influenced by discharges that occurred prior to stream measurements. For example, in many streams in the Piedmont small amounts of bed material are transported and deposited during low discharges due to the sandy composition of bed material resulting in aggradation during prolonged periods of low discharge. In contrast, sediment transport and scour are much greater during bankfull discharges. To evaluate the potential influence of stream discharge, we calculated the 2-year recurrence interval (RI) discharge as a proxy for bankfull discharge at each gage using USGS peak stream flow measurements. We then estimated the time since a 2-year RI or greater discharge using the daily discharge data. Time since high flow event was coded in year units (e.g. 6 months = 0.5). When a measurement is made at 2-year RI or greater discharge, time since high flow was set to zero.

Land cover data were retrieved from the University of Georgia (UGA) Natural Resources Spatial Analysis Laboratory (NARSAL). The Georgia land-use trends (GLUT) dataset has land cover data measured six times from 1974 to 2005 in unequal periods (mean 6 years, SD = 2.8 years). Data were available at the watershed or county level. For this analysis we chose to use county level data because it better reflected land cover trends in the proximity of the gages and focused on the changes in urban land cover. To evaluate the relative influence of long-term diffuse urban growth or short-term urban growth on stream channel adjustments, we estimated average urban growth (percent increase) that had occurred 0-5 years before the gage measurement (BGM) for short-term urban growth and 15-20 years BGM as long-term urban growth. The land cover data were only available for six discrete time periods, where as the stream gage measurements were made during several times a year. To interpolate urban land cover between periods, we performed a linear regression between urban land cover and time and used the estimated urban land cover data to calculate short and long tern urban growth for each measurement at each gage. There was excellent agreement when land cover data were natural log transformed.

Modeling Approach

To describe the hierarchical linear modeling approach for evaluating the influence of land cover and high flows on stream channel adjustment, we begin with the approach used by previous studies where stage is modeled as function of discharge and the residuals are analyzed over time (James, 1991). When data are log transformed to achieve linearity we can use the linear regression models as:

$$Y_i = \mathrm{b}_{0\mathrm{q}} + \mathrm{b}_{\mathrm{q}} Q_i + r_i \qquad (1)$$

where Y is the stage, b_{0q} is the intercept, b_q the discharge slope, Q is the discharge, and r is the residual for measurement i. Residuals then are then modeled as a function of time:

$$r_i = b_{0t} + b_t T_i + e_i \qquad (2)$$

where b_{0t} is the intercept and b_t the time slope, T is the time of measurement, and e is the residual which is assumed normally distributed with a mean of zero and variance s^2. The slope of the relationship (b_t) is then examined to evaluate temporal adjustments to the streambed as inferred from water surface elevation (Juracek and Fitzpatrick, 2009). We can combine equations (1) and (2) to obtain what can be viewed as a multiple regression inverse rating curve:

$$Y_i = b_0 + b_q Q_i + b_t T_i + e_i \qquad (3)$$

where $b_0 = b_{0q} + b_{0t}$, b_q is the relationship between discharge and stage, and $b_t T_i$ is the relationship between the residual (streambed) and time.

Assuming that we had measurements from a random selection of gages we can model the relationship between stage and the dependent variables at any gage (j) using the same model as above (eq. 3) as:

$$Y_{ij} = b_{0j} + b_{qj}\, Q_{ij} + b_{tj} T_{ij} + e_{ij}, \qquad (4)$$

where (i) still refers to the individual measurement at a gage and (j) refers to the gages. This model (eq. 4) is defined as a level-1 model and discharge (Q) and time (T) are defined as level-1 predictors. In the level-1 model, there are unique intercept and slopes for each gage. The values of the level-1 intercepts and slopes can be modeled as a function of gage specific characteristics, defined as level-2 predictors. Essentially, we are modeling the level-1 coefficients (the b) as a function of gage specific predictors as:

$$b_{0j} = b_{00} + b_{01} W_{1j} + \ldots\ b_{0S} W_{Sj} + u_{0j} \qquad (5a)$$

$$b_{qj} = b_{q0} + b_{q1} W_{1j} + \ldots\ b_{qS} W_{Sj} + u_{qj} \qquad (5b)$$

$$b_{tj} = b_{t0} + b_{t1} W_{1j} + \ldots\ b_{tS} W_{Sj} + u_{tj} \qquad (5c)$$

where $g_{0000} \ldots g_{00tS}$ are the fixed effects (also referred to as the level-2 coefficients), $u_{0j}, \ldots u_{qj}$ are the random effects that are assumed normal with mean 0 and variance t^2, and W_{Sj} are the predictor variables for gage j. The random components $u_{0j}, \ldots u_{qj}$ represent the unique effect associated with each gage that is unexplained in the predictors in the level 2 model.

For our study, we were primarily interested in evaluating the influence of gage - specific characteristics on the relationship between the residuals and time (b_{tj}) Therefore, we allowed the intercept (b_{0j}) and discharge-stage relationship (b_{qj}) to vary randomly across gages and modeled b_{tj} as a function of gage- specific characteristics.

To evaluate relative plausibility of hypotheses regarding the influence of land cover and high flows on stream channel adjustment, we used an information-theoretic approach (Burnham and Anderson 2002). We created a global (saturated) HLM that consisted of all variables and interactions hypothesized to be responsible for streambed adjustments. However, there was a strong correlation (Pearson r = 0.99) between the short-term and long-term urban change. To avoid multicolinearity, we developed a set of models with several models differing only in the urban change parameter. Essentially this resulted in two "global like" models each with sets of candidate models representing different hypotheses (Table 2). The relative plausibility of the models was assessed by analyzing the residuals and using Akaike Information Criteria (AIC; Akaike, 1973). Specifically, we calculated Akaike weights (*w*) according to Burnham and Anderson (2002) and used them to evaluate the relative support for models in a candidate set. Akaike weights range from 0 to 1 with the best approximating models having highest weight.

To achieve a linear relationship between stage and discharge data were base 10 log transformed prior to model fitting. We also coded time as year number for each gage; where the first year equals zero then each successive year is plus one. To facilitate model-fitting, we standardized all the independent variables, with the exception of discharge, to a mean of zero and standard deviation of one. The advantage of working with standardized data is that the relative influence of a variable can be compared across variables with very different scales (e.g. percent, years, cubic meters per second, etc.) because all data is in standard score format. All models were fit using SAS Proc Mixed (SAS institute, 2001).

RESULTS

Nine candidate models were evaluated with different combinations of variables and interactions. Only two of the models were strongly supported as indicated by Akaike weights. Both of these were the global like models containing all of the variables but, only differing in the urbanization parameter (table 2). However, the global model containing short-term urban growth was 25 times more plausible than the same model containing long-term urban growth as indicated by the ratio of Akaike weights. The most plausible model of bed level adjustment contained short-term urban growth, time since high flow event and its quadratic term, and the interactions of short-term urban growth with time since high flow event. Models containing short-term urbanization were consistently more plausible (i.e., larger Akaike weights) than corresponding models containing long-term urbanization suggesting that bed level adjustment was most strongly related to short-term land conversion. Similarly, models containing the quadratic term for time since high flow event were more plausible than similar models with only the linear term suggesting that effect of high flow events varied through time.

The best approximating model indicated that streambed change was negatively related to short-term urbanization, whereas it was positively related to time since high discharge (Table 3). The parameter estimates also suggested that time since high discharge had a greater influence on streambed adjustments than any of the other factors considered. The interaction of short-term urbanization and the quadratic term for time since high discharge was negatively related to streambed change indicating a degradading or scour effect. Predictions of the relationship between time and the residuals (bed level) based on the most plausible model suggest that bed level decrease over the range of time since scenarios as short-term urban growth increases. The general trend of time since was less negative residual time slopes as time since high flow increased, when time since is viewed independently (i.e. at the Y-axis, 0% urban growth). When time since is viewed as interacting with short-term urban growth the trends are all negative with increasing short-term urban growth.

DISCUSSION

Traditional empirical models used to evaluate streambed change have not incorporated the variables that could be responsible for the observed channel adjustment. Rather they are correlated or associated. We presented a modeling approach where streambed response was modeled as a function of potential factors. Results of this analysis generally supported our initial hypotheses. Increases in urban growth had a negative effect on streambed elevation, time since a high flow event may affect the streambed positively or negatively, and the interaction of these two would most likely lead to a decrease in the time slope (bed level).

The greater frequency of high flow (0.5, 1, and 2 years since) events tended to result in negative time slopes (bed level). In contrast, 3-4 years since a high flow event results in a positive slope. These results are based on zero percent short-term (y-intercept) urban growth. However the magnitude of the short-term urban growth effect varies with frequency of event. When events occur at moderate frequency, i.e., 1–2 years, the urban effect on the time slope is less dramatic, possibly because the effect of frequency of high flows has already lead to a decreasing bed level and there was less loose surficial material available to transport. short-term urban growth had the greatest effect on the time slope (steepest decrease) when high flows occurred less frequently (every 3-4 years). Although the magnitude of short-term urban growth on the time slope was not as great for the 0.5 year since scenario, it had the next steepest slope. From Figure 3, it appears that short-term urban growth had the greatest effect on the time slope (bed level) when events occurred infrequently (3-4 years) or very frequently (0.5 year). A possible scenario could include; the accumulation of sediment over time during low flow. Then as urban growth increases so will impervious surfaces. This could lead to an imbalance of stream power to available material to transport. Thus when a high flow finally occurred it had greater transport capacity than before and possibly a greater supply to transport from prolonged lower flows. The more dramatic effect observed for the 0.5 year since may be due to a compounding effect of less sediment supply, (i.e. less time between high flows for sediment to accumulate) and greater energy from increasing urban cover leading to progressive bed degradation.

Although this analysis provided insight into streambed response to urban growth and frequency of high flow events it did not account for a great deal of the residual variability. When comparing the most plausible model to the “naïve model”, which only contained the original variable (year number), we only accounted for 15% more variability in the time slope of the residuals (bed level adjustment). This could be due to many factors that may affect short-term bed level, such as the portion of the hydrograph that was measured (i.e. rising or falling limb) for a particular observation. It may also be that many other variables could have had greater support (ex. geology, soil type, or gradient). Other studies have found these to be important variables exerting greater control over reach scale channel adjustments than broad scale impervious cover (Booth, 1990; Allen and Narramore, 1985). This study may have also been improved if we could have better defined a threshold for sand bed form movement rather than using such a large event. Nonetheless this analysis provided insight into the interaction of high flow events and urbanization and their effect on streambed adjustments.

CONCLUSIONS

The primary goal of this study was to illustrate a robust statistical technique, and secondarily to demonstrate the technique by modeling streambed adjustment as a function of urban growth and time since high flow events. This approach is applicable in many situations where studies are concerned with spatial or temporal relationships across a range of locations or scales. It allows data to be pooled together and analyzed simultaneously without violations often encountered with traditional statistical methods. Our demonstration also illustrated the effect of short-term urban growth and frequency of high flow events on the residual time slope (bed level) at these particular sites. Because our gage locations were not randomly selected, inferences are generally site specific. However from the large body of literature on the effects of urbanization across many physiographic regions it is possible, and even likely, that similar effects may be encountered in other locations. Of course this will depend on boundary conditions and many local factors.

Future research in this area may consider structural aspects, other types of land use, or direct channel modification on controlling channel adjustments. It is possible to include all elements at the watershed scale as well as the reach scale, this will allow inferences as to which variables and spatial scales are more appropriate for certain studies. However one must consider parsimony to avoid an overly complicated interpretation. It may also be possible to estimate recovery rates since a disturbance, such as channelization, as both temporal and spatial considerations can be incorporated into a single model. Much of the data collected in the study of fluvial systems is hierarchical by nature. This modeling approach is a novel tool that has the potential to advance understanding of processes driving change and the appropriate scales for inference.

REFERENCES

Akaike, H. 1973. Information theory and an extension of the maximum likelihood principle. Pages 267-281 in Second International Symposium on Information Theory. B.N. Petrov and F. Csaki, editors. Akademiai Kiado, Budapest, Hungary.

Allen, P. and Narramore, R., 1985. Bedrock controls on stream channel enlargement with urbanization, North Central Texas. *Water Resources Bulletin*. 21(6): 1037-1048.

Blench, T., 1969. Mobile-Bed Fluviology: A Regime Theory Treatment of Canals and Rivers for Engineers and Hydrologists, University of Alberta Press, Edmonton (1969).

Booth, D.B., 1990. Stream channel incision following drainage basin urbanization. Water Resources Bulletin. 26(3): 407-417.

Booth, D. B. and Jackson, C. R., 1997. Urbanization of Aquatic Systems — Degradation Thresholds, Stormwater Detention, and the Limits of Mitigation. Journal of the American Water Resources Association 33(5):1077-1090.

Bryk, A. S. & Raudenbush, S. W. 1992. *Hierarchical linear models*. Sage, Newbury Park, CA.

Burnham, K.P., and D.R. Anderson. 2002. Model Selection and Multimodel Inference: A Practical-Theoretic Approach, 2nd edition Springer-Verlag, New York.

Du, X., 2008. The Application of the Specific Gage Technique and Aerial Photographs in Kaskaskia River Degradation Studies. American Geophysical Union, Fall Meeting 2008, abstract #H43B-1001

Eash, D. A., 1996. Flood-Plain and Channel Aggradation at Selected Bridge Sites in the Iowa and Skunk River Basins, Iowa. U.S. GEOLOGICAL SURVEY Water-Resources investigations Report 95-4290

Georgia Land Use Trends, 2005. Land cover of the upper Flint watershed: Natural Resources Spatial Analysis Laboratory, Institute of Ecology, Athens, Ga., accessed August 19, 2007, at http://narsal.ecology.uga.edu/glut.html

Gilvear,D. J. and Bryant, R., 2003. Analysis of Aerial Photography and Other Remotely Sensed Data. In Kondolf, G. M. and Piegay,H. (eds) Tool in Fluvial Geomorphology. John Wiley and Sons New York, 2003.

Grant, G.E., Schmidt, J.C. and Lewis, S.L. 2003. A Geological Framework for Interpreting Downstream Effects of Dams on Rivers. in J.E. O'Connor and G.E. Grant eds. A Peculiar River. Water Science and Application 7. American Geophysical Union, p203-219.

Hoyle, J., Brooks, A., Brierley, G., Fryirs, K., and Lander, J., 2008. Spatial variability in the timing, nature and extent of channel response to typical human disturbance along the Upper Hunter River, New South Wales, Australia. Earth Surface Processes and Landforms 33, 868–889

Hughes, W.B., Freeman, M.C., Gregory, M.B., and Peterson, J.T., 2007, Water availability for ecological needs in the upper Flint River Basin, Georgia—A USGS Science Thrust project: Proceedings of the 2007 Georgia Water Resources Conference, March 27-29, 2007, Athens, Georgia, accessed online at http://cms.ce.gatech.edu/gwri/uploads/proceedings/2007/6.6.1.pdf

Jacobson, R. B. 1995. Spatial controls on patterns of land use induced stream disturbances at the drainage-basin scale an example for gravel-bed streams in the Ozark Plateaus, Missouri. In: J.E Costa, A.J. Miller, K.W. Potter, and P. R. Wilcock, eds. Natural and Anthropogenic Influences in Fluvial Geomorphology. American Geophysical Union Monograph 89: pp. 219-239

James, L. A., 1991. Incision and morphologic evolution of an alluvial channel recovering from hydraulic mining sediment. Geological Society of America Bulletin: 723-736.

Juracek, K. E. and Fitzpatrick, F.A., 2009. Geomorphic applications of stream-gage information. River Research and Applications. v.25, p.329-347

Knighton, D.1998, *Fluvial Forms and Processes: A new perspective.* Oxford University Press, New York 1998, pp.168

Kondolf, G.M., 1997. Hungry water: Effects of dams and gravel mining on river channels. Environmental Management. Vol. 21(4): 533-551.

Lane, E.W., 1955. The importance of fluvial morphology in hydraulic engineering, *Proceedings of the American Society of Civil Engineers* 81 (1955), pp. 1–17

Leopold, Luna B., Wolman, M.G., and Miller, J.P., 1964. Fluvial Processes in Geomorphology, San Francisco, W.H. Freeman and Co., 522p

Landers, M.N., and Mueller, D.S., 1996, Channel scour at bridges in the United States: Federal Highway Administration Report FHWA-RD-95-184.

Mazeika, S., Sullivan, P., Watzin, M. and Hession, W., 2004. Understanding stream geomorphic state in relation to ecological integrity: Evidence using habitat assessments and macroinvertebrates. Environmental Management 34(5): 669-683.

Maul, J. D., Farris, J. L., Milam, C. D., Cooper, C. M., Testa, S. III, and Feldman, D. L., 2004. The influence of stream habitat and water quality on macroinvertebrate communities in degraded streams of northwest Mississippi. Hydrobiologia. 518: 79-94.

Newson, M. D. and Newson, C. L. (2000). Geomorphology, ecology and river channel habitat: Mesoscale approaches to basin-scale challenges. Progress in Physical Geography 24(2): 1195-217.

Peterson, J.T., and C.F. Rabeni. 2001. The relation of fish assemblages to channel units in an Ozark stream. Transactions of the American Fisheries Society 130:911-926.

Niezgoda, S. L. and Johnson, P. A., 2005. Improving the urban stream restoration effort: Identifying critical form and processes relationships. Environmental Management 35(5): 579-592.

Pinter, N., and R.A. Heine,, 2005. Hydrodynamic and morphodynamic response to river engineering documented by fixed-discharge analysis, Lower Missouri River, USA. Journal of Hydrology, 302: 70-91.

SAS Institute. 2001. SAS/STAT user's guide, release 8.02. SAS Institute, Inc., Cary, North Carolina.

Schlosser, I.J. 1982. Fish community structure and function along two habitat gradients in a headwater stream. Ecological Monographs 52:395-414.

Scott, M. C. and Helfman, G. S., 2001. Native Invasions, Homogenization, and the mismeasure of Integrity of Fish Assemblages. Fisheries:26(11)

Schumm, S.A., Harvey, M.D. and Watson, C.C., 1984. Incised Channels: Morphology dynamics and control: Water Resources Pub., Littleton, CO. 200 p.

Simon, A. and Hupp, C.R., 1986. Channel evolution in modified Tennessee channels. In: *Proceedings of the Fourth Interagency Sedimentation Conference, March 1986* vol. 2, Subcommittee on Sedimentation, Las Vegas, NV, pp. 5-71–5-82

Simon, A. (1989). A model of channel response in disturbed alluvial channels. EarthSurface Processes and Landforms 14(1): 11-26.

Simon, A. and Rinaldi, M., 2006. Disturbance, stream incision, and channel evolution: The roles of excess transport capacity and boundary materials in controlling channel response. Geomorphology 79(3-4): 361-383.

Smelser, M. G. and Schmidt J. C., 1998. An assessment methodology for determining historical changes in mountain streams. General Technical Report RMRS-GTR-6. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. pp. 29

Sullivan, S., Watzin, M., & Hession, W., 2006. Influence of stream geomorphic condition on fish communities in Vermont, U.S.A. *Freshwater Biology*, *51*(10), 1811-1826.

Trimble, S.W., 1974. Man-Induced Soil Erosion on the Southern Piedmont 1700-1970 Soil Conservation Society of America, Ankeny, Iowa

Waters, T. F., 1995. Sediment in stream: Sources, biological effects, and controls. American Fisheries Society Monograph 7.

Williams, G.P. and Wolman, M.G., 1984. Downstream effects of dams on Alluvial rivers, *Professional Paper* vol. 1286, US Geological Survey, Washington D.C. (1984).

Wilson, K.V., Jr., and Turnipseed, D.P., 1994, Geomorphic response to channel modifications of Skuna River at the State Highway 9 crossing at Bruce, Calhoun County, Mississippi: U.S. Geological Survey Water-Resources Investigations Report 94-4000, 43 p.

Winterbottom, S. J. and Gilvear,D. J., 2001. Quantification of channel bed morphology in gravel-bed rivers using airborne multispectral imagery and aerial photography. Regulated Rivers: Research & Management 13 (6): 489-499.

Wolman, M.G., 1967. A cycle of sedimentation and erosion in urban river channels: Geografiska Annaler, v. 49A, no. 2-4, p. 385–395.

Yarnell, S. M., Mount, J. F. and Larsen, E. W., 2006. The influence of relative sediment supply on riverine habitat heterogeneity. Geomorphology 80(3-4): 310-324.

Table 1. Characteristics of stream gages used in the analysis

Station Number	Station Name	Record Length (years)	Drainage Area (km^2)
02344350	FLINT RIVER NEAR LOVEJOY, GA	21	334
02344500	FLINT RIVER NEAR GRIFFIN, GA	69	702
02344700	LINE CREEK NEAR SENOIA, GA	42	264
02347500	FLINT RIVER NEAR CARSONVILLE, GA	78	4839

Table 2. Parameters used in the candidate set of models and a description of their use and/or significance

Parameter code	Parameter	Description/Hypothesis
ID	Station Identifier	Name of gage location (level -2 subjects)
yr_no	Year number, with the first year measures = 0 and each successive year +1	Variable used to model residuals to detect trends over time
Log10_q_cms	LOG10 of discharge in cubic meters per second (cms)	Used to predict stream stage for each gage
Log10stage_m	LOG10 of stage in meters (m)	Dependent variable from the initial analysis, modeled as a function of Log10_q_cms, to obtain stage residuals
long_urb	Average long-term urbanized area (15-20 years before measurement)	Variable used to model the long-term effects of lower intensity diffuse urbanization on the time slope of residuals (bed level)
shrt_urb	Average short-term urbanized area (0-5 years before measurement)	Variable used to model the effect of temporally concentrated urbanization on the time slope of residuals (bed level)
time_since	Time since last 2 year RI or greater flood (in year units e.g. 6 months = 0.5 years)	Time since a large sediment transporting event could lead to greater filling/aggradation or if the frequency of events increases lead to scour/degradation.

Table 3. Predictor variables, log-likelihood (Log*L*), number of parameters (*K*), Akaike's Information Criterion with the small-sample bias adjustment (AICc), bDAICc, and Akaike weights (*w*) for the set of candidate models

Model	LogL	K	AICc	dbaicc	wbi
log10_q_cms yr_no shrt_urb*yr_no yr_no*time_since*time_since yr_no*time_since yr_no*time_since*time_since*shrt_urb yr_no*time_since*shrt_urb	3082.28	12	-6140.39	0.00	0.961
log10_q_cms yr_no long_urb*yr_no yr_no*time_since*time_since yr_no*time_since yr_no*time_since*time_since*long_urb yr_no*time_since*long_urb	3079.08	12	-6133.99	6.41	0.039
log10_q_cms yr_no yr_no*time_since shrt_urb*yr_no yr_no*time_since*shrt_urb	3051.67	10	-6083.22	57.17	0.000
log10_q_cms yr_no yr_no*time_since long_urb*yr_no yr_no*time_since*long_urb	3049.88	10	-6079.63	60.76	0.000
log10_q_cms yr_no yr_no*time_since	3035.67	8	-6055.27	85.12	0.000
log10_q_cms yr_no yr_no*time_since yr_no*time_since*time_since	3035.70	9	-6053.30	87.09	0.000
log10_q_cms yr_no yr_no*shrt_urb	2993.25	8	-5970.42	169.97	0.000
log10_q_cms yr_no yr_no*long_urb	2993.08	8	-5970.08	170.31	0.000
log10_q_cms yr_no	2984.33	7	-5954.60	185.80	0.000

Table 4. Parameter estimates from most plausible model as indicated by Akaike weights

Effect	Estimate	Error	DF	t-value	Pr > t	Alpha
Intercept	-0.3376	0.1579	3	-2.14	0.1221	0.1
log10_q_cms	0.4076	0.05201	3	7.84	0.0043	0.1
yr_no	-0.02917	0.009778	3	-2.98	0.0584	0.1
yr_no*shrt_urb	-0.00774	0.005283	1835	-1.46	0.1432	0.1
yr_no*time_s*time_si	0.007944	0.001184	1835	6.71	<.0001	0.1
yr_no*time_since	0.004251	0.002072	1835	2.05	0.0403	0.1
yrbn*shrt*time*timeb	-0.00577	0.000808	1835	-7.14	<.0001	0.1

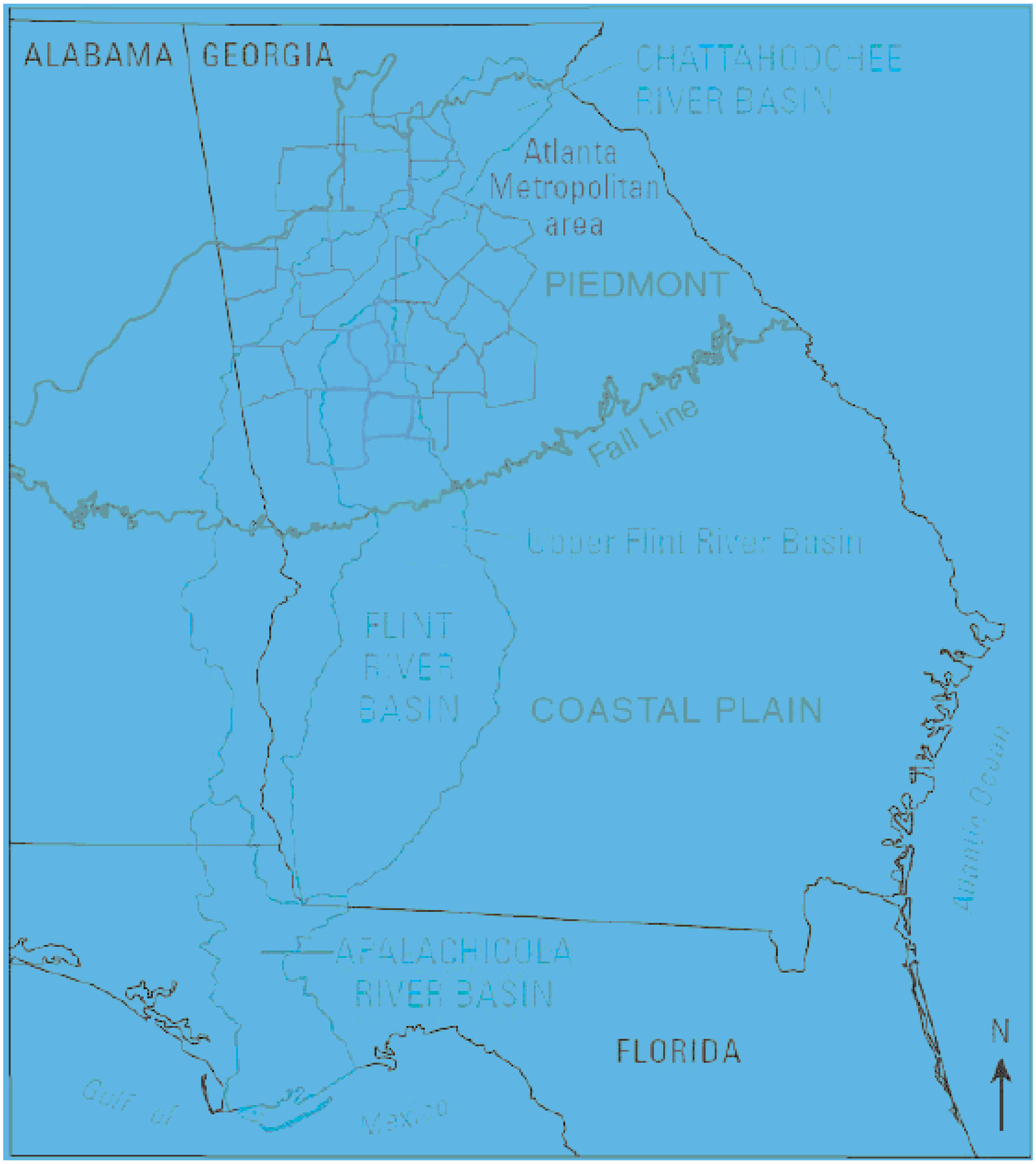

Figure 1. Regional Map showing the location of Upper Flint River Basin. Adapted from USGS Upper Flint River fact sheet.

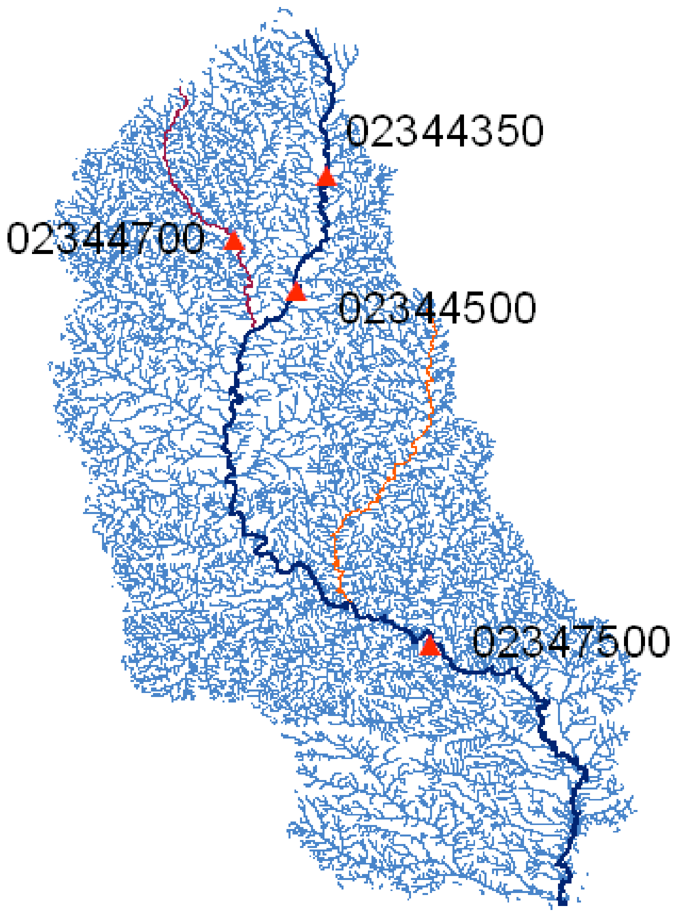

Figure 2. Location of stream gages used in the analysis

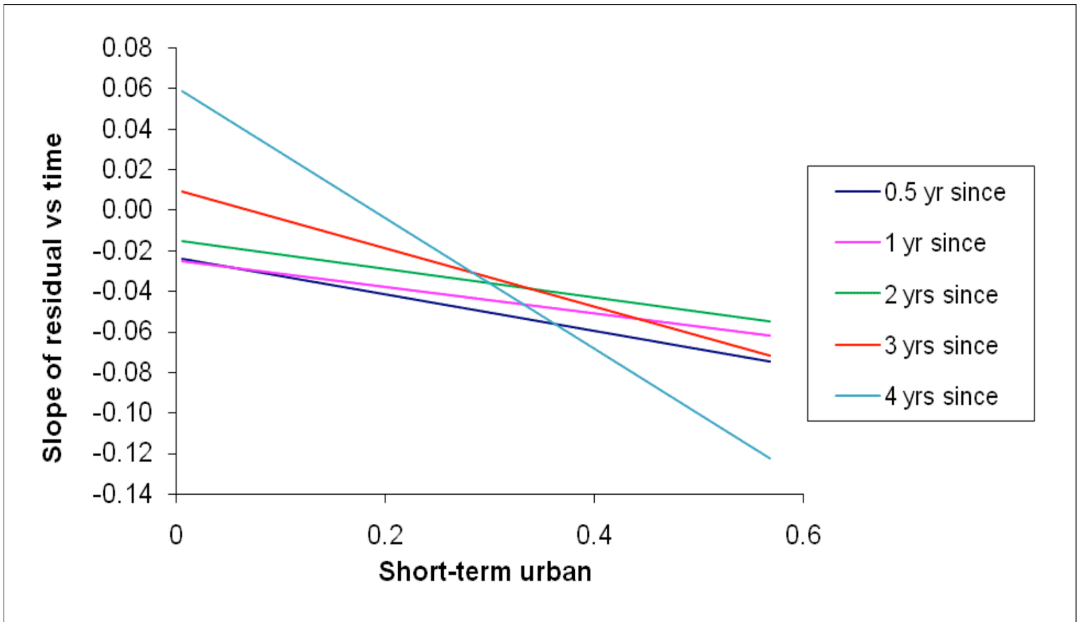

Figure 3. Plot used to evaluate the relationship between bed level change and short-term urban growth over five different time_since high flow scenarios.

Appendix B

Data Entry Form - Channel-Stability Ranking Scheme

CHANNEL-STABILITY RANKING SCHEME

River__________________________ Site Identifier_____________________________________

Date ______________ Time________ Crew ________________ Samples Taken__________________________

Pictures (circle) U/S D/S X-section Slope__________ Pattern: Meandering / Straight / Braided

1. Primary bed material

	Bedrock	Boulder/Cobble	Gravel	Sand	Silt Clay	
	0	1	2	3	4	_____

2. Bed/bank protection

	Yes	No	(with)	1 bank protected	2 banks	
	0	1		2	3	_____

3. Degree of incision (Relative elevation of "normal" low water; floodplain/terrace @ 100%)

	0-10%	11-25%	26-50%	51-75%	76-100%	
	4	3	2	1	0	_____

4. Degree of constriction (Relative decrease in top-bank width from up to downstream)

	0-10%	11-25%	26-50%	51-75%	76-100%	
	0	1	2	3	4	_____

5. Stream bank erosion (Each bank)

	None	Fluvial	Mass wasting (failures)	
Left	0	1	2	_____
Right	0	1	2	_____

6. Stream bank instability (Percent of each bank failing)

	0-10%	11-25%	26-50%	51-75%	76-100%	
Left	0	0.5	1	1.5	2	_____
Right	0	0.5	1	1.5	2	_____

7. Established riparian woody-vegetative cover (Each bank)

	0-10%	11-25%	26-50%	51-75%	76-100%	
Left	2	1.5	1	0.5	0	_____
Right	2	1.5	1	0.5	0	_____

8. Occurrence of bank accretion (Percent of each bank with fluvial deposition)

	0-10%	11-25%	26-50%	51-75%	76-100%	
Left	2	1.5	1	0.5	0	_____
Right	2	1.5	1	0.5	0	_____

9. Stage of channel evolution

	I	II	III	IV	V	VI	
	0	1	2	4	3	1.5	_____