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Linking channel instability to urbanization in the upper Beaver Creek Watershed, Knox County, Tennessee

Esther Sullivan Parish

University of Tennessee

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To the Graduate Council:

I am submitting herewith a thesis written by Esther Sullivan Parish entitled "Linking channel instability to urbanization in the upper Beaver Creek Watershed, Knox County, Tennessee." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Geography.

Carol Harden, Major Professor

We have read this thesis and recommend its acceptance:

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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Acceptance for the Council:

Vice Provost and Dean of
Graduate Studies

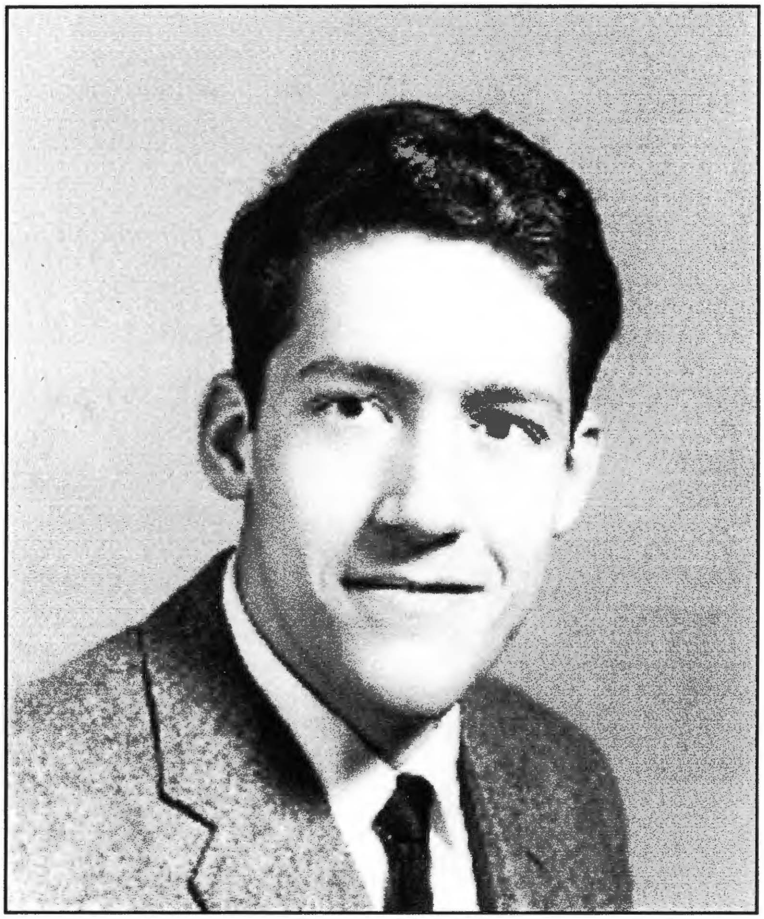
LINKING CHANNEL INSTABILITY TO URBANIZATION IN THE UPPER BEAVER CREEK WATERSHED, KNOX COUNTY, TENNESSEE

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Esther Sullivan Parish
May 2002

DEDICATION

This thesis is dedicated to my father, Michael Sullivan, who fostered my love of science and continually admonished me to "be aware of the world around me."



Dr. James M. Sullivan
October 1, 1950 - November 8, 2000

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ABSTRACT

Within the past 15 years, the 223 km^2 Beaver Creek watershed of Knox County, Tennessee has begun to undergo rapid development. Past studies of urbanizing watersheds have indicated that even small degrees of development can impact channel stability through increased runoff from impervious areas. Already, bank erosion seems to be prevalent throughout the upper reaches, and it is likely that this channel instability is contributing to the watershed's severe flooding and water quality problems.

To determine whether urban development is a cause of the channel instability observed in upper Beaver Creek, I took qualitative and quantitative field measurements of channel stability at 10 sites within eight adjacent sub-basins and tested for bivariate correlation between the channel stability indicators and 10 urbanization metrics generated using a geographic information system (GIS). The selected sub-basins ranged from 3.1 km^2 to 10.1 km^2 in area, varied from predominately rural to urban in land use, and encompassed many of the different types of topography and underlying geology found throughout the upper Beaver Creek watershed.

I found that the prevalence of bank erosion does increase as urbanization increases within the upper Beaver Creek watershed. My data suggest that a total impervious area greater than 13-20% and a wooded area of less than 38-51% may lead to channel instability within the upper Beaver Creek sub-basins. The observed channel erosion is also correlated with the proportion of human to natural uses within the catchment and the 30-meter riparian buffer zone, as well as the proportion of wooded riparian buffer upstream of the site.

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CHAPTER I
INTRODUCTION

The Effects of Urbanization on Channel Stability

Stream channels change in response to land use changes within the drainage basin, and a change from rural to suburban land use may yield dramatic responses in hydrologic and geomorphic systems (Graf 1977). During urbanization of a watershed, forested and agricultural lands are typically converted to a combination of impervious surfaces—such as roads, parking lots, rooftops and sidewalks—and less-permeable surfaces—such as lawns, parks and construction areas compacted by heavy machinery (Schueler 1994, Barnes *et al.* 2000, Finkenbine *et al.* 2000). Typically, development takes place in a "quiltwork pattern," with some tracts of land becoming intensely developed while other nearby areas remain unchanged (Graf 1977). As a watershed is urbanized, numerous artificial channels are added to its network and some natural channels may be paved over or straightened (Graf 1977, Marsh 1997).

Sediment yields change as a watershed becomes increasingly developed. Wolman (1967) found that a decline in active farming will decrease sediment yields, but that land exposed by construction projects will produce sediment yields several times greater than land used for agriculture and sediment yields several hundred times greater than forested land. Thus, development tends to cause temporary aggradation in streams (Wolman 1967). During the suburbanization of the Denver area, for instance, so much sediment was introduced into the Meadow Hills stream network that the watershed's floodplain area increased by 270% as the excess alluvium was deposited (Graf 1975). A more recent study of an urbanizing tropical watershed in Nigeria showed that the channels were aggrading and narrowing due to dramatic increases in sediment yield (Jacobson *et al.* 2001). After construction activities have been completed, stormwater runoff will increase and sediment inputs will coincidently decrease; ultimately, sediment yields from completely urbanized areas may be even less than from forested areas (Wolman 1967).

As land is developed, storm water runoff will enter the channel network more quickly due to an increase in impervious surfaces, an increase in the number of storm drains delivering runoff directly to the stream channel, or both. Thus, lag time, or the elapsed time between the center of mass of a storm event and the center of mass of the resulting hydrograph, decreases as suburban land uses increase within a previously rural watershed (Graf 1977). Runoff volumes may also increase as a result of development. Low-level suburban development (i.e., 10-20% impervious area) has been shown to increase peak flows by two to three times, and formerly inconsequential storms may begin to produce substantial amounts of runoff (Booth 1990). Sewered watersheds may experience an eightfold increase in peak storm flow as imperviousness increases from 0% to 100% (Barnes *et al.* 2000).

Many studies have shown that higher peak flows cause stream channel enlargement through bed and bank erosion (Wolman 1967, Booth 1990, Finkenbine *et al.* 2000, Jacobson *et al.* 2001). Channel widths have been known to double as watersheds are urbanized (Trimble 1997; Doyle *et al.* 2001). Streams may either enlarge at a rate roughly proportional to the increased discharges, or they may incise deeply and rapidly in a manner completely disproportionate to the increased discharge (Booth 1990). The channel slope and geologic material, as well as the flow, topography, and channel roughness, are the controls of channel incision (Booth 1990). Riparian vegetation is also a factor in channel stability, as studies have shown that the effectiveness of water to erode banks is reduced by one to two orders of magnitude in the presence of flourishing riparian vegetation (Simon and Downs 1995). Vegetated banks may deliver large woody debris to the channel, thereby increasing the frictional resistance of the bed and possibly causing a switchover to aggrading conditions (May *et al.* 1997). However, in urbanized areas there is a tendency to purposefully remove the large woody debris from the stream channel as a flood control measure (Jacobson *et al.* 2001).

While streams are inherently dynamic features of the landscape over geologic timescales, from the human perspective an "unstable" stream or stream reach is generally considered to be one which changes its pathway and channel structure within several years or decades. Johnson *et al.* (1999) define an unstable channel to be one in which aggradation, width adjustment, or planform changes are actively occurring in time and space, but note that the main requirement is that there be net morphological change over engineering time scales. Similarly, Doyle *et al.* (2001) define an unstable channel to be one which experiences rapid erosion or sedimentation when compared to channels in similar geologic or climatic regions.

De-stabilized banks have been shown to significantly contribute to sediment yields, and eroding riparian zones may be a substantial, though often overlooked, cause of nonpoint source pollution (Booth 1990, Trimble 1997, Jacobson *et al.* 2001). According to Booth (1990), most sediment input to stream systems comes from mass failures of stream bank material, particularly when the upper watershed is paved. During his 10-year study of an urbanizing basin in southern California, Trimble (1997) found that channel erosion accounted for approximately two-thirds of the measured sediment yield from San Diego creek. Eroding banks are known to de-stabilize engineering structures such as bridges, culverts and roadways and often damage expensive waterfront property (Trimble 1997, Johnson, Gleason and Hey 1999, Grable 2000). It seems logical that excess sediment yields might exacerbate flooding in downstream reaches by prematurely filling watershed storage areas.

Recent studies have shown that channel instability rapidly alters aquatic habitat and may reduce stream biodiversity (Bledsoe and Watson 2001, Doyle *et al.* 2001, Jacobson *et al.* 2001). Unpredictable flows are particularly hard on the most sensitive aquatic species, and several studies have shown that changes in substrate size and distribution profoundly impact insect populations (Doyle *et al.* 2001, Jacobson *et al.* 2001). As channels begin to widen due to increased runoff, there is often an opening of the tree canopy which formerly sheltered the stream from direct rays of the sun (Jacobson *et al.* 2001). This may lead to increased water temperatures and decreased oxygen levels, thereby harming aquatic organisms (Jacobson *et al.* 2001).

According to a recent U.S. federal-state review of studies relating land use change to changes in physical stream habitat (Jacobson *et al.* 2001), links between channel erosion and basin-scale land use have been hard to document except in cases of extreme urbanization. In his Australian study, Neller (1998) used erosion pins to monitor bank erosion over an 18-month period in adjacent rural and urban catchments and found that the rate of channel erosion in the urbanized watershed was three to six times greater than that of the rural watershed. Several successful studies have related channel widening/incision to land use changes in the salmon-rich Pacific Northwest, such as a 1991 study that found that channel stability and fish habitat quality both declined rapidly after 10% of the watershed was covered by impervious surfaces (Scheuler 1994, Booth 1996, Booth and Jackson 1997, May *et al.* 1997). A recent study of three Indiana watersheds (Doyle *et al.* 2001) found that measurements of excess shear stress, bankfull discharge recurrence interval and critical discharge recurrence interval are indicators of bank stability that may be linked to the percentage of dense residential housing in the drainage area. The group concluded, however, that more research would be needed to establish a definitive relationship between channel erosion and urbanization. Bledsoe and

Watson (2001) recently modeled the effects of watershed imperviousness on channel instability and aquatic ecosystem degradation, but stated that measured data on the effects of urbanization on stream channel form are still rare.

Research Objective

While many studies have attempted to correlate urbanization with the degradation of water quality and aquatic habitat, relatively few have tried to correlate urban development with channel morphology. This is surprising because a direct relationship exists between physical changes in a stream and changes in stream health and biodiversity (Booth 1996, May *et al.* 1997, Jacobson *et al.* 2001). Physical habitat changes are actually thought to be more pervasive and persistent than changes in stream chemistry (Jacobson *et al.* 2001). Moreover, diffuse, or nonpoint, sources are now the leading cause of water pollution in the United States, and sediment influxes from bank erosion may be a significant contributor to nonpoint source pollution (Booth 1990, Trimble 1997, Barnes *et al.* 2000, Jacobson *et al.* 2001).

This study was undertaken to establish a relationship between simple, inexpensive measurements of channel stability and surrounding land use. While some researchers have found a relationship between changes in channel geometry and changes in land use over time (Booth 1996), I hypothesized that there would be a relationship between bank stability and different degrees of urbanization within adjacent sub-basins. By establishing current relationships between physical channel parameters and surrounding land use, it might become possible to predict the degree of physical stream habitat change that is likely to occur at various levels of urban development. Ultimately, by determining the point at which urbanization impacts streams beyond an ecologically sustainable level within a given area, it might become possible for local policy makers to establish a threshold level of development for a particular watershed or county before irreparable damage to streams and aquatic life occurs.

Organization of Thesis

This thesis is divided into six major sections. The "Introduction" has presented an overview of research related to the effects of urban development on stream channel morphology and has identified the objective of this study. Chapter II, "The Study Area," introduces the reader to the general physiography of the selected focus area, the upper Beaver Creek watershed in north Knox County, Tennessee, and summarizes the environmental and development issues currently faced by the watershed's inhabitants. The study methods, results and discussion are divided into two main categories. Chapter III, "Evaluation of Channel Stability," contains all of the information related to efforts to characterize channel stability using qualitative and quantitative indicators. Chapter IV, "Evaluation of Land Use and Urbanization," explains the geographic information system (GIS) and statistical analyses undertaken to relate basin-wide urbanization levels to the bank stability measurements. An overall summary of the results and their implications for future study are included in the final chapter.

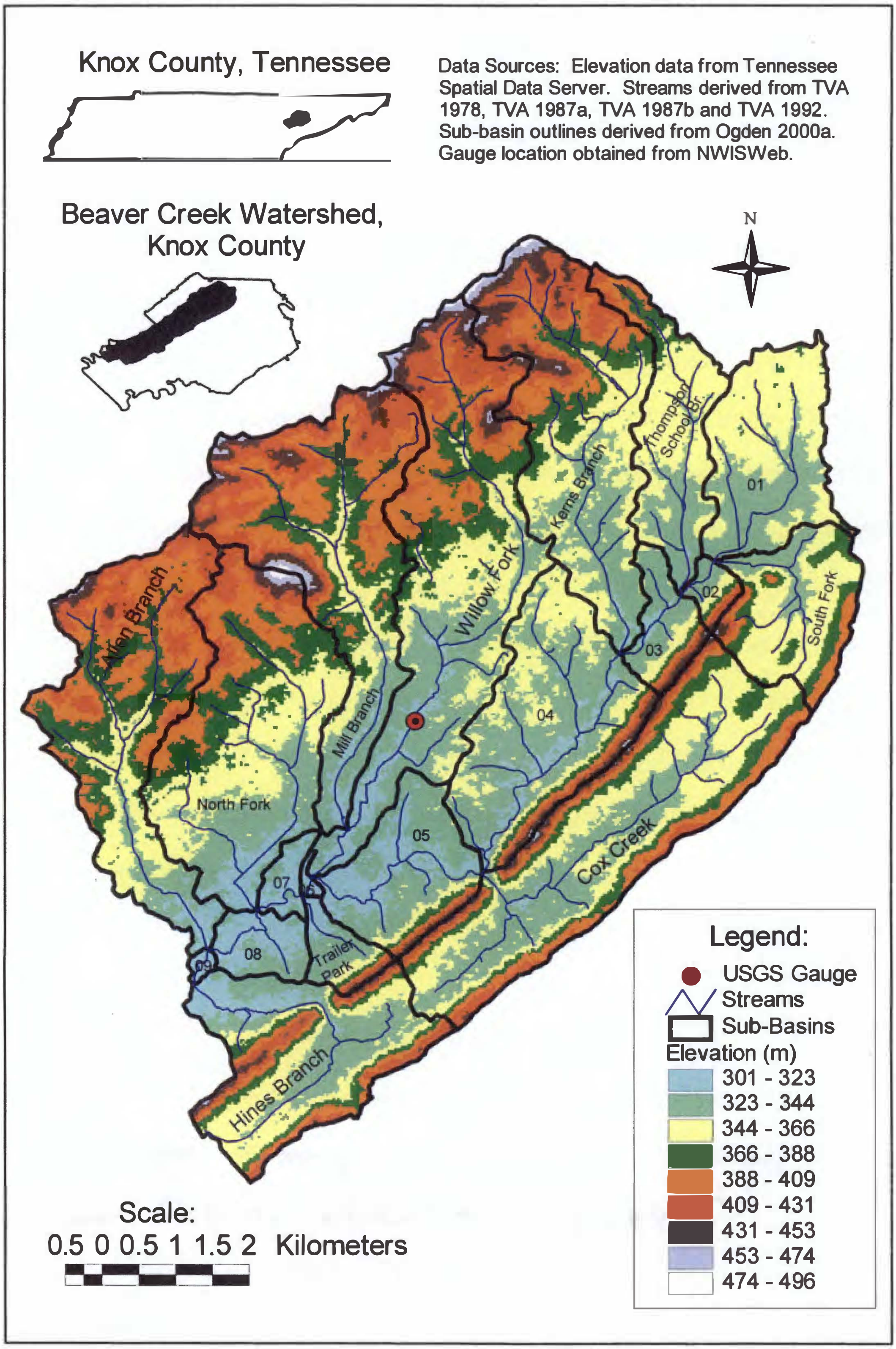
The Appendix contains supplementary information, including a copy of the evaluation sheet used during the qualitative assessment of channel stability, channel measurements related to baseflow (rather than bankfull) conditions, and bankfull cross sections for future reference.

CHAPTER II
THE STUDY AREA

The Knoxville/Knox County area is one of the fastest growing regions in the southeastern United States (Silence 1998) and an ideal location in which to study the relationships between urbanization and channel stability. A comparison of water budgets computed for urban and non-urban uses within the Knoxville area suggest that urbanization has increased annual water surpluses of the Knoxville drainage basins by amounts ranging from 95.3 mm to 294.7 mm per year (Kung and McCabe 1987). Over the past several years, citizens and local agencies have become particularly concerned about development impacts within the Beaver Creek watershed of north Knox County. Beaver Creek has a reputation for flooding problems and is showing increasingly poor water quality (Marcum 1993, Marcum 1995, Silence 1998, Marcum 2001). The Knoxville Water Quality Forum (WQF) estimates that the Beaver Creek watershed as a whole already has 18% impervious cover (Craig 2001b). This is alarming because previous studies of streams within humid areas of the United States have shown that channel instability and possibly irreversible declines in aquatic ecosystems commonly begin at 10-20% impervious cover (Bledsoe and Watson 2001).

General Physiographic Setting

The Beaver Creek watershed is located within north Knox County in eastern Tennessee (**Figure 2-1**). Beaver Creek lies within the Lower Clinch River watershed, and the upper half of Beaver Creek has been assigned the 12-digit hydrologic unit code 060102070301. The 223 km^2 (or 86 mi^2) Beaver Creek watershed is a rectangular area bounded by Copper Ridge to the north and Black Oak Ridge to the south (Ogden 2000b). It completely contains Beaver Ridge. Beaver Creek runs for 71 km (or 44 mi) from its



Data Sources: Elevation data from Tennessee Spatial Data Server. Streams derived from TVA 1978, TVA 1987a, TVA 1987b and TVA 1992. Sub-basin outlines derived from Ogden 2000a. Gauge location obtained from NWISWeb.

Figure 2-1. The Upper Beaver Creek Watershed, Knox County, Tennessee

headwaters at Harbison Crossroads to its confluence with the Clinch River at Melton Valley Lake (Silence 1998). From its headwaters to its mouth, Beaver Creek only descends 85 m (or 279 ft), a gradient of 0.013% (Silence 1998). This low gradient causes peak flows to move through the channel very slowly, and flooding is common in many areas adjacent to the stream (Silence 1998).

Beaver Creek lies within the Valley and Ridge province in the humid southeastern United States. Located at the contact between the Knox Group and the Middle/Lower Chickamauga, the watershed is predominately underlain by sedimentary rocks, including limestone, dolomite, sandstone and shale (Cattermole 1966, Ogden 2001a). While most of the watershed contains moderately drained soil, some areas have poorly drained soils (*e.g.* clay layers over 30 meters deep) that generate a lot of runoff (Ogden 2000a). Several springs and sinkholes in the upper part of the watershed are characteristic of the karst terrain prevalent in this area of Tennessee (TVA 1978, TVA 1987a, TVA 1987b, TVA 1992).

Hydrologic Data

One continuous record of hydrologic data exists for the Beaver Creek watershed: annual peak discharge data from 1967 through 2000 taken at USGS stream gauging station 0353180 on Willow Fork near Harbison Crossroads (**Figure 2-1**). Years of hydrological studies have demonstrated that the 1.5-year peak discharge recurrence interval typically correlates to bankfull discharge (Knighton 1998). To estimate the bankfull discharge at Willow Fork, I entered the annual maximum peak discharge values into an Excel spreadsheet and ranked the 34 values from largest to smallest. I then calculated the recurrence interval (in years) associated with each discharge using the equation $T_r = (n+1)/m$, where "n" is equal to the number of peak discharge measurements, and "m" is equal to the ranking of the discharge measurement (Dunne and Leopold 1978). By graphing the recurrence intervals versus the maximum annual discharge values on Gumbel probability paper and fitting a straight line to the data (**Figure 2-2**), I was able to estimate the discharge corresponding to a 1.5-year recurrence interval, namely 4.0 m^3/s. I would later be able to compare this bankfull discharge value to bankfull discharge values obtained through channel geometry measurements. The probability graph shows that, as of 2000, a 100-year flood event had not occurred in the Beaver Creek watershed for at least 34 years.

For future research purposes, it should be noted that intermittent annual peak discharge measurements were taken on the South Fork tributary of Beaver Creek (USGS stream gauge 03535140) from 1967-1978. Also, within the past few years, USGS has begun placing several new peak flow gauges within the Beaver Creek watershed, including one in the lower watershed at Solway (gauge 03535400), one in the middle part of the watershed in Powell (03535195), and another gauge on Willow Fork in Halls (035351830). The Solway gauge is measuring discharge in addition to stage and precipitation, but it will be several more years before a hydrologic rating curve can be developed (Mihlbachler 2001).

Environmental Concerns

Beaver Creek is listed on Tennessee's 1998 Clean Water Act Section 303(d) list of impaired waterways due to habitat alteration, nutrients, pathogens and siltation, and is categorized as having a high priority for Total Maximum Daily Load (TMDL) development (Tennessee Department of Environment and Conservation web site at www.tdec.com). The likely causes of impairment have been identified as agriculture, drainage and filling of wetlands, land development and municipal point sources.

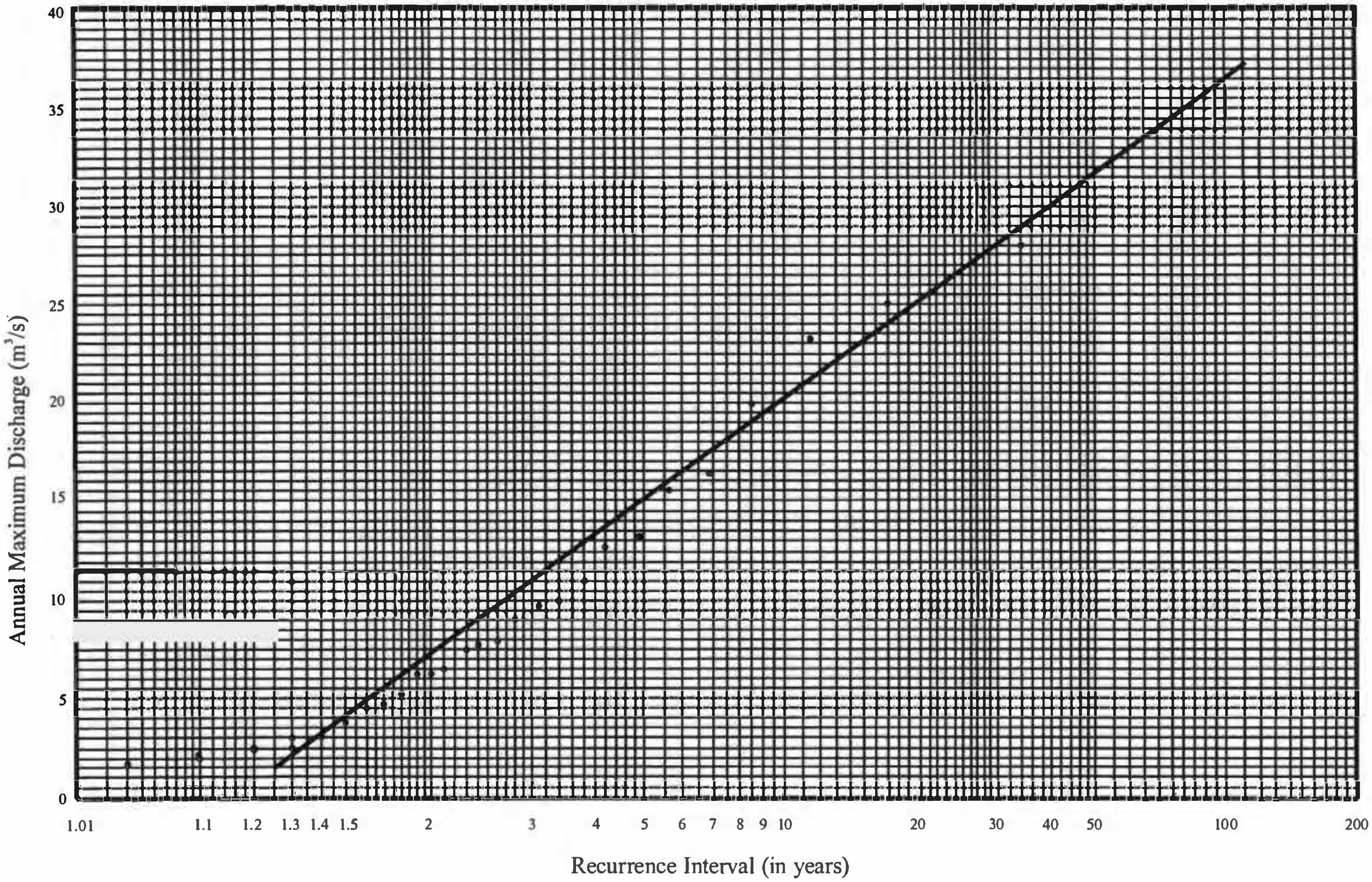


Figure 2-2. Willow Fork Annual Maximum Discharge at Harbison Crossroads (1967-2000)

According to the Beaver Creek Watershed Assessment Team, the stream has high fecal coliform counts and large phosphorous and nitrogen loads, and has experienced significant habitat alteration (Craig 2001, Knoxville Water Quality Forum (WQF) 2001). The Team thinks that the water quality problems in Beaver Creek are due to poor construction practices, poor landscaping practices (*e.g.*, over-fertilization), leaking sewer pipes and septic systems, and in-stream dumping of trash and debris (Craig 2001). During a preliminary reconnaissance of the Kerns Branch watershed, I observed that many cows have direct access to the stream and have trampled down banks in several areas (Parish and Young 2001).

Citizen concerns about flooding and water quality deterioration have led to several recent governmental studies in the Beaver Creek Watershed. While updating its General Plan for Knoxville in 1993, the Metropolitan Planning Commission (MPC) became concerned that more and more developers were trying to build on steep ridges and floodplain areas within Knox County (Marcum 1993). Local citizens had been warning MPC that building proposed subdivisions within the Beaver Creek area would worsen the area's flooding problems. MPC suggested that the Tennessee Valley Authority (TVA) produce an updated floodplain map of the Beaver Creek area to address these concerns (Marcum 1993). In the spring of 1995, a group of citizens incorporated themselves as the Halls Neighbors Association and began to vocalize their concerns about increasing development within the Beaver Creek floodplain (Marcum 1995, Silence 1998). The association was convinced that floodplain boundaries had been drawn at least two feet too low and petitioned the county to re-map the area (Marcum 1995).

In response, Knox County contracted with Ogden Environmental and Energy Services, Inc. (hereafter referred to as "Ogden") to perform a two million dollar project in

1998 to digitally re-map the Beaver Creek floodplain and model flooding based on future development scenarios (Silence 1998). The flood study was designed to update the Flood Insurance Study published in 1982 by the Federal Emergency Management Agency (FEMA), and was intended for presentation to FEMA and TVA (Ogden 2000b, Silence 1998). The resulting two-volume *Beaver Creek Watershed Flood Study* (Ogden 2000a) provides the 100-and 500-year flood boundaries for selected stream reaches as well as water surface profiles for the 2-, 5-, 10-, 25-, 100-, and 500-year floods. Ogden used HEC-1 and HEC-RAS models to determine frequency discharges and stages along Beaver Creek and twelve of its tributaries (Ogden 2000a). The flood models showed that peak discharges and flood elevations are most sensitive to inflows from the surrounding drainage area north of the Allen Branch tributary, or the upper third of the watershed (Mihlbachler 2001). Thus, the control of peak discharges and hydrograph timing in the upper watershed will be critical to effective storm water management (Ogden 2000a).

Current and Expected Land Use

Land use within Beaver Creek may be generalized as rural with developed areas throughout (Ogden 2000a). The majority of the developed areas are residential in nature, and most are clustered around the main traffic corridors (Ogden 2000b). The current percent land use distribution within the uppermost 19 sub-basins of the Beaver Creek watershed is depicted in **Figure 2-3**, and it can be seen that the individual sub-basins range from rural (*e.g.*, Sub-basin 03, Kerns Branch) to wholly urbanized (*e.g.*, Sub-basin 06). The Knoxville WQF estimates that the Beaver Creek watershed as a whole already has 18% impervious cover (Craig 2001b), and the Knoxville-Knox County Metropolitan Planning Commission (2000) predicts that 85% of the watershed will be developed within the next 15 years.

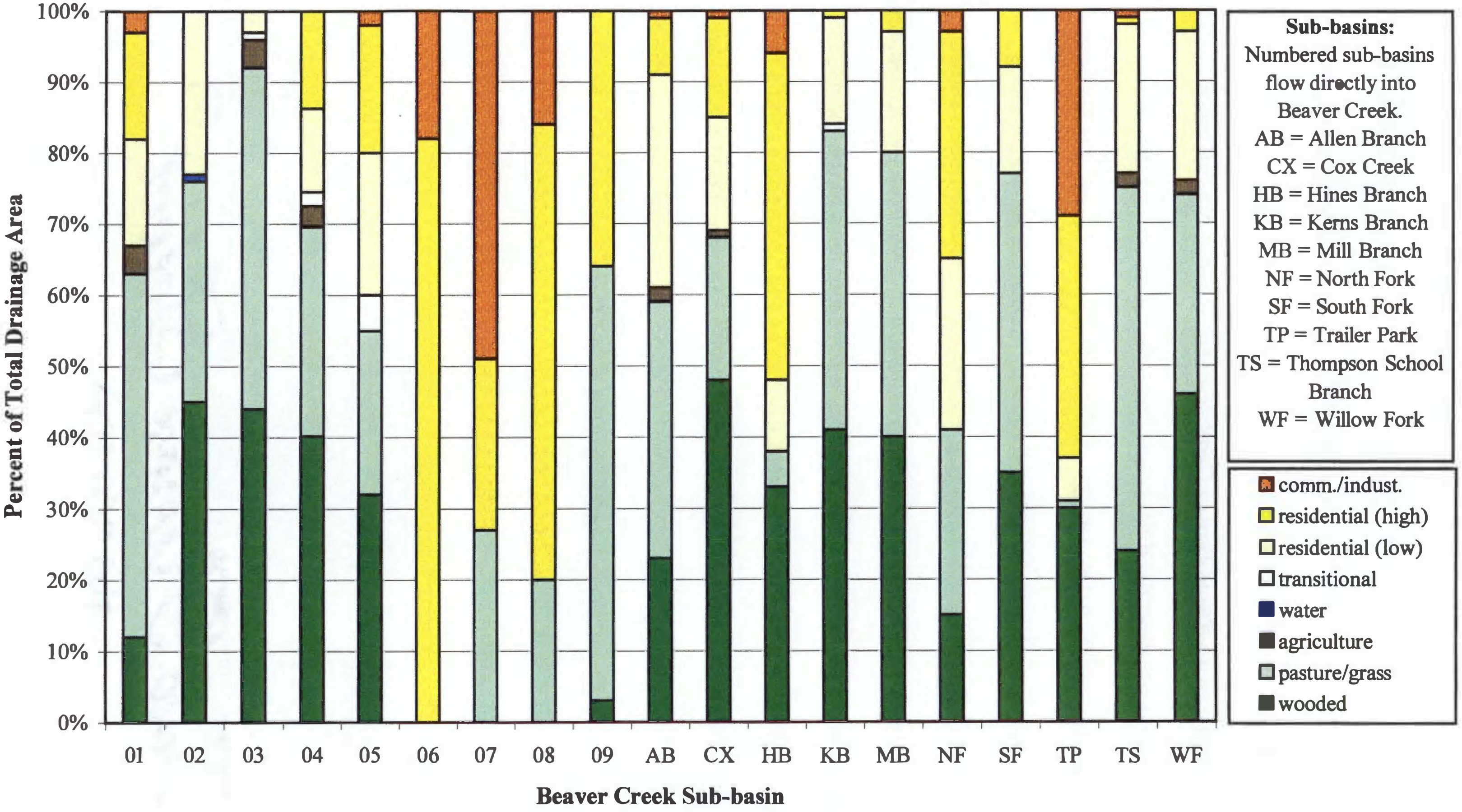


Figure 2-3. Land Use Distribution within the 19 Sub-basins of the Upper Beaver Creek Watershed

The results of the Beaver Creek flood study and floodplain mapping project have led to an integrated effort to look at the status of the entire watershed, including zoning and development, water quality, and wildlife (Marcum 2001). Knox County, Knox Land and Water Conservancy (KLWC), Hallsdale-Powell Utility District (HPUD), the Knoxville Field Office of the United States Department of Agriculture's (USDA) Natural Resources Conservation Service (NRCS), Ogden, the University of Tennessee's (UT's) Water Resources Research Center (WRRC), UT's Energy, Environment, and Resources Center, and the National Association of Conservation Districts have partnered together as the Beaver Creek Watershed Assessment Team in an effort to control flooding, improve water quality, and allocate land for open space, recreation, and trails (Craig 2001a, Knoxville WQF 2001). KLWC has received a grant from TVA to develop a conservation easement acquisition program within the watershed, and an Americorps team is helping the group to identify wetland areas and establish greenways (Craig 2001b, Knoxville WQF 2001). The work undertaken in the Beaver Creek area and the lessons learned will be applied to the assessments of other Knox County watersheds (Craig 2001b), many of which face the same intense development pressures in a similarly restrictive valley and ridge setting.

As of March 2003, Knox County will be required to obtain a permit to discharge storm waters to the waters of the State (Ogden 2000a). To qualify for the permit, the county will need to have a storm water program in place to address public needs for education and outreach, public involvement, illicit discharge detection and control, construction runoff controls, post-construction runoff controls, and best management practices for municipal operations (Ogden 2000a). In 2000, Knox County decided to make Beaver Creek the subject of its first Storm Water Master Plan due to development pressures within the watershed, the frequency and extent of flooding, and the high potential for future development and associated flooding (Ogden 2000a). Knox County re-hired Odgen Environmental and Energy Services, Inc. to examine flood solution alternatives for "priority areas," or those areas that had experienced recent and/or frequent flooding. In its report, Ogden (2000a) has recommended placing several detention basins in the upper part of the watershed, but these have not been constructed to date.

Study Design

In a recent review of studies relating physical stream changes to changes in land use, the United States Geological Survey (USGS) categorized the work to date into four categories: historical, process, modeling and associative (Jacobson *et al.* 2001). After weighing the advantages and disadvantages of each approach, I decided to conduct an associative study within the upper Beaver Creek watershed.

Historical studies document the sequence and causes of disturbance so that researchers are better able to discern natural versus human influences on channel structure and estimate baseline conditions. It may take many years for land use change impacts to be transmitted through a channel network. Only one historical gauging station exists in the Beaver Creek watershed (located on Willow Fork), and it has only recorded annual peak flows since 1967; until recently, no studies of water quality had been conducted in this watershed. Thus, in spite of the availability of historic aerial photographs of the area, there seemed to be little opportunity for relating land use change to changes in physical stream habitat over time.

Process-based studies are experimental in nature and are often conducted by comparing stream responses between treatment and control sites or by monitoring a single site before, during and after land use change. Funding and time constraints prevented me from conducting this type of in Beaver Creek. However, there are still locations within the upper watershed that might make a process-based study feasible for another researcher.

While computer modeling studies of urbanization impacts on streams have been performed on a basin scale and channel scale, researchers are only just beginning to incorporate both scales into a single model (Jacobson *et al.* 2001). Many of the equations used in such models are based on experiments and monitoring activities conducted in disparate areas of the country on very large basins, and might not be truly applicable to a small basin in East Tennessee. Thus, I decided not to do a modeling study in this area.

Associative studies correlate basin-scale and/or riparian-scale land use to physical habitat variables, and per Jacobson *et al.* (2001), they are useful tools for screening potential links between land use and stream habitat before more expensive and time-consuming types of studies are conducted. Land use within each of the 19 sub-basins of upper Beaver Creek is quite varied, ranging from predominately rural to predominately urban, so I expected the upper Beaver Creek watershed to provide a good opportunity for linking the presence/absence of channel erosion to different land use patterns within adjacent sub-basins sharing very similar climatic and geologic histories. In the spring of 2001, the University of Tennessee's Department of Geography made qualitative observations about land use, water quality and bank stability in the upper Beaver Creek watershed (Parish and Young 2001). Nine out of eleven groups reported moderate to significant bank erosion in their assigned areas, suggesting that both stable and unstable sites could be located within the upper watershed. By combining qualitative and quantitative field observations of channel stability with GIS-based land use calculations (Doyle *et al.* 2001), I planned to establish a threshold value of urban development for the upper Beaver Creek watershed beyond which channel instability would be likely to occur. I reasoned that channel instability within the upper watershed would exacerbate downstream flooding and water quality problems.

I initially set out to measure bank stability at least one location within each of the 19 sub-basins in the upper third of the Beaver Creek watershed, or that area of the watershed upstream of Allen Branch and east of Interstate 75. After driving for several days throughout the 83 km^2 (32 mi^2) upper Beaver Creek watershed, however, I discovered that even though "windshield" surveys had been possible in most of the area, the majority of the streams are fenced out at the water's edge by private property owners and there are very few places to park (due to a lack of shoulders on any of the roads). These conditions made it very difficult to gain access to sampling locations within some of the basins. In addition, because I conducted field work during a period of extreme drought, many of the smaller streams were completely dry. In the end, I was able to locate 10 accessible and suitable study sites within eight of the upper Beaver Creek sub-basins: Beaver Creek Sub-basin 05, Cox Creek, Hines Creek, Kerns Branch, Mill Branch, North Fork, Thompson School Branch, and Willow Fork. These eight second- and third-order sub-basins ranged from 3.1 km^2 to 10.1 km^2 in size, and varied from predominately rural to urban (**Table 2-1**). The 10 site locations also encompassed many of the different types of topography and underlying geology found throughout the upper watershed.

Table 2-1. Land Use Distribution (by Percent) within the Eight Sub-basins Selected for Study

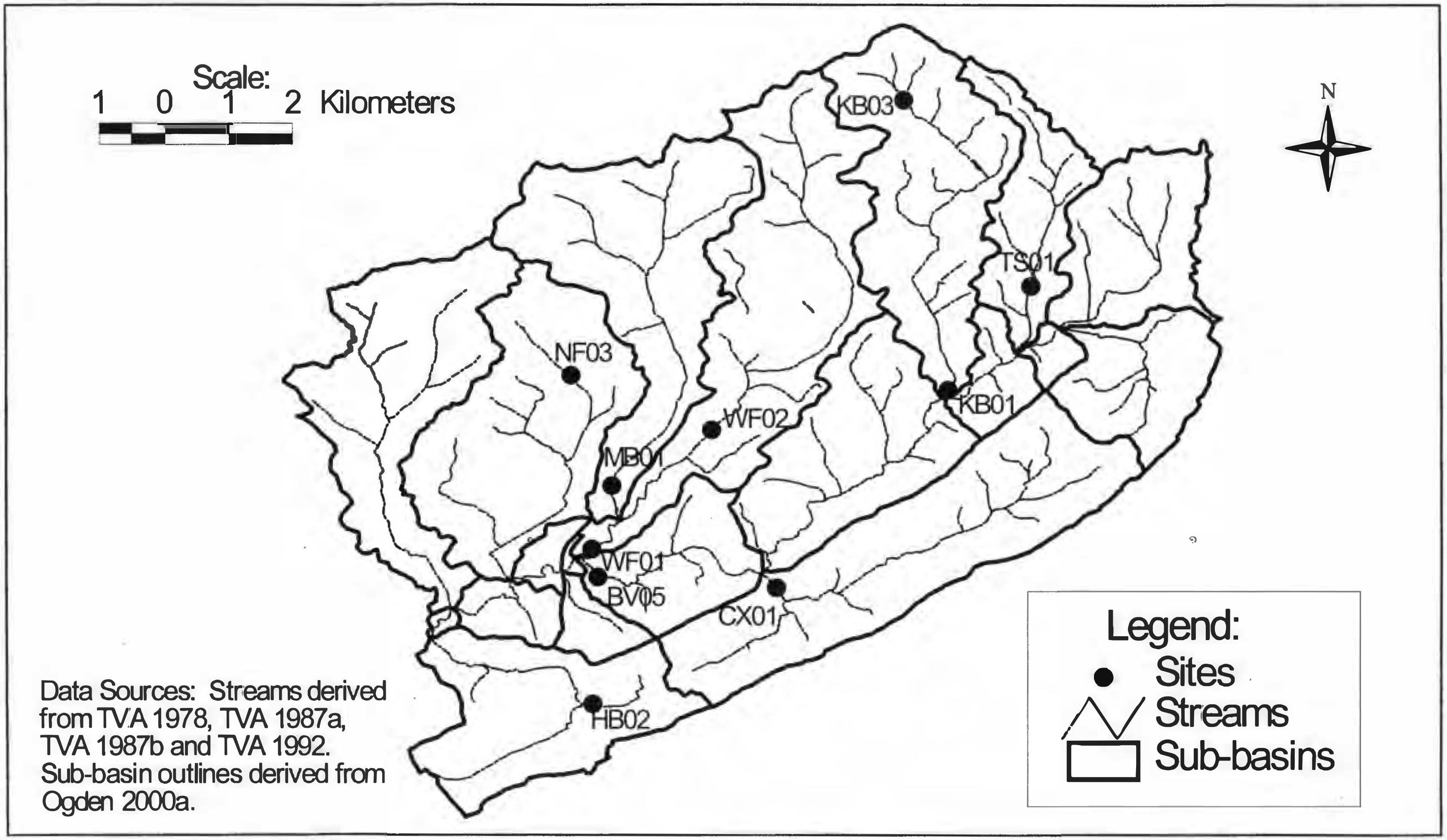
Sub-basin	**Area (km^2)**	**Wooded**	**Pasture/ Grass**	**Agricultural**	**Transitional**	**Residential (low density)**	**Residential (high density)**	**Commercial/ Industrial**
Beaver Creek, 05	3.11	32	23	0	5	20	18	2
Cox Creek	9.58	48	20	1	0	16	14	1
Hines Branch	5.96	33	5	0	0	10	46	6
Kerns Branch	8.03	41	42	0	1	15	1	0
Mill Branch	8.55	40	40	0	0	17	3	0
North Fork	8.29	15	26	0	0	24	32	3
Thompson School Branch	3.37	24	51	2	0	21	1	1
Willow Fork	10.10	46	28	2	0	21	3	0

CHAPTER III
EVALUATION OF CHANNEL STABILITY

I hypothesized that channel instability, as evidenced by the prevalence of bank erosion, would be correlated with urbanization in the upper Beaver Creek watershed such that an increase in development would lead to more visible bank erosion. I reasoned that this relationship would occur due to the tendency of developed, or more densely paved land, to produce greater volumes of storm runoff and speed that runoff directly to stream channels, thereby altering the original hydrologic conditions of the watershed. I decided that I would use both a qualitative and quantitative field method to designate each site as "stable" or "unstable." This chapter discusses the two field techniques used to assess channel stability and compares their results.

Site Locations and Timeframe of Study

From November 3, 2001 to December 18, 2001, I took quantitative and qualitative field measurements of channel stability at 10 different locations within the upper Beaver Creek watershed (**Figure 3-1** and **Table 3-1**). These 10 locations included one site along the main stem of Beaver Creek (in Sub-basin 05) and nine sites along seven different tributaries—Cox Creek (CX), Hines Branch (HB), Kerns Branch (KB), Mill Branch (MB), North Fork (NF), Thompson School Branch (TS), and Willow Fork (WF). The site numbering scheme for the tributaries includes the two letter code used for each sub-basin during the Knox County flood study (Ogden 2000a) combined with my own two-digit code representing the general location of the reach along the stream, such that 01 = near the mouth (lower sub-basin), 02 = in the middle, and 03 = near the headwaters (upper sub-basin). It took approximately four hours for me and an assistant



Data Sources: Streams derived from TVA 1978, TVA 1987a, TVA 1987b and TVA 1992. Sub-basin outlines derived from Ogden 2000a.

Figure 3-1. Map of Site Locations

Table 3-1. Site Locations

Site ID	Stream Location	Site Address	Date Sampled
BV05	Beaver Creek, Sub-basin 05	Lower baseball field at Halls Community Park off of Recreation Drive	12/03/01
CX01	Cox Creek, lower	Brown Gap Road, just upstream of confluence with Beaver Creek	12/04/01
HB02	Hines Branch, middle	Behind Weigel's gas station at junction of Highway 441 and Old Maynardville Pike	12/03/01
KB01	Kerns Branch, lower	Twin Brooks Subdivision on Beeler Road	11/03/01
KB03	Kerns Branch, upper	Across from Clear Springs Baptist Church at Wood Road and Thompson School Road	11/05/01
MB01	Mill Branch, lower	North of Christ United Methodist Church at intersection of Maynardville Highway and Temple Acres Drive	11/26/01
NF03	North Fork, upper	Brookhaven Subdivision on McCloud Road	12/04/01
TS01	Thompson School Branch, lower	Across from Fairview Baptist Church at the intersection of Emory Road and Thompson School Road	12/18/01
WF01	Willow Fork, lower	Behind CVS Pharmacy and Bi-Lo Grocery Store at the junction of Maynardville Highway and Emory Road	11/14/01
WF02	Willow Fork, middle	Willow Fork Youth Park on Quarry Road	11/19/01

who recorded data to take a complete set of qualitative and quantitative measurements at each site.

Qualitative Assessment of Channel Stability

Qualitative Methods

At the recommendation of the Beaver Creek Watershed Assessment Team, I used the U.S. Department of Agriculture's *Stream Visual Assessment Protocol* (USDA 1998) to assess the general stream health and bank stability at each site. The SVAP measurement for bank stability was simpler then most and allowed me to easily compare my study sites. It also provided more information than the four-tier method outlined by Booth (1996) in his suggested methodology for relating channel stability to land use change. After walking down and sketching a portion of the stream that was approximately 12 times longer than the active channel width (i.e., an average reach length of 28 meters), I scored 10 criteria using a scale of 10 (best) to 1 (worst). The 10 assessment elements and their evaluation criteria are summarized in **Table 3-2**. Intermediate scores were possible for each indicator.

At each site, I sketched the site and recorded the qualitative indicator scores on a copy of the "NRCS Stream Visual Assessment Protocol" field checklist (**Figure A-1**). In accordance with the protocol, I added together the 10 indicator scores and divided the sum by 100 to obtain an overall site score ranging from 10 to 1. These overall site scores may be interpreted as follows: ≥ 9.0 = excellent condition; 7.5 - 8.9 = good condition; 6.1 - 7.4 = fair condition; and, ≤ 6.0 = poor condition (USDA 1998).

Since the bank stability indicator was of primary interest, I documented any evidence of significant bank erosion with verbal descriptions and digital photographs. Signs of erosion included undercut banks and exposed tree roots (**Figure 3-2a**), exposed

Table 3-2. USDA Stream Visual Assessment Protocol Indicators (USDA 1998)

Assessment Element	Score of 10	Score of 7	Score of 3	Score of 1
Channel Condition	Natural channel; no structures, dikes. No evidence of downcutting or excessive lateral cutting	Evidence of past channel alteration, but with significant recovery of channel and banks. Any dikes or levies are set back to provide access to an adequate floodplain.	Altered channel; <50% of the reach with riprap and/or channelization. Excess aggradation; braided channel. Dikes or levees restrict floodplain width.	Channel is actively downcutting or widening. >50% of the reach with riprap or channelization. Dikes or levees prevent access to the floodplain
Hydrologic Alteration	Flooding every 1.5 - 2 years. No dams, no water withdrawals, no dikes or other structures limiting the stream's access to the floodplain. Channel is not incised.	Flooding occurs only once every 3 - 5 years; limited channel incision. OR Withdrawals, although present, do not affect available habitat for biota	Flooding only once every 6 - 10 years; channel deeply incised. OR Withdrawals significantly affect available low flow habitat for biota.	No flooding; channel deeply incised or structures prevent access to floodplain or dam operations prevent flood flows. OR Withdrawals have caused severe loss of low flow habitat. OR Flooding occurs on a 1-year rain event or less.
Riparian Zone	Natural vegetation extends at least two active channel widths on each side.	Natural vegetation extends more than 1/2 but less than one active channel width on each side.	Natural vegetation extends 1/3 of active channel width on each side. OR filtering function moderately compromised	Natural vegetation less than 1/3 of active channel width on each side. OR lack of regeneration OR filtering function severely compromised

Table 3-2. Continued

Assessment Element	Score of 10	Score of 7	Score of 3	Score of 1
Bank Stability	Banks stable; erosion or bank failure absent or minimal; little potential for future problems; <5% of bank affected	Moderately stable; infrequent, small areas of erosion mostly healed over; 5-30% of banks in reach have areas of erosion	Moderately unstable; 30-60% of banks in reach have areas of erosion; high erosion potential during floods	Unstable; many eroded areas; “raw” areas frequent along straight sections and bends; 60-100% of banks have erosion scars
Water Appearance	Very clear, or clear but tea-colored; objects visible at depth 3-6 ft (less if slightly colored); no oil sheen or foaming on surface; no noticeable film on submerged objects or rocks	Occasionally cloudy, especially after storm event, but clears rapidly; objects visible at depth 1.5-3 ft; may have slightly green color; no oil sheen or foam on water surface	Considerable cloudiness most of the time; objects visible to depth 0.5-1.5 ft; slow sections may appear pea-green; bottom rocks or submerged objects covered with heavy green or olive-green film; may have some foam on surface OR Moderate odor of ammonia or rotten eggs.	Very turbid or muddy appearance most of the time; objects visible to depth < 1/2 ft; slow moving water may be bright-green; other obvious water pollutants; floating algal mats, surface scum, sheen or heavy coat of foam on surface OR Strong odor of chemicals, oil, sewage, other pollutants
Nutrient Enrichment	Clear water along entire reach; diverse aquatic plant community includes low quantities of many species of macrophytes; little algal growth present	Fairly clear or slightly greenish water color along entire reach; moderate algal growth on stream substrates	Greenish water color along entire reach; over-abundance of lush green macrophytes; abundant algal growth, especially during warmer months	Pea green, gray, black or white water color along entire reach; dense stands of macrophytes clog stream; severe algal blooms create thick algal mats in stream
Barriers to Fish Movement	No barriers	Seasonal water withdrawals inhibit movement within the reach	Drop structures, culverts, dams, or diversions (> 1 foot drop) within 3 miles of the reach	Drop structures, culverts, dams, or diversions (> 1 foot drop) within the reach
Instream Fish Cover	>7 cover types available	5 to 6 cover types available	2 to 3 cover types available	None to 1 cover type available

Table 3-2. Continued

Assessment Element	Score of 10	Score of 7	Score of 3	Score of 1
Pools	Deep and shallow pools abundant; greater than 30% of the pool bottom is obscure due to depth, or the pools are at least 5 feet deep	Pools present but not abundant; between 10 - 30% of the pool bottom is obscure due to depth, or the pools are at least 3 feet deep	Pools present but shallow; between 5 -10% of the pool bottom is obscure due to depth, or the pools are less than 3 feet deep	Pools absent or the entire bottom is discernible
Invertebrate Habitat	At least 5 types of habitat available. Habitat is at a stage to allow full insect colonization (woody debris and logs not freshly fallen).	3-4 types of habitat. Some potential habitat exists, such as overhanging trees, which will become habitat but have not yet entered the stream.	1-2 types habitat. The substrate is often disturbed, covered, or removed by high stream velocities and sediment deposition.	None to 1 type of habitat.

A. An undercut bank with exposed tree roots at KB01.

B. An exposed sewer line at TS01.

C. An exposed bridge footing at TS01.

Figure 3-2. Examples of Bank Erosion

edges of sewer lines crossing stream channels (**Figure 3-2b**), and exposed bridge footings (**Figure 3-2c**). I also looked for tilting vegetation, scalloped edges (USDA 1998), and knickpoints (Neller 1998). At the conclusion of each qualitative assessment, I added an overall qualitative descriptor of "stable," "eroding" or "aggrading" to the comments section of the NRCS form. Whenever I used the photographs to document some of the visual observations, I also recorded the site-specific photo numbers and corresponding descriptions on the NRCS form. General information about each of the 10 sites, including an overall visual assessment of channel stability and a summary of adjacent land use, is provided in **Table 3-3**.

Qualitative Results

None of the stream reaches examined during this study received an "excellent" health rating, and six out of the 10 reaches were ranked as "fair" (**Table 3-4**). The upper Kerns Branch site (KB03) and lower Cox Creek site (CX01) had the best overall ratings (8.0 and 7.6 out of 10, respectively), whereas the upper North Fork site (NF03) had the worst rating (4.2 out of 10). KB03 and CX01 both run alongside a two-lane road in a wooded area with scattered houses. NF03 is located at the intersection of three two-lane roads at the entrance of a subdivision which appears to be several decades old.

Of primary interest to this study are the SVAP scores relating to bank stability. The upper North Fork site (NF03) and the middle Hines Branch site (HB02) received the lowest bank stability scores (1 out of 10). NF03 appears to be deeply incised, as was evidenced by a tree hanging with its roots completely suspended one foot above the channel center, a knickpoint of greater than 1 foot downstream of a culvert at the north end of the reach, an exposed gas pipe, and over 60% of the channel reach exhibiting scoured (or "raw") banks with exposed tree roots. It was difficult to take photographs

Table 3-3. General Information about Channel Stability and Land Use at Each Site

Site	Stable?	Dominant Substrate	Type(s) of Bedrock	Adjacent Land Use(s)	Other Comments
BV05	Stable	Mud	Shale and limestone	Recreation	Formerly eroding and now aggrading? Just upstream of the park, land on the south bank has been cleared for a new subdivision. Looks as though part of the channel has been dredged in the past.
CX01	Stable	Boulders	Sandstone, siltstone and shale	Woods, Residential	Exposed bedrock. May be widening, but banks appear stable.
HB02	Eroding	Gravel	Limestone	Commercial, Subdivisions	Lots of trash. Several bedrock steps.
KB01	Eroding	Gravel	Shale	Subdivision	Downstream from ongoing construction within the Twin Brooks subdivision. Also downstream from cattle access.
KB03	Stable	Cobbles	Dolomite	Woods, Residential, Church	Land is being cleared just downstream of study area, presumably for an expansion of the Clear Springs Church parking lot.
MB01	Stable	Gravel	Shale	Residential, Recreation	Located in a mowed area behind a small driving range. Per a local resident, this site used to be pasture.
NF03	Eroding	Cobbles	Dolomite	Subdivision	Deeply incised channel with a knickpoint downstream of road crossing. Located at the entrance of an older subdivision.

Table 3-3. Continued

Site	Stable?	Dominant Substrate	Type(s) of Bedrock	Adjacent Land Use(s)	Other Comments
TS01	Eroding	Silt	Shale	Open land, Two road crossings	Silt may be coming from two subdivisions being built upstream. Larger "particles" appear to be pieces of rotting bedrock. Site lies in between two road crossings.
WF01	Aggrading	Mud	Shale	Open land	Several feet of mud on both sides of active channel.
WF02	Eroding	Gravel	Shale	Park, Church, Residential	Moderately incised. Some bedrock outcrops.

Table 3-4. Results of the USDA Stream Visual Assessment

Site Name		Channel Condition	Hydrologic Alteration	Riparian Zone	Bank Stability	Water Appearance	Nutrient Enrichment	Barriers to Fish Movement	Instream Fish Cover	Pools	Invertebrate Habitat	Overall Score	Overall Health
Creek	ID												
Beaver Creek, Sub-basin 05	BV05	9	10	1	5.5	4	7	10	3	8	3	6.1	Fair
Cox Creek, lower	CX01	10	10	2	8	10	9	5	5	10	7	7.6	Good
Hines Branch, middle	HB02	10	10	8	1	3	7	5	5	3	10	6.2	Fair
Kerns Branch, lower	KB01	10	10	7	3	10	7	10	1	1	7	6.6	Fair
Kerns Branch, upper	KB03	10	7	8	10	10	10	10	5	3	7	8.0	Good
Mill Branch, lower	MB01	10	1	1	9	10	10	8	1	1	1	5.2	Poor
North Fork, upper	NF03	2	3	3	1	10	7	3	5	1	7	4.2	Poor
Thompson School Branch, lower	TS01	10	10	10	3	1	7	5	5	3	10	6.4	Fair
Willow Fork, lower	WF01	9	10	5	10	10	7	4	3	2	3	6.3	Fair
Willow Fork, middle	WF02	10	9	4	3	5	6	6	8	6	10	6.7	Fair

and measurements at this site because the channel was filled with thorny brambles. Located behind a Weigel's gas station just downstream of a subdivision and two-lane road crossing, HB02 also appeared to be deeply incised. Its banks were de-vegetated and inlaid with trash (drink bottles, plastic bags, oil containers, *etc.*), and several bedrock steps were found within the reach. I saw many exposed tree roots and an exposed gas line running beneath the road crossing.

Out of the 10 sites, the lower Willow Fork site (WF01) was the only reach that appeared to be aggrading, or storing a large volume of sediment. WF01 lay 2591 m downstream from eroding site WF02. The channel was deceptively shallow; after stepping into the water to measure pebbles, it became apparent that the banks were obscured by at least one meter of mud. I found in-stream vegetation growing along the center of the waterway, and I picked up several mussel shells. Located in the middle of a flat, grassy area, the WF01 reach runs alongside the foot of an elevated shopping center that includes a pharmacy and a large grocery store. A black plastic silt screen was still in place between the shopping center and the channel at the time of sampling, indicating that construction of the CVS Pharmacy had only been recently completed. I speculate that the aggradation at WF01 was either due to recent land disturbance at the nearby CVS pharmacy, or to infilling from the channel erosion noted upstream at WF02. Either of these factors would be compounded by the especially low gradient at this location (only 0.001). Per Reid and Dunne (1996), alluvial reaches, or those stream segments bounded by lowland floodplains and alluvial terraces, have the greatest risk of aggradation. Because the SVAP equates bank stability to the degree of channel erosion, WF01, with no apparent erosion, received 10 out of 10 for bank stability. Sites KB03 and MB01 also received bank stability scores of 10 out of 10, but neither of these sites showed any signs of aggradation.

Quantitative Assessment of Channel Stability

Quantitative Methods

In addition to making a qualitative determination of channel stability, I sought to classify the 10 sites as having stable or unstable banks based upon a quantitative measurement of excess shear stress, or the ability of the channels to mobilize their sediments. Excess shear stress, τ_e, is equal to τ_o/τ_c, the ratio of cross-section averaged boundary shear stress exerted on the bed to the critical shear, or the shear at which bed motion is initiated (Johnson *et al.* 1999, Doyle *et al.* 2001). When τ_o exceeds τ_c, particles will begin to roll, slide or saltate along the bed (Knighton 1998). Because τ_e accounts for both erosive and resistive forces, it is better suited to characterizing channels of variable substrate size than more traditional measurements of τ_o alone (Doyle *et al.* 2001). According to Johnson *et al.* (1999), a reach with a τ_o/τ_c ratio of less than 1.0 is considered to have "excellent" stability, and a ratio value of 1.0 to 1.5 implies "good" stability. In contrast, stream reaches with excess shear values of 1.5 to 2.5 are considered to have only "fair" stability, and reaches with values greater than 2.5 are considered to have "poor" stability. Although excess shear stress is a new measure of bank stability that has not been widely tested, I chose it because it does not require any hydrologic data, as very little historical hydrologic data exist for the Beaver Creek watershed.

Shear stress (τ_o) and critical shear (τ_c) may be calculated according to the following two equations:

(1) $\tau_o = \gamma RS$,

where γ is the unit weight of water, R is the hydraulic radius, and S is the energy slope; and

(2) $\tau_c = \tau_c{}^*(\gamma_s - \gamma)D$,

where τ_c* is the dimensionless Shields parameter for entrainment of particle of size D, the value D is assumed to be the median grain size of the bed sediment, and γ_s and γ are the unit weight of sediment and water, respectively (Doyle *et al.* 2001). To calculate excess shear stress, I measured the bankfull channel geometry and the median pebble size at each site.

Per Reid and Dunne (1996), measurements to be used in the calculation of sediment transport should be taken within straight, single-stranded reaches that are free of local complications. I therefore selected straight reaches without noticeable point bars, debris jams or other disruptive features to ensure that an evenly distributed bed sample would be measured. I also stayed at least 600 m back from the tributary confluences (Reid and Dunne 1996). In keeping with the study by Doyle *et al.* (2001), the selected reaches generally corresponded to riffle reaches. However, given the much smaller size of the streams in the Beaver Creek study area then those measured by Doyle at al. (2001) in Indiana, it was not possible to pick riffle reaches that were 200 meters in length; instead, the average length of the riffle reaches used in this study was 7 meters. These sampling reaches appeared to be representative of the larger qualitatively assessed reaches and the particular lower, middle or upper sub-basin area.

I used eight survey flags to mark the boundaries of the sampling reach and aid in the measurement of channel geometry (**Figure 3-3**). Flags 1-4 were used to mark the boundaries of the active channel, or that part of the stream channel currently occupied by water. Flags 5-8 were used to mark the boundaries of the approximated bankfull flow, or the level of flow which would cause the stream to overtop its banks. To identify the bankfull stage, I looked for breaks in topography from steeply sloping banks to flatter floodplain areas and changes in vegetation, such as bare to grass or treeless to trees (Reid and Dunne 1996).

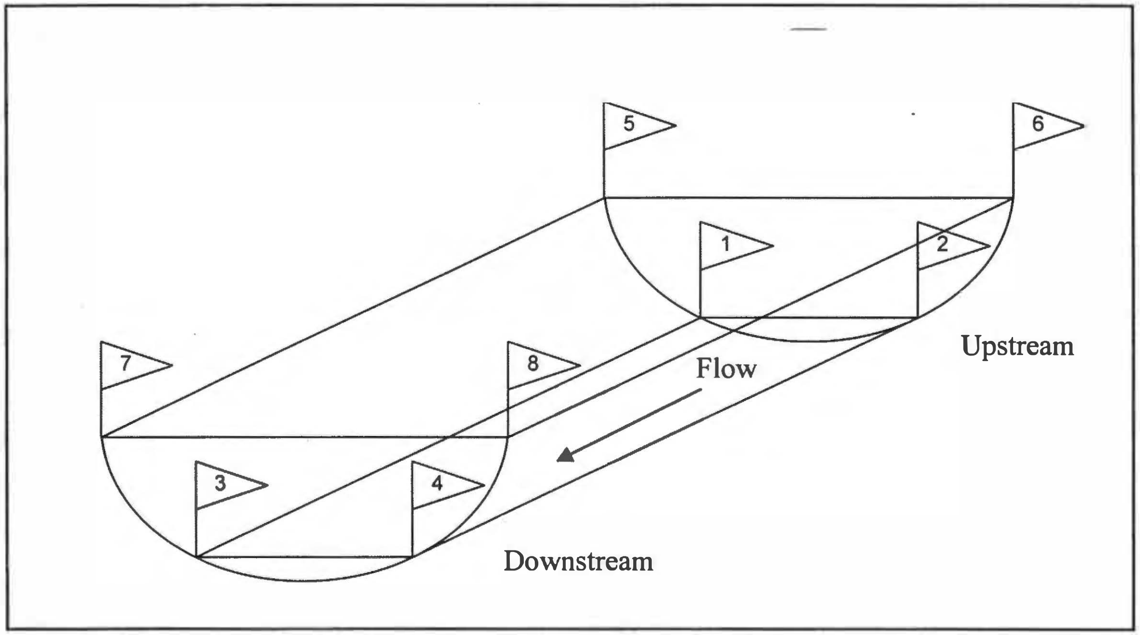


Figure 3-3. Establishing the Sampling Reach Boundaries

I measured the length of the reach and took cross-sectional measurements at each end of the reach to verify channel uniformity. To measure the width of the upstream baseflow cross section, I stretched a plastic tape from flag 1 to flag 2 (perpendicular to the flow) at water level. I then used a yardstick to measure the depth of the water to the nearest 6 mm (0.25 in) at 0.31 m (1 ft) increments along the tape. I made similar baseflow cross section measurements downstream using flags 3 and 4. To measure the width of the upstream bankfull cross section, I measured the distance between flags 5 and 6. I took depth measurements from the streambed to the height of the suspended tape using a single yardstick or two stacked yardsticks. Again, I took depth measurements at 0.31-m (1-ft) increments along the tape and recorded to the nearest 6 mm (0.25 inch). I made similar bankfull cross section measurements downstream using flags 7 and 8.

To calculate the bankfull hydraulic radius (R) for each site, I graphed each bankfull cross section at a 1:24 scale and used the graphs to calculate the cross-sectional area (A) and wetted perimeter (WP). I then calculated R as A/WP and averaged the two values for each site to get a representative R for the site (**Table 3-5**). For comparison, similar baseflow measurements are in **Table A-1**.

Table 3-5. Average Bankfull Cross-sectional Area (A), Wetted Perimeter (WP) and Hydraulic Radius (R)

Site	A (m^2)	WP (m)	R (m)
BV05	7.25	8.17	0.89
CX01	7.19	9.85	0.73
HB02	2.31	4.36	0.53
KB01	3.40	6.63	0.51
KB03	1.72	5.85	0.29
MB01	0.98	4.24	0.23
NF03	5.48	6.86	0.80
TS01	2.68	4.69	0.57
WF01	0.33	2.24	0.15
WF02	2.63	5.20	0.51

I used the Wolman (1954) pebble count method to measure the intermediate axis of 100 streambed pebbles at regularly spaced intervals along each study reach. By dividing 100 by the length of the sampling reach, I determined how many surface pebbles would need to be picked up across the width of the stream at each length increment. In other words, if the reach was 25 m long, then 100/25 or 4 pebbles would need to be measured each time I walked across the stream at one-meter increments. I drew the resulting 100-cell grid (*e.g.*, 4 columns by 25 rows) on a sheet of graph paper to help with the data recording. I strung a plastic measuring tape from flag 1 to flag 3 (parallel to the stream) and left it in place for reference.

To avoid sampling bias, I kept an even pace and attempted to pick up whichever pebble was directly under the toe of my boot without looking. Because it was fall, I frequently had to gently lift or push aside leaves to access the streambed material. Once I had measured a pebble, I cast it a short distance behind me so that I would not accidentally pick it up and measure it a second time. At most sites, I used a metal caliper accurate to 0.01 mm to measure the pebble axes. When the streambed material consisted of cobbles and boulders, I used a transparent 12-inch plastic ruler to measure the "pebble" axes to the nearest millimeter. Whenever I picked up a handful of smooth colloidal material rather than distinguishable grains or pebbles, I recorded the measurement as "S." I later assigned these "S" particles an intermediate diameter of 0.03 mm, the average size of silt particles (Knighton 1998, Bunte and Abt 2001).

In accordance with Doyle *et al.* (2001), I assumed that the particle size (D) in equation 2 was equivalent to the median grain size of the bed sediment (D_{50}). To determine D_{50} for each site, I entered the 100 pebble count measurements from each site into Excel spreadsheets and calculated the median values. The median particle sizes ranged from 1 mm to 87 mm, indicating a significant difference in bed material across the upper Beaver Creek watershed (**Table 3-6**). In general, the upper reaches had coarser bedload material than the lower reaches, as would be expected (Reid and Dunne 1996).

By converting the particle sizes to phi units, or $-\log_2$(particle size in mm), and graphing their frequency, one can check to see that the particle size distribution has the general backward-S shape expected from natural gravel riverbeds (Wolman 1954, Bunte and Abt 2001). A comparison of the particle distributions for my 10 sites (**Figure 3-4**) reveals that nine of the 10 sites showed the expected particle size distribution, but that TS01 had a very different particle size distribution (as explained in the Discussion section of this chapter).

Because the bed slope may be used to approximate the energy slope (S) during bankfull conditions (Doyle *et al.* 2001), I used 7.5-minute topographic maps to calculate the channel gradients (**Table 3-6**) by measuring the rise/run in the immediate vicinity of each study site. The study area is found at the intersection of four 1:24,000 topographic quadrangles, namely the Graveston (TVA 1987b), Fountain City (TVA 1978), John Sevier (TVA 1992) and Big Ridge Park (TVA 1987a) quads. I also tried using an Abney level to calculate channel bed gradients directly, but the changes in slope were too subtle for meaningful measurement.

I selected roughness coefficients, or Manning "n" values (**Table 3-6**), for each site by examining the bedload material (Marsh 1997) and comparing the appearance of each reach to photographs published by Barnes (1967). The selected n-values roughly agree with the ranges of channel n-values listed in Table 4-9 of the Ogden flood study for each tributary, which are said to vary according to season and channel depth (Ogden 2000a).

To calculate excess shear stress, I still needed to determine values for the three remaining variables: the unit weight of water (γ), sediment density (γ_s), and the

Table 3-6. Summary of Site Physical Characteristics

Site	Drainage area (km^2)	Gradient	Roughness value (n)	D_{50}, mm	Q_{bf}, m^3/s	Width to depth ratio
BV05	3.11	0.001	0.025	5	7.69	4.6
CX01	9.58	0.003	0.055	87	6.12	8.7
HB02	1.28	0.010	0.040	20	3.79	2.9
KB01	8.03	0.008	0.030	9	6.41	5.2
KB03	1.05	0.029	0.050	68	2.57	11.7
MB01	8.55	0.005	0.035	14	0.74	5.6
NF03	1.73	0.014	0.045	45	12.55	1.6
TS01	2.60	0.006	0.030	1	4.73	3.9
WF01	10.10	0.001	0.025	8	0.10	20.2
WF02	8.49	0.010	0.035	14	4.77	4.2

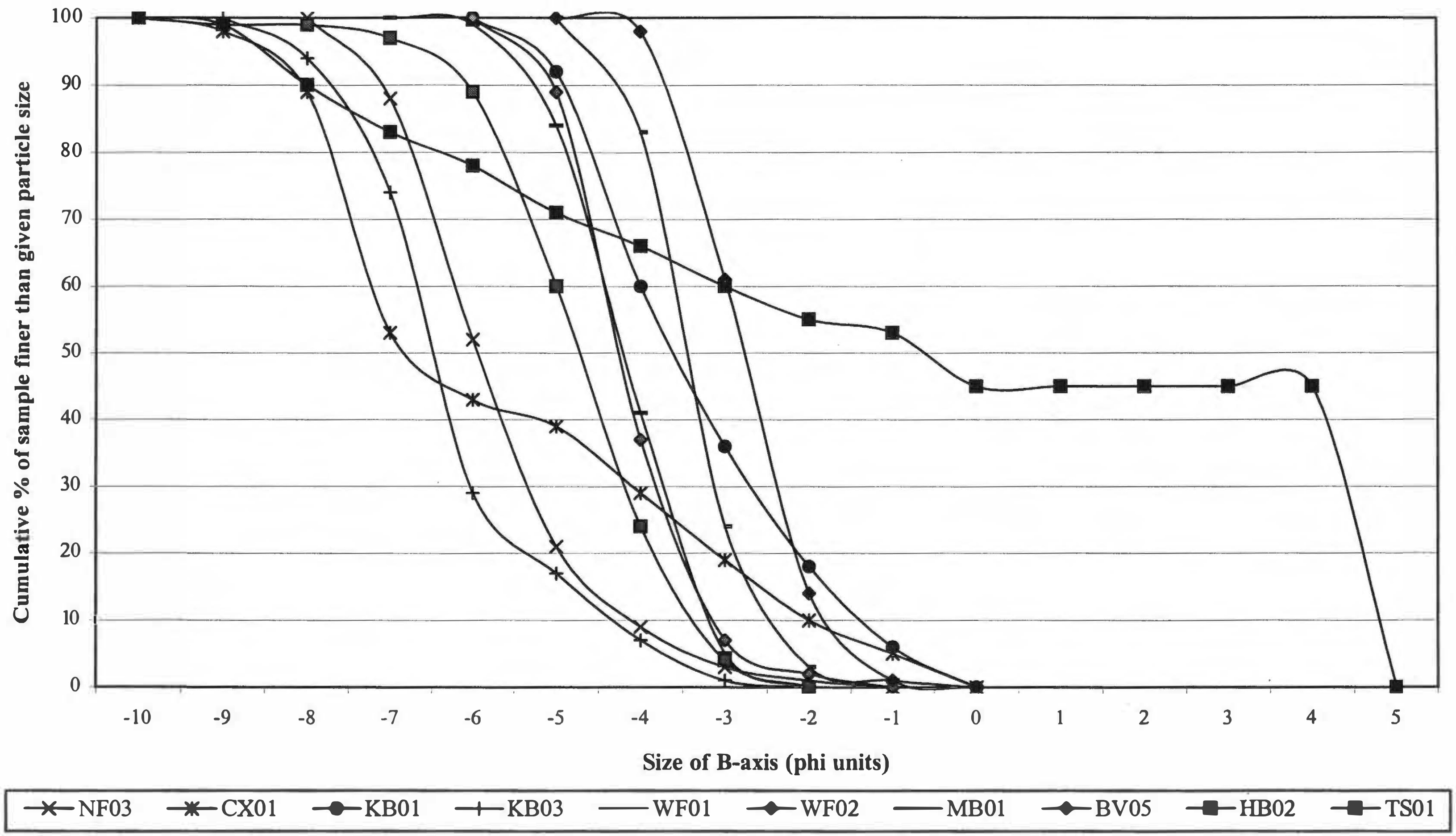


Figure 3-4. Particle Size Distributions

dimensionless Shields parameter (τ_c*). After conducting a literature search, I decided that for each site, I would set the unit weight of water (γ) equal to 1000 kg/m^3, the average density of clear water at 4 degrees Celsius, and the sediment density (γ_s) equal to 2,650 kg/m^3, the average density of limestone, dolomite and sandstone particles (Bunte and Abt 2001). I set the dimensionless Shields parameter (τ_c*) equal to 0.065, an approximate average of values derived from reference-based incipient motion studies (Doyle *et al.* 2001). Setting τ_c* > 0.060 ensured that any bed armoring would be overcome and that most of the bedload would begin to move (Knighton 1998). I then calculated the excess shear stress ratio (τ_e) for each of the 10 site locations (**Table 3-7**).

Statistical Method

Due to the nonparametric nature of the collected data, I selected the Kendall rank correlation coefficient, τ, for analysis of bivariate correlation between the qualitative and quantitative channel stability measurements and for correlation between each set of channel stability indicators and the urbanization metrics (discussed in Chapter IV). Like the Pearson product-moment correlation coefficient, the Kendall τ ranges from -1 to 1, with a value of 0 indicating no relationship between the two variables and a value of 1 or -1 indicating a perfect, 1:1 correlation between the selected variables. I reported a correlation coefficient as "significant" when the probability of a Type I error was determined to be ≤ 10% (*i.e.*, $p \leq .10$) using a 1-tailed distribution. For more information about the Kendall rank correlation coefficient, the reader may consult Siegel (1956) or Burt and Barber (1996).

Quantitative Results

A comparison of the excess shear stress measurements and SVAP bank stability scores (**Table 3-7**) reveals that the five sites with a Johnson stability ranking of "fair" or

Table 3-7. Comparison of Quantitative and Qualitative Measures of Channel Stability

Site	Boundary Shear Stress (τ_o) in kg/m^2	Critical Shear Stress (τ_c) in kg/m^2	Excess shear stress (τ_e)	Johnson Stability Ranking (Doyle et al. 2001)	SVAP Bank Stability Score (USDA 1998)	Visual Summary
BV05	0.73	0.54	1.37	Good	5.5	Stable
CX01	2.43	9.33	0.26	Excellent	8	Stable
HB02	5.31	2.15	2.47	Fair	1	Unstable
KB01	4.00	0.97	4.14	Poor	3	Unstable
KB03	8.39	7.29	1.15	Good	10	Stable
MB01	1.13	1.50	0.76	Excellent	9	Stable
NF03	11.42	4.83	2.37	Fair	1	Unstable
TS01	3.37	0.11	31.44	Poor	3	Unstable
WF01	0.12	0.86	0.14	Excellent	10	Stable
WF02	5.06	1.50	3.37	Poor	4	Unstable

"poor" (based on thresholds of excess shear stress) were the same sites that showed a SVAP bank stability score of less than 5 out of 10 and an overall visual description of "unstable" (*i.e.*, eroding through widening or incision). The five stable sites had a mean excess shear stress value of 0.74, and the five unstable sites had a mean excess shear stress value of 8.76 (or 3.09 if TS01 is excluded due to its odd pebble-size distribution). A plot of the SVAP bank stability scores versus the excess shear stress measurements (**Figure 3-5**) shows that there is a significant correlation between the quantitative and qualitative bank stability measurements ($\tau = -.55$, $n = 10$, $p < .02$).

Verification of Channel Geometry Measurements

I estimated the bankfull discharge (Q_{bf}) at each site (**Table 3-6**) by deriving bankfull velocity from the Manning equation and multiplying it by the average bankfull cross-sectional area. The Manning equation states that velocity (v) is equal to $1.49*[(R^{2/3}*s^{1/2})/n]$, where R is the hydraulic radius, s is the channel gradient, and n is the roughness coefficient. Using this method, I determined that the 10 sites had an average estimated bankfull discharge of 4.95 m^3/s and that site WF02 had a bankfull discharge of 4.77 m^3/s. Data from the USGS gauging station upstream of site WF02 indicate that Willow Fork has a bankfull discharge of 4.0 m^3/s (**Figure 2-2**). Thus, I was satisfied that the Q_{bf} estimates for the upper Beaver Creek watershed were realistic.

Discussion of Channel Stability Indicators

During the field work portion of this project, I observed and measured channel stability at 10 different sites scattered across the upper Beaver Creek watershed, including one site along the main channel (BV05) and nine sites along seven tributaries. The eight selected second- and third-order sub-basins ranged from 3.1 km^2 to 10.1 km^2 in

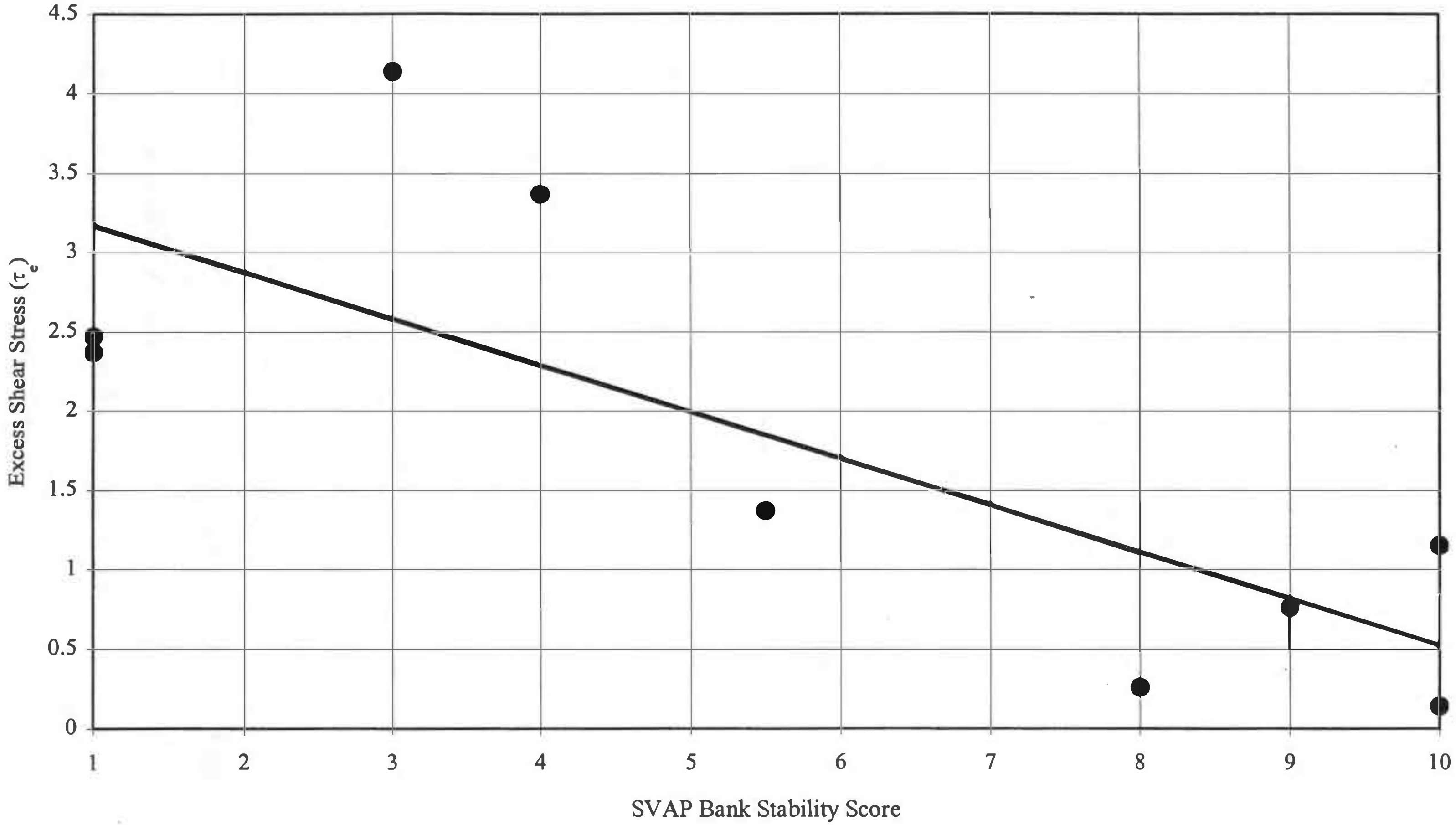


Figure 3-5. Qualitative versus Quantitative Measurements

size, and varied from predominately rural to urban. The 10 site locations also encompassed many of the different types of topography and underlying geology found throughout the upper watershed.

Using a qualitative indicator of bank stability described in the USDA's *Stream Visual Assessment Protocol* (USDA 1998) and a quantitative measurement of excess shear stress (τ_e) based on channel geometry and median surface particle size (Johnson *et al.* 1999, Doyle *et al.* 2001), I determined that five of the 10 sites had unstable, or eroding, banks. The selected qualitative and quantitative indicators of bank stability correlated well with one another ($\tau = -.55$, $n = 10$, $p < .02$) and agreed with the visual observations recorded at each site. Thus, it would seem that both the SVAP bank stability rating system and the excess shear stress method worked successfully in the upper Beaver Creek area. The results from site TS01, however, reveal that there is an inherent limitation to the excess shear stress measurement method of quantifying bank stability: namely, the Wolman (1954) pebble count method used to approximate the particle size (D) used in the critical shear calculation is based upon the assumption that the bedload contains coarse gravel.

The bedload of the lower Thompson School Branch site, TS01, consisted of a mucky mixture of colloidal silt particles and broken pieces of shale, and exhibited fewer of the intermediate gravel-sized particles than were found at the other nine sites. The site lay less than 1.6 km (1 mi) downstream of two new subdivision construction sites, or two large tracts of newly devegetated and compacted land, so the abundant silt particles may have washed in from the construction sites during the proceeding days of heavy rainfall. It is also possible that the fine bedload material might have been generated by the mass wasting that was evident along the reach. A longitudinal profile of the Thompson School Branch (**Figure 3-6**) shows that TS01 was located just downstream of a bedrock shelf

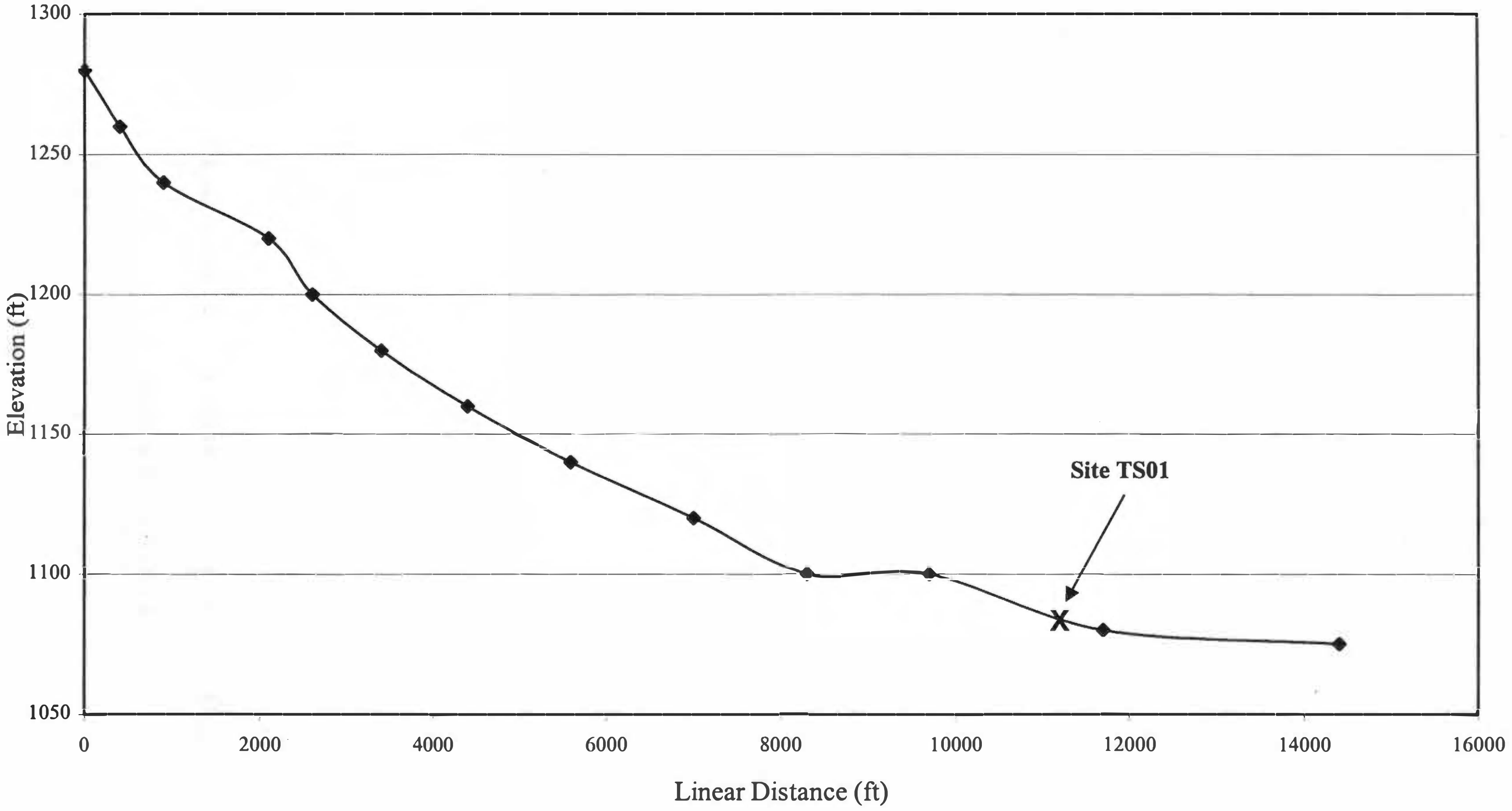


Figure 3-6. Longitudinal Profile of Thompson School Branch
(TVA 1987b and TVA 1992)

marking the contact between the Moccasin Formation (shale units interbedded with limestone) and the Martinsburg Shale (TVA 1987b, TVA 1992, Cattermole 1966). Per Knighton (1998), a significant break in slope of the longitudinal profile may lead to a rapid transition from coarse to fine sediments. No matter what the reason for the fine bedload at TS01, the Wolman pebble count method was not intended for addressing bedload with 45% of the material less than 1 mm in size (Wolman 1954, Bunte and Abt 2001).

It is worth noting that the accuracy of the excess shear stress measurements might have been improved had I measured the actual average particle density at each site rather than using an average value based upon the three main types of lithology found in the study area (limestone, dolomite and sandstone). Technically, the unit weight of the sediment at each site could have varied by as much as 800 kg/m^3 (Bunte and Abt 2001), which might have altered the calculated critical shear stress measurements for D_{50} by as much as a factor of 1.7. A measurement of water temperature at each site would also have improved the accuracy of the measurements.

Overall, the qualitative measurements of bank stability, or the SVAP bank stability scores, are the more reliable of the two sets of measurements. This is not unusual given the complexity of channel-related questions (Reid and Dunne 1996). Wolman (1967) also noted that erosion and flooding characteristics of streams might be more easily compared through visual and subjective analysis than through any measurable parameters.

Because channel morphology is typically influenced by topography, geology, bed roughness and/or riparian vegetation, I attempted to correlate each set of bank stability indicators with local morphological controls (**Table 3-8**). The excess shear stress measurements were correlated with the average mean slope of the drainage area

Table 3-8. Typical Controls of Channel Morphology in Relation to Bank Stability Indicators

Site	Stable?	SVAP Bank Stability	Excess shear stress	Slope	SVAP Riparian Zone	Roughness (n)	Bedrock Type(s)	Soil Type*	Catchment Area (km^2)
BV05	Yes	5.5	1.37	0.001	1	0.025	shale, limestone	C	3.11
CX01	Yes	8	0.26	0.003	2	0.055	sandstone, siltstone, shale	C	9.58
HB02	No	1	2.47	0.010	8	0.04	limestone	D	1.28
KB01	No	3	4.14	0.008	7	0.03	shale, limestone	C	8.03
KB03	Yes	10	1.15	0.029	8	0.05	dolomite	B	1.05
MB01	Yes	9	0.76	0.005	1	0.035	shale	C	8.55
NF03	No	1	2.37	0.014	3	0.045	dolomite	C	1.73
TS01	No	3	31.44	0.006	10	0.03	shale	B	2.60
WF01	Yes	10	0.14	0.001	5	0.025	shale	D	10.10
WF02	No	4	3.37	0.010	3	0.035	shale	D	8.49

* Hydrologic soil groups are derived from a soil map contained in the *Beaver Creek Watershed Flood Study* (Ogden 2000a). Type B soils have a moderate infiltration rate (52%), Type C soils have a slow infiltration rate (33%), and Type D soils have a very slow infiltration rate (15%). There are no Type A (high infiltration) soils within the Beaver Creek watershed (Ogden 2000a).

($\tau = -.33$, $n = 10$, $p < .09$) and the SVAP riparian zone scores ($\tau = .37$, $n=10$, $p<.07$), such that channel stability decreased as average slope decreased and increased as the width of the riparian zone decreased. Because the mean slope of the drainage area was strongly related to the median particle size found at each site ($\tau = .67$, $n=10$, $p < 0.004$), it made sense that the excess shear stress measurements tended to decrease as the particle size and slope increased. However, it was unexpected for the bank stability to decrease as the riparian buffer increased in width. Perhaps the Beaver Creek channels become less stable when there is a greater availability of large woody debris (Jacobson *et al.* 2001). There were no significant relationships between either set of bank stability indicators and channel roughness, underlying geology, or soil type.

Both the qualitative and quantitative indicators of channel stability were correlated with the size of the area draining directly to the observation point (SVAP: $\tau = .46$, $n = 10$, $p< .04$; excess shear stress: $\tau = -.38$, $n=10$, $p<.06$) and the estimated bankfull discharge at each site (SVAP: $\tau = -.41$, $n = 10$, $p< .05$; excess shear stress: $\tau = .33$, $n=10$, $p<.09$). The fact that channel erosion potential increased as basin size and discharge increased suggests that a cumulative effect of flow and/or sediment yield—both of which could be altered by land use change—might have impacted the 10 sites (Jacobson *et al.* 2001).

In the next chapter, I will discuss the degree of correlation between each set of bank stability measurements and the 10 urban development indicators that I derived for the upper Beaver Creek watershed.

CHAPTER IV
EVALUATION OF LAND USE AND URBANIZATION

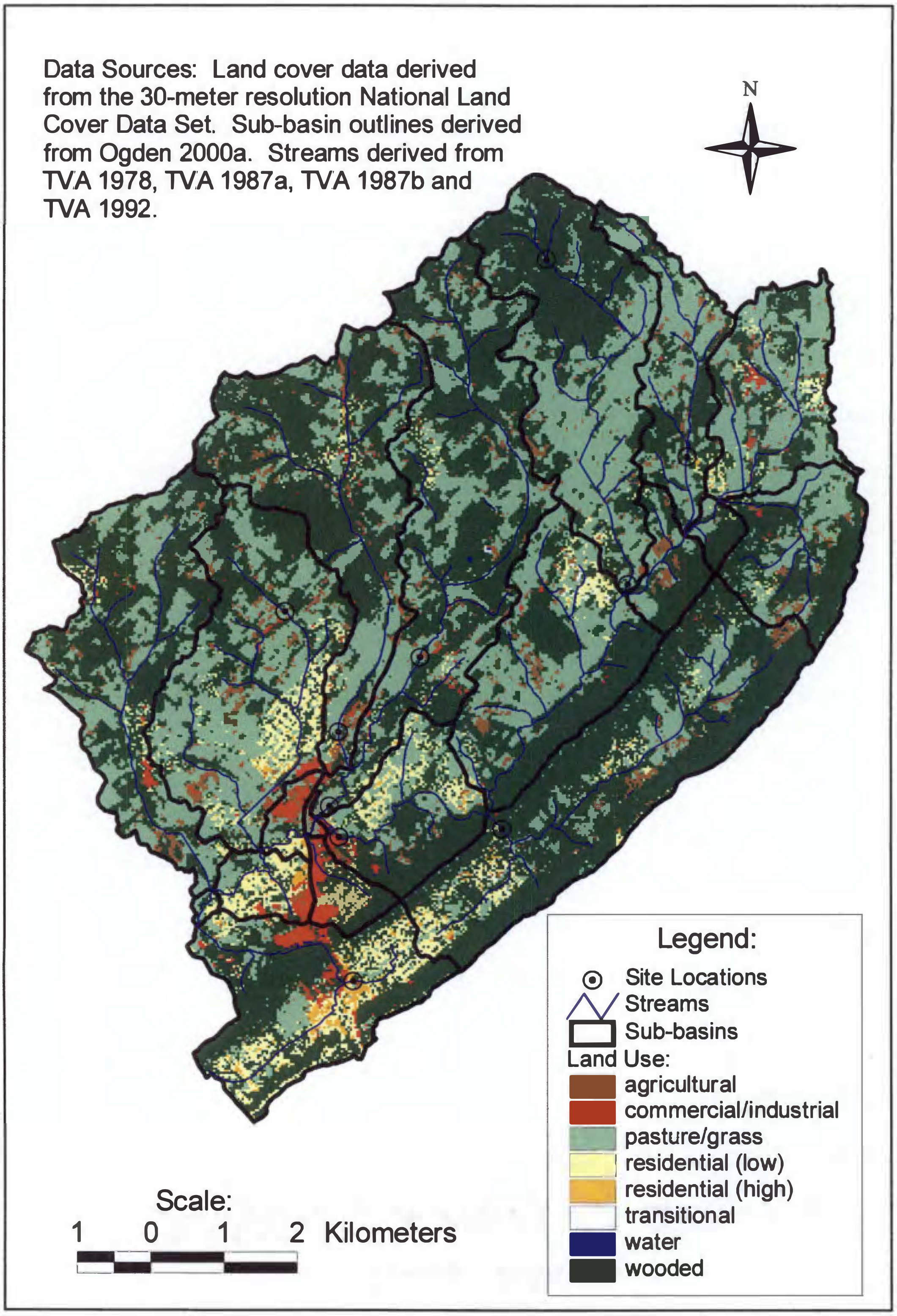
Creation of a Geographic Information System

During the second phase of my project, I created a geographic information system (GIS) to test for relationships between my field measurements of channel stability and the level of urban development found within the catchments contributing to each of the 10 site locations. I created the GIS using ESRI software, including ArcView 3.2, ArcInfo 8, and ArcGIS. This section discusses the steps that I took to obtain or create the various layers needed for land use determination and the calculation of 10 urbanization metrics: three estimates of total impervious area, a human use index, wooded area, road density, road and stream crossing density, population density, and riparian land use as represented by the proportion of human to natural uses and by the total percent of wooded, or mature, buffer.

I was able to obtain Beaver Creek sub-basin outlines, land use polygons, hydrologic soil types, and soil curve number (SCS) polygons in digital format from Ogden, now known as AMEC (Mihlbachler 2001). These files were created in 1999 as part of the Knox County flood study (Ogden 2000a) and were provided to me in Lambert projection. The watershed and sub-basin boundaries were delineated using four-foot contour intervals, knowledge of drainage conveyance and land use, and field verification; drainage to or from surface streams via sinks, seeps or springs was not considered in the basin boundary analysis (Ogden 2000a). I clipped all of the Ogden layers to match my study area within the upper watershed (*i.e.*, those 19 sub-basins upstream of Interstate 75 and the Allen Branch tributary) and overlaid them with other data layers, such as roads and streams, for analysis.

I created a stream layer in line format by downloading digital raster graphics (DRGs) of the Fountain City, Graveston, John Sevier and Big Ridge Park 7.5-minute topographic quadrangles from the Tennessee Spatial Data web site (http://63.148.169.50), importing the images into ArcView, and tracing over the 1:24,000 blue lines with a mouse. I created a layer of sample points by using field notes and site sketches to locate and digitize the 10 sites over the DRGs. When the sampling point was located within the upper or middle portion of the sub-basin, I digitized the polygonal boundary of the smaller catchment area by tracing a new watershed divide over the DRGs. I obtained road data for the study area by clipping ESRI's 1995 detailed roads coverage of the southeastern United States with the sub-basin polygons. The roads were originally derived from US Bureau of Census TIGER/Line files.

I tried using two different datasets to describe land use within the study area: (1) 30-meter grid Multi-Resolution Land Characteristics Consortium (MRLC) National Land Cover Data (NLCD) for the coterminous United States in equal-area Albers projection (**Figure 4-1**), known hereafter as the MRLC dataset; and (2) Ogden land use polygons re-projected into equal-area Albers projection (**Figure 4-2**), known hereafter as the Ogden dataset. The MRLC dataset was based on interpretation of 30-meter resolution Landsat 5 Thematic Mapper (TM) satellite data, and the base dataset for the Tennessee NLCD coverage was leaves-off/on Landsat TM data collected between February 1991 and June 1993. The Ogden land use polygons for Beaver Creek had been created in March 1999 during the 2000 Knox County flood study. According to Ogden personnel, these polygons were created by field-verifying zoning coverages from the Knox County GIS, with special emphasis placed on land uses greater than 100 acres (Mihlbachler 2001). For easier comparison of the two coverages, I simplified the land use categories (**Table 4-1**). Homes on plots ≥ 1 acre were considered to be low density



Data Sources: Land cover data derived from the 30-meter resolution National Land Cover Data Set. Sub-basin outlines derived from Ogden 2000a. Streams derived from TVA 1978, TVA 1987a, TVA 1987b and TVA 1992.

Figure 4-1. Land Use, 1991-1993

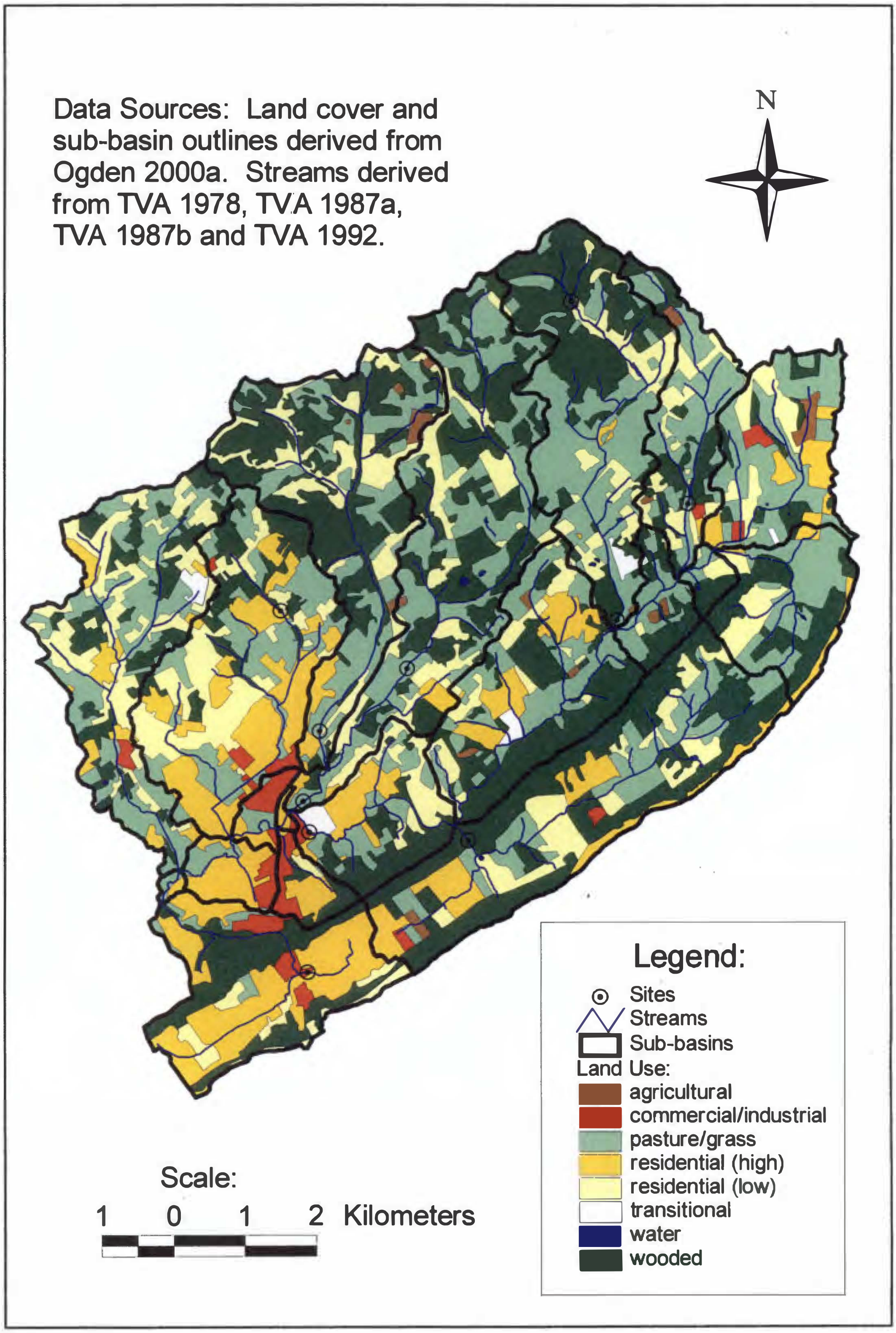


Figure 4-2. Land Use, 1999

Table 4-1. Land Use Categories

Land Use	MRLC Land Use Categories	Ogden Land Use Categories
water	open water	water
residential (low)	low intensity residential	residential (low density)
residential (high)	high intensity residential	residential (med. density)
	▨	residential (high density)
commercial/industrial	high intensity commercial/industrial/ transportation	commercial
		industrial
		impervious
transitional	transitional	disturbed/transitional
wooded	deciduous forest	woods (thick cover)
	evergreen forest	woods (thin cover)
	mixed forest	▨
agricultural	row crops	agricultural
pasture/grass	pasture/grass	open land - good
	other grasses (urban/recreational)	meadow

residential housing. Row crops were considered to be agriculture, and pasture was lumped together with other grassy areas.

Calculation of Landscape Metrics: Methods and Results

Land Use Percentages

To determine the percent of each land use type within each of the 10 catchments during 1991-1993, I converted the catchment polygons to grids and used them to mask (or clip) the MRLC land cover grid. I then exported the grid values to a Microsoft Access database for manipulation. Since each 30-meter grid cell was equivalent to 0.22 acres of land, I used the following equation to determine the percent of land used for a particular purpose within a given watershed:

$$\%\ land\ use = 100 * [(Pixel\ count\ for\ combined\ land\ use\ value\ and\ catchment\ value) * 0.22\ acres]/(Catchment\ size\ in\ acres).$$

To determine the percent of each 1999 land use type within each of the 10 catchments, I clipped the Ogden land cover polygons with the catchment polygons and recalculated the area of each resulting polygon. To determine the percent of land used for a particular purpose within a given watershed, I used the following equation:

$$\%\ land\ use = 100 * [(\sum Catchment\ areas\ devoted\ to\ a\ given\ land\ use\ in\ m^2)/(Catchment\ size\ in\ m^2)$$

The two sets of land use percentage results are compared in **Table 4-2**. It is possible that the difference column (Ogden% - MRLC%) actually shows a six-year land use change, which would indicate a significant increase in development throughout the upper Beaver Creek watershed from 1991-1993 to 1999. However, some of the differences in percentages are undoubtedly due to differences in the way the data were collected (satellite interpretation versus field verification of zoning maps). Based upon

Table 4-2. Comparison of Land Use (by Percent) within Each Catchment

Catchment	Land Use	MRLC%	Ogden%	Difference
BV05	wooded	50	32	-18
	transitional	0	5	+5
	residential (low)	14	20	+6
	residential (high)	1	19	+18
	pasture/grass	29	23	-6
	commercial/industrial	3	2	-1
	agriculture	3	0	-3
CX01	wooded	74	48	-26
	residential (low)	6	16	+10
	residential (high)	1	14	+13
	pasture/grass	16	20	+4
	commercial/industrial	0	1	+1
	agriculture	3	1	-2
HB02	wooded	58	21	-37
	residential (low)	31	13	-18
	residential (high)	4	65	+61
	pasture/grass	6	0	-6
	commercial/industrial	1	1	0
KB01	wooded	51	40	-11
	transitional	0	1	+1
	residential (low)	1	15	+14
	residential (high)	0	1	+1
	pasture/grass	45	42	-3
	agriculture	3	0	-3
KB03	wooded	88	84	-4
	residential (low)	0	4	+4
	pasture/grass	11	12	+1
MB01	wooded	61	46	-15
	residential (low)	2	21	+19
	residential (high)	0	3	+3
	pasture/grass	31	28	-3
	commercial/industrial	1	0	-1
	agriculture	6	2	-4
NF03	wooded	62	43	-19
	residential (low)	0	18	+18
	residential (high)	0	15	+15
	pasture/grass	34	23	-11
	commercial/industrial	0	1	+1
	agriculture	4	0	-4
TS01	wooded	41	25	-16
	residential (low)	0	15	+15
	pasture/grass	53	58	+5
	agriculture	6	2	-4

Table 4-2. Continued

Catchment	Land Use	MRLC%	Ogden%	Difference
WF01	wooded	59	40	-19
	residential (low)	2	17	+15
	residential (high)	0	2	+2
	pasture/grass	35	40	+5
	commercial/industrial	1	0	-1
	agriculture	4	0	-4
WF02	wooded	60	44	-16
	residential (low)	1	15	+14
	pasture/grass	34	41	+7
	agriculture	4	0	-4

my own observations within the upper Beaver Creek watershed, I decided that the more recent Ogden dataset presented a more realistic picture of current land use and used it to calculate the following estimates of urbanization.

Impervious Cover

Measurement of impervious surface cover is emerging as a key urban environmental indicator because it has been shown to relate to, and effectively integrate, a complex variety of issues related to stream health (Arnold and Gibbons 1996). Impervious surfaces are those land surfaces which prevent water from infiltrating into the underlying soil. Paved roads, parking lots, sidewalks and rooftops are typically considered to be 100% impervious, though they may contain some cracks (Barnes *et al.* 2000). Compacted soil, lawns and parks are considered to be semi-pervious. The imperviousness of a watershed may be raised or lowered by factors such as topographic relief, soil and land cover types, the density of the stream network, and/or the distribution of the impervious land cover (Prisloe *et al.* 2001).

The total amount of land within a basin considered to be impervious is known as the "total impervious area," or TIA, whereas impermeable land that drains directly to streams and storm systems is considered to be the "effective impervious area," or EIA (Booth and Jackson 1997, Barnes *et al.* 2000). Over the past 15-20 years, a variety of studies have shown that water quality and stream quality begin to degrade at 10% impervious cover and become irreversible by 30% impervious cover (Arnold and Gibbons 1996; Prisloe *et al.* 2000). However, it is not always clear which type of impervious area, namely TIA or EIA, has been used to establish the relationship. During their study of watersheds urbanized for 20 years or more with total impervious area ranging from 5-77%, Finkenbine *et al.* (2000) could find no definitive relationship between the percentage of TIA and the degree of bank erosion in a watershed. However, in their study of watersheds in western Washington state, Booth and Jackson (1997) found that an EIA of 8-10% causes channel instability, and that an EIA greater than 10% may cause permanent changes in aquatic ecosystems (*e.g.*, a reduction in the number of viable species).

Because impervious surfaces typically generate much more runoff than pervious surfaces, I hypothesized that the likelihood of channel instability would increase as the percentage of impervious area within the catchment increased. To test this hypothesis, I calculated the percentage of TIA within each catchment using a weighted sums approach based on land use type (Castle 1996, Prisloe *et al.* 2000). I chose to use the TIA method rather than the EIA method because I already had a good set of land use data for the area, but would have had to spend many hours tracing over maps, aerial photos, and storm drains to derive a good set of data for EIA calculations.

Because there is not yet a consensus on the impervious coefficients that should be applied to different types of land use within different parts of the country, I applied three different sets of imperviousness coefficients to the Ogden land use dataset for comparison: (1) Ogden imperviousness coefficients used during the HEC-RAS modeling of Beaver Creek for the Knox County flood study (Ogden 2000a); (2) Camp, Dresser & McKee coefficients used during their 1992 preparation of Knoxville's National Pollutant Discharge Elimination System (NPDES) permit application (Castle 1996); and (3) US Environmental Protection Agency (EPA) imperviousness coefficients based upon studies in the Pacific Northwest and presented in their experimental Analytical Tools Interface for Landscape Assessments (ATtILA), Beta Version 3.0 software (Ebert *et al.* 2001). I calculated TIA for each catchment using the following formula (Prisloe *et al.* 2000):

$$\%\ TIA = 100 * \sum [(\text{Impervious coefficient for land use } X) * (\text{Area of land use } X)].$$

The three sets of imperviousness coefficients are summarized in **Table 4-3**, and a comparison of the percent TIA generated for each catchment is shown in **Figure 4-3**.

The ATtILA coefficients consistently yielded the highest value of TIA in each of the 10 catchments. This is due to the fact the ATtILA coefficients for low density residential land (0.40) and pasture/grass (0.10) are significantly higher than the corresponding Ogden coefficients (0.15 and 0) and the corresponding Camp, Dresser & McKee coefficients (0.25 and 0.01). Within the 10 catchments, low density residential land use ranged from 4-21% and pasture/grass ranged from 0-58%. This led to quite a bit of variation between the ATtILA-based TIA results and the other two sets of TIA results, except in the case of the most highly developed catchment, the middle Hines Branch area (HB02). Differences between the Ogden-based TIA values and the Camp, Dresser & McKee-based TIA values were primarily due to the difference in the coefficient for high density residential housing (0.65 versus 0.40). High density residential housing varied from 0-65% of total land use within the 10 catchments. All three sets of coefficients indicated that the middle Hines Branch catchment (HB02) was covered with the most impervious surface (30-45%), and that the upper Kerns Branch catchment (KB03) was covered with the least amount of impervious surface (1-3%).

To determine if there was any correlation between the field observations of channel stability and TIA as an indicator of urban development within the catchments, I plotted each set of TIA results against the SVAP bank stability scores and excess shear stress measurements and looked for simple linear relationships. There was no significant relationship between the excess shear stress values and any of the TIA calculations. However, I did find significant relationships between the SVAP bank stability scores and all three of the TIA calculations (**Figure 4-4**). The strongest relationships were with the Camp, Dresser & McKee-based calculations of TIA ($\tau = -.37$, $n = 10$, $p < .07$) and the

Table 4-3. Three Sets of Imperviousness Coefficients

Land Use	**Ogden** (Ogden 2000a)	**Camp, Dresser & McKee** (Castle 1996)	**ATtILA** (Ebert *et al.* 2001)
water	1.00	0	0
residential (low dens.)	0.15	0.25	0.40
residential (high dens.)	0.65	0.40	0.60
commercial/industrial	0.79	0.85	0.90
transitional	0	0.05	0
wooded	0	0.01	0.02
agricultural	0	0.01	0
pasture/grass	0	0.01	0.10

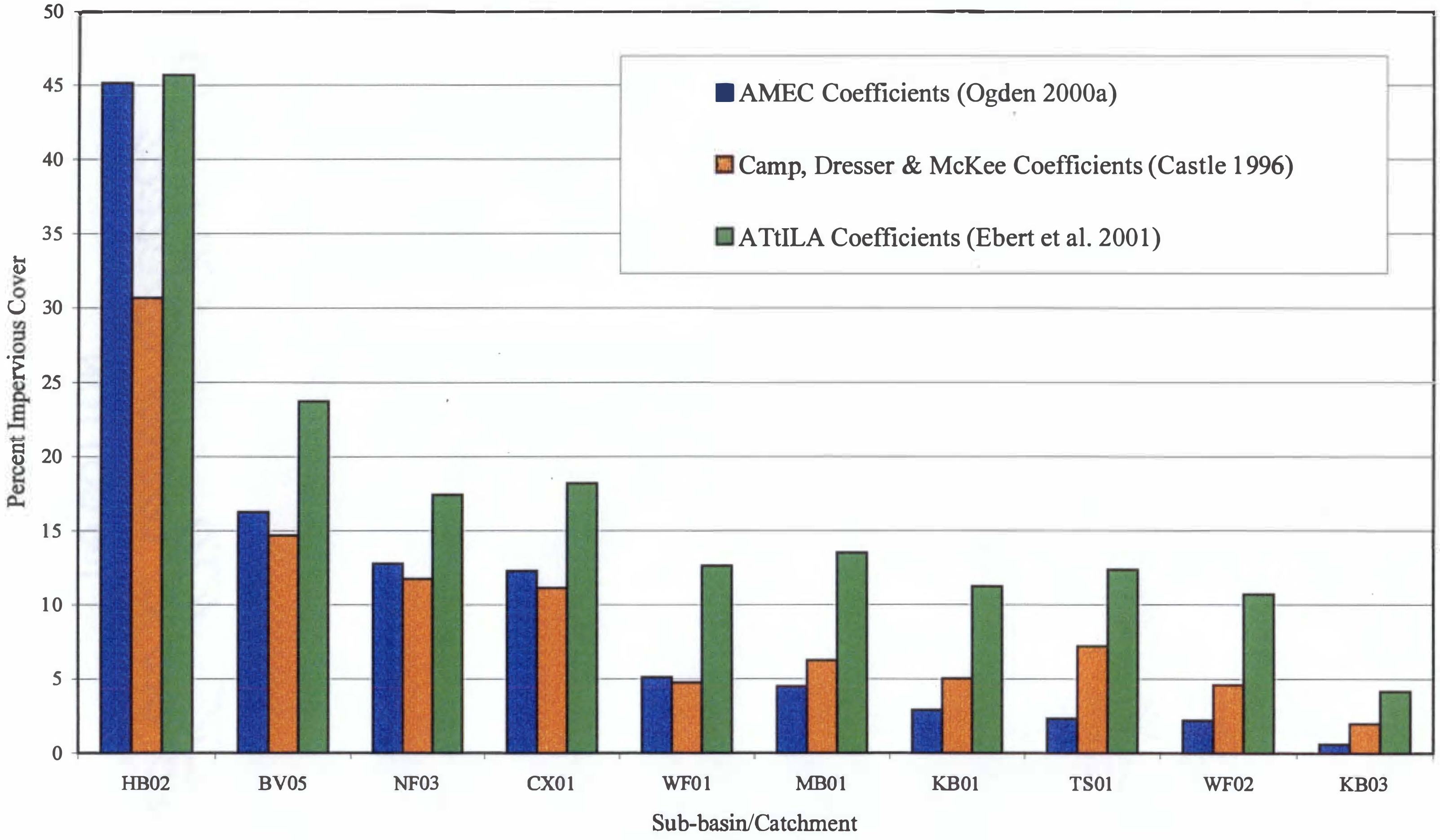


Figure 4-3. A Comparison of Three Total Impervious Area (TIA) Calculations

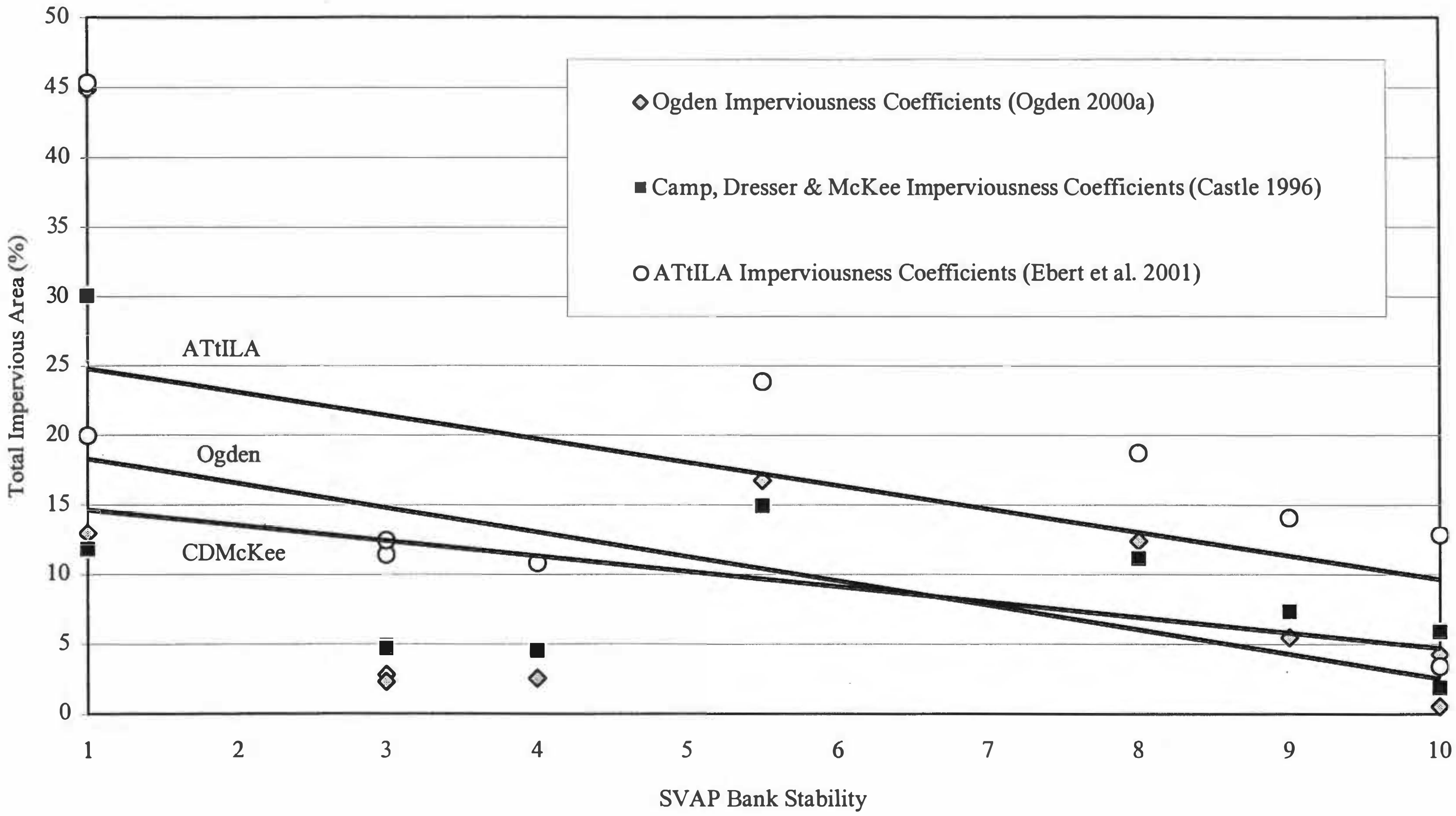


Figure 4-4. Correlation of SVAP Bank Stability Scores with Total Impervious Area Calculations

ATtILA-based calculations of TIA ($\tau = -.37$, $n = 10$, $p < .07$), but in all three cases, the banks tended to become less stable as the percentage of TIA within the catchment increased. Thus, my hypothesis was upheld.

Human Use Index

The human use index, or U-index, of a watershed is a simple EPA land use indicator that has demonstrated good correlation with a variety of environmental variables (Ebert *et al.* 2001). The U-index of a watershed is equal to the total percentage of the watershed area dedicated to "human" uses (meaning the "residential," "commercial/industrial" and "agricultural" uses within the selected land use categorization scheme), excluding transitional areas from the total land area (Jones *et al.* 1997, Ebert *et al.* 2001). The U-indices of the 10 catchments used in this study ranged from 4% within the KB03 catchment to 79% within the HB02 catchment (**Table 4-4**). The SVAP bank stability indicators were correlated to the U-indices ($\tau = -.37$, $n = 10$, $p < .07$) such that bank stability decreases as the catchment-wide U-index increases.

Wooded Area

Assuming that the MRLC and Ogden land cover datasets can be used to interpret land use changes within the Beaver Creek watershed from 1991-1993 to 1999, then the 10 catchments have each lost a substantial amount of wooded area to development activities over the past decade (**Table 4-2**). For this reason, I decided to test for bivariate correlation between the two sets of channel stability indicators and the current amount of wooded area in each catchment. There was, in fact, a significant relationship between each set of indicators and the percentage of wooded area (SVAP: $\tau = .51$, $n = 10$, $p < .02$; excess shear stress: $\tau = -.38$, $n = 10$, $p < .06$), such that the

Table 4-4. Human Use Index and Population Density by Catchment

Catchment	Human Use Index (%)	Population Density (persons/km^2)
HB02	79	863
BV05	42	462
NF03	33	144
CX01	32	266
MB01	26	170
WF01	19	199
TS01	17	84
KB01	16	98
WF02	15	160
KB03	4	99

prevalence of channel erosion increased as the percentage of wooded area decreased within each catchment (**Figure 4-5**).

Road Density

Roads can significantly alter stream quality through runoff of oil, antifreeze, tire particles, and other vehicular contaminants (Jones *et al.* 1997). Because roads are made of nearly 100% impervious asphalt or concrete, they can significantly increase the amount of runoff that enters nearby channels (Barnes *et al.* 2000). Studies in the northwestern United States have found that roads account for over 60% of the impervious cover of suburban watersheds, and that road density is highly correlated to overall imperviousness (Arnold *et al.* 1996, May *et al.* 1997, Barnes *et al.* 2000). For these reasons, I hypothesized that the increasing bank erosion would also be related to increasing road density.

A map of the road and stream networks within the upper Beaver Creek watershed is depicted in **Figure 4-6**. To calculate a road density value for each catchment, I first intersected the linear road coverage with the catchment polygons and summed the resulting arc lengths for each catchment. I then divided the road length sums (in m) by the catchment areas (in km^2) to get the density values (Jones *et al.* 1997).

Road density ranged from 1752 m/km^2 in the upper North Fork catchment (NF03) to 6558 m/km^2 in the middle Hines Branch catchment (HB02) (**Table 4-5**). While a comparison of the road density values and the verbal bank stability descriptions for each site make it appear that the majority of the stable sites were actually located in the catchments with the highest road densities, there were no statistically significant relationships between the road density values and either set of bank stability indicators.

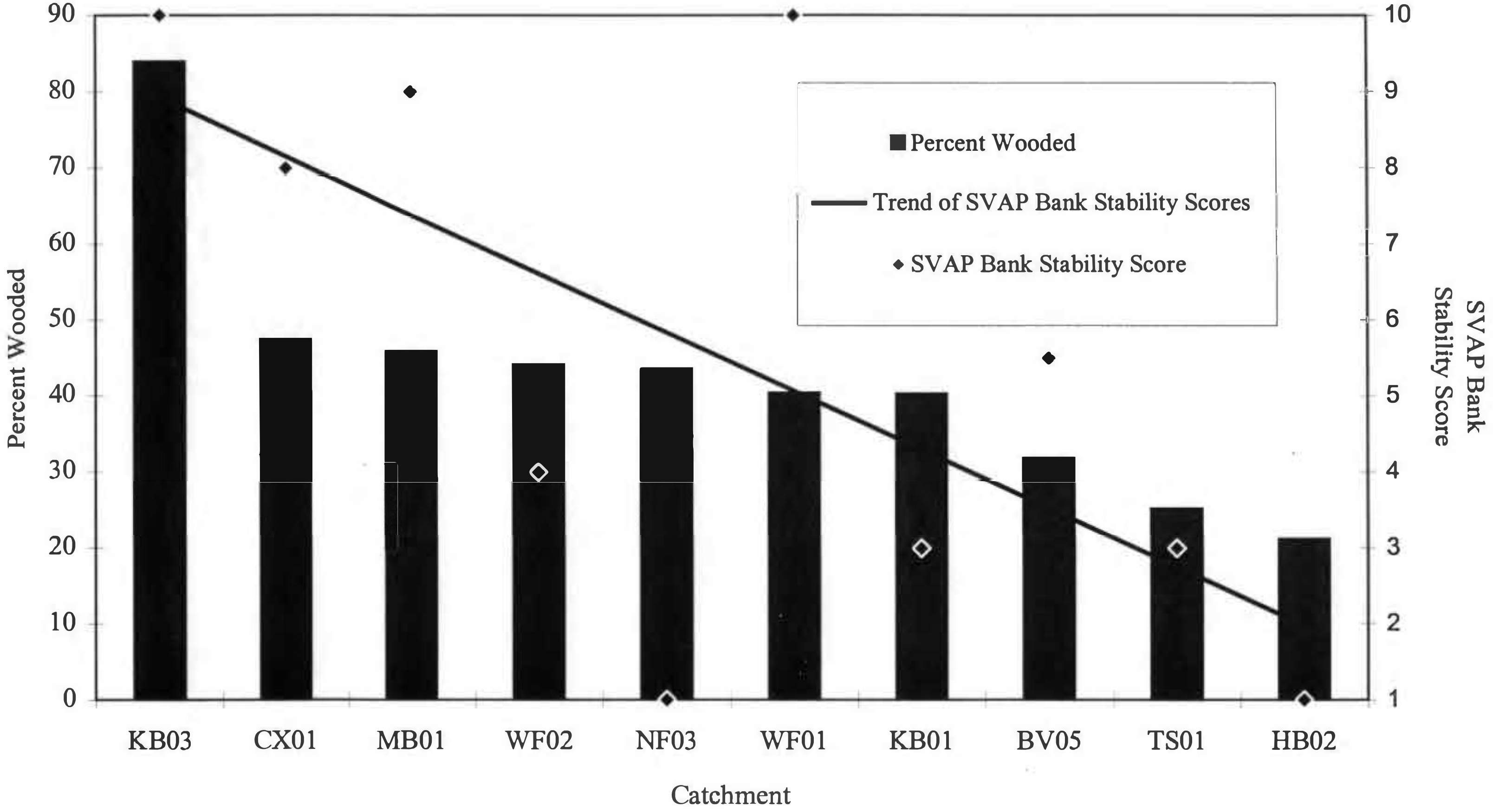
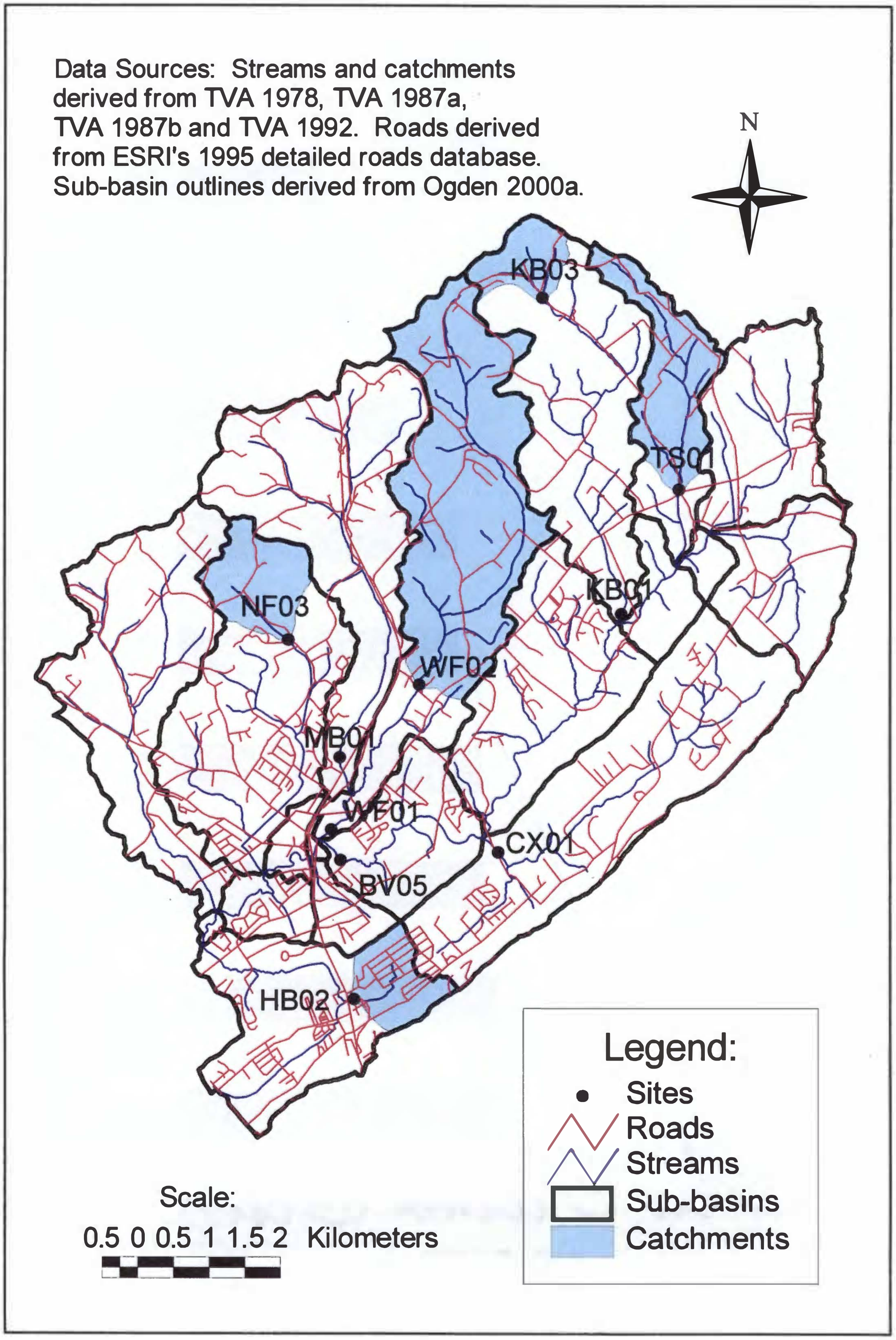


Figure 4-5. Bank Stability versus Wooded Area



Data Sources: Streams and catchments derived from TVA 1978, TVA 1987a, TVA 1987b and TVA 1992. Roads derived from ESRI's 1995 detailed roads database. Sub-basin outlines derived from Ogden 2000a.

Figure 4-6. Roads and Streams

Table 4-5. Road and Stream Data

Basin	Basin Size (km^2)	Road Density (m/km^2)	Stream Density (m/km^2)	Count of Road/ Stream Crossings	Crossing Density ($count/km^2$)	Channel Stability
HB02	1.27	6,558	845	8	6.3	Unstable
BV05	3.18	3,457	1,722	12	3.8	Stable
MB01	8.41	3,381	1,381	102	12.1	Stable
CX01	9.42	3,374	1,337	63	6.7	Stable
KB03	1.04	2,850	2,030	31	29.8	Stable
TS01	2.57	2,725	2,341	47	18.3	Unstable
WF01	10.09	2,403	1,659	49	4.9	Stable
WF02	8.41	2,074	1,502	34	4.0	Unstable
KB01	7.86	1,922	1,737	95	12.1	Unstable
NF03	1.71	1,752	661	14	8.2	Unstable

Density of Road and Stream Crossings

Because I found no demonstable relationship between road density and channel stability, I decided to test for a relationship between the density of road/stream crossings and bank stability. Other researchers have found that road crossings frequently damage stream systems (May *et al.* 1997, Jones *et al.* 1997), so I postulated that the more times that roads crossed (or came within 30 m of) the streams within each catchment, the more likely it would become to find unstable channels within the catchment.

I converted the road and stream layers to 30-meter grids with cell values of 1. Then I added the two grids together to produce a grid containing cell values of 2 wherever the roads and streams come within 30 meters of one another. Next, I clipped the road/stream crossing grid with the catchments in order to get a count of road/stream crossings per catchment. I normalized the data for comparison by dividing the total number of crossings found in each catchment by the total catchment area. The road/stream crossing densities (**Table 4-5**) ranged from 3.8/km^2 in catchment BV05 to 29.8/km^2 in catchment KB03.

At first I thought that the unusually high road/stream crossing density in catchment KB03 resulted from the fact that the grid calculation method considered all roads within 30 m of the streams to be road/stream crossings, when in actuality, many of the streams within the steeper portions of the upper Beaver Creek watershed run alongside roads for long distances. However, a hand count of road/stream crossings performed while looking at a map of roads and streams (**Figure 4-6**) yielded a similar result. Neither set of road/stream crossing calculations showed any significant relationship with the bank stability indicators.

Population Density

A recent Connecticut study found a general correlation between impervious cover and population density (Prisloe *et al.* 2000), and a recent Vancouver study developed a formula relating TIA to population density in persons per hectare (Hicks and Shaw 2000). Because I had already found a relationship between TIA and the SVAP bank stability scores, I hypothesized that there would be a similar relationship between population density and bank stability, such that channel instability would increase as population density increased.

I downloaded 2000 United States Census data from www.census.gov for those census blocks which were contained in or overlapped with the study area. I then used EPA's ATtILA software (Ebert *et al.* 2001) to derive population densities for each catchment by area-weighting. The resulting population densities of the 10 catchments ranged from 84 persons/km^2 in TS01 to 863 persons/km^2 in HB02 (**Table 4-4**). A map of sub-basin population density by quartiles (**Figure 4-7**) reveals that out of the eight sub-basins examined in this study, Thompson School Branch, Kerns Branch and Mill Branch were the least densely populated sub-basins (98-181 persons/km^2), and Hines Branch and Sub-basin 05 were the most densely populated sub-basins (375-650 persons/km^2).

I did find a bivariate correlation between population density and my excess shear stress measurements ($\tau = -.38$, $n = 10$, $p < .06$), but it was the opposite of the relationship that I had expected. Unlike Prisloe *et al.* (2001), I found that bank erosion *decreased* as population increased. This unexpected result may have resulted from the inaccurate assumption that the population was evenly spread across the census block areas, particularly given that several of the catchment areas were very small by comparison.

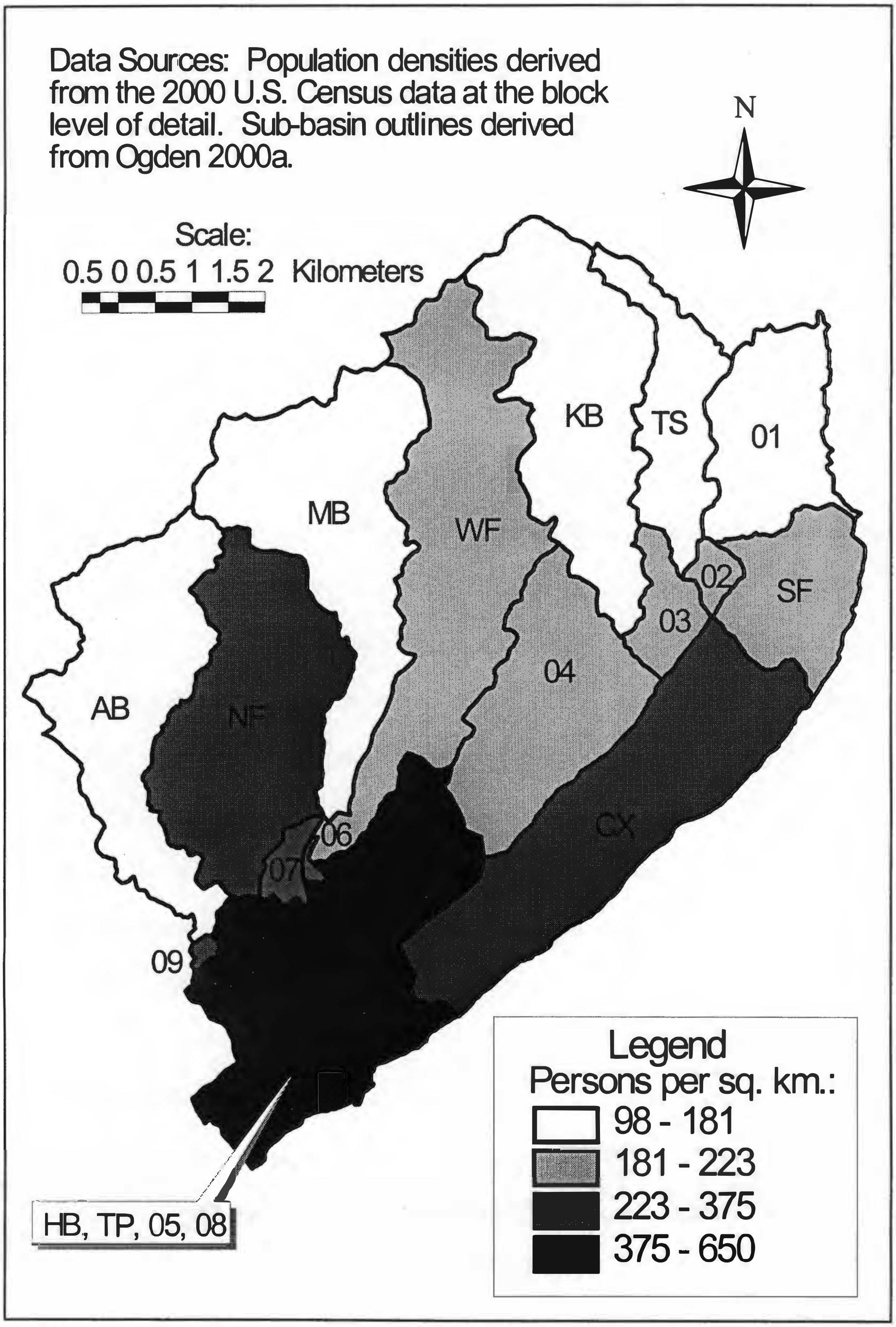


Figure 4-7. Population Density

Riparian Land Use

Per Jacobson *et al.* (2001), there is usually a clearer connection between riparian land use change and changes in channel morphology than there is between basin-wide land use changes and channel morphology. Thus, I postulated that the types of riparian buffers in each catchment would likely have an impact on the channel stability observed.

Most literature suggests that 30-meter buffers of natural vegetation be left on either side of a stream (Thibault 1997). To create a riparian land use layer for the GIS, I buffered the streams by 30 meters on each side and used the resulting polygonal layer to clip the Ogden land use coverage. I used the following equation to derive the percentage of riparian buffer devoted to each land use within each catchment:

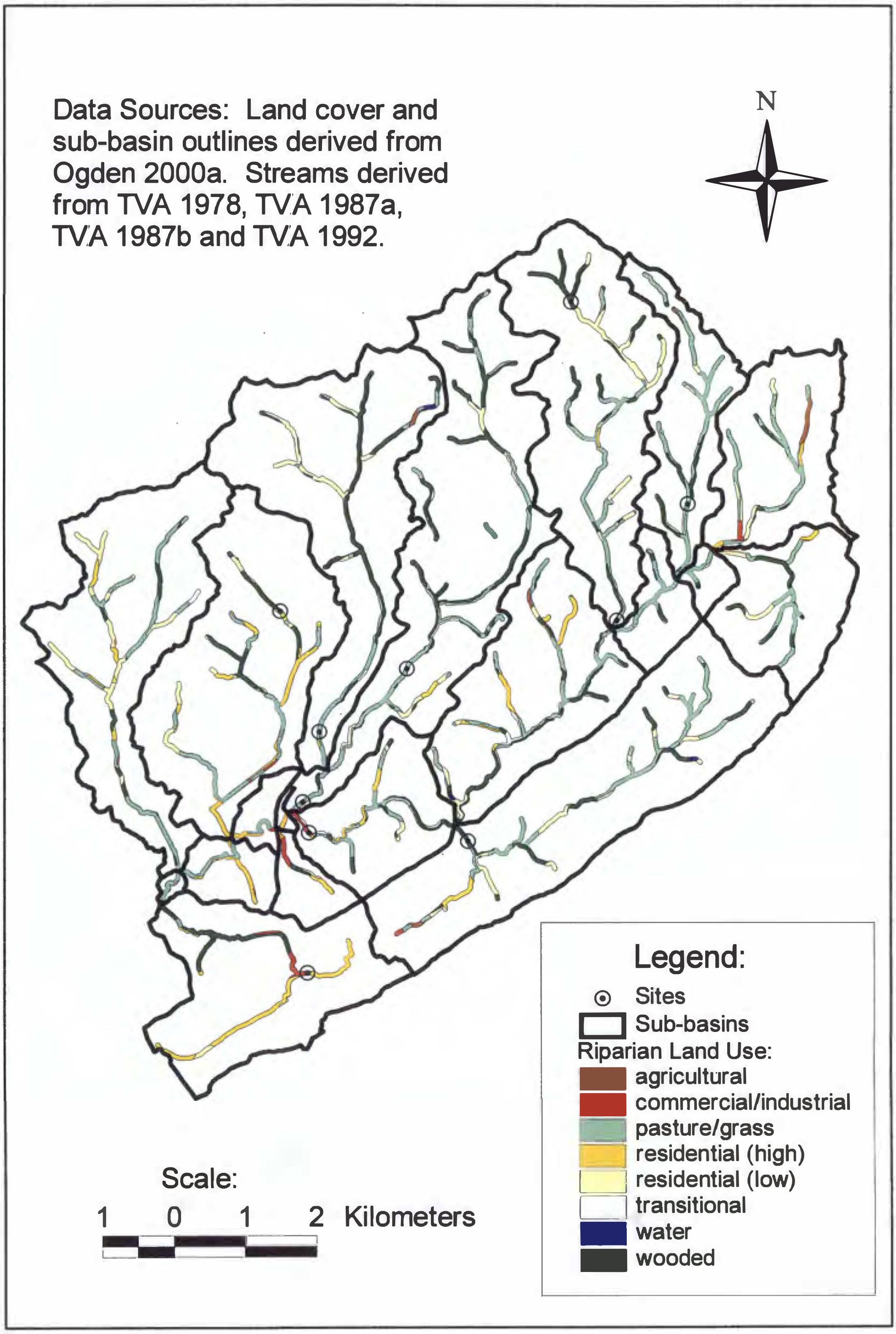
$$\%\ \text{riparian land use} = 100 * [(\textstyle\sum \text{Riparian areas devoted to a given land use in } m^2)/ (\text{Total riparian buffer size in } m^2).$$

The resulting data indicate that many of the riparian zones within the upper Beaver Creek watershed have been fragmented by multiple types of land use in the immediate vicinity of the streams (**Table 4-6**, **Figure 4-8**). All of the catchments contained at least two different types of riparian land use, and CX01 contained seven different types of land use within 30 meters of its streams.

To simplify the visualization of urbanization impacts on riparian land use, I created a human use index, or U-index, for each catchment (**Table 4-6, Figure 4-9**). The U-index is equal to the total percentage of each catchment's riparian buffer dedicated to "human" uses, or residential, commercial/industrial and agricultural uses, rather than "natural" uses, meaning wooded and pasture/grass areas (Jones *et al.* 1997). Transitional uses are excluded from the calculation. The riparian U-indices of the 10 catchments ranged widely, from 6% for catchment TS01 to 100% for catchment HB02. There was a

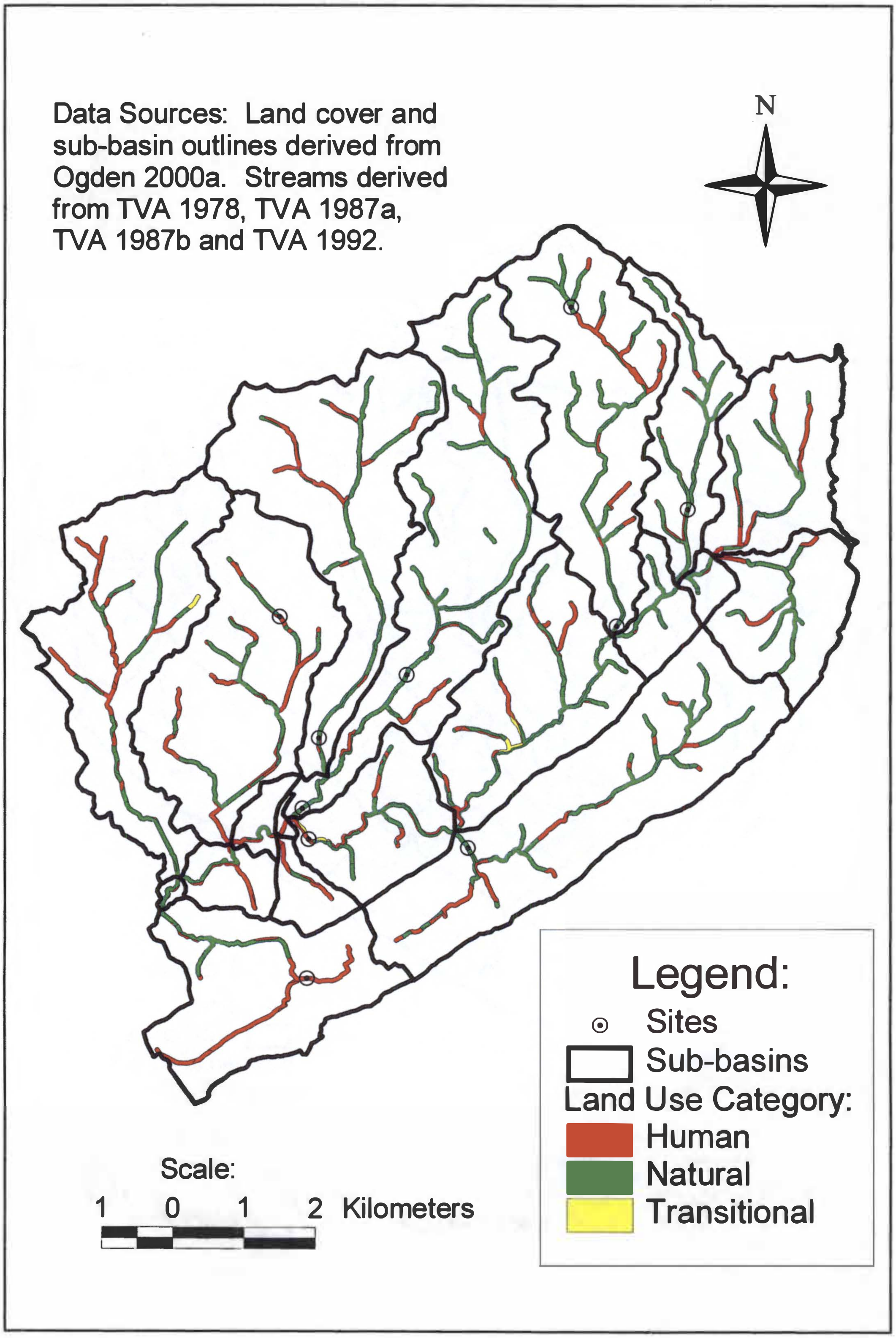
Table 4-6. Comparison of Riparian Land Use

Catchment	Riparian Land Use	Percent	U-index
BV05	wooded	25	34
	transitional	4	
	residential (low)	11	
	residential (high)	16	
	pasture/grass	38	
	commercial/industrial	6	
CX01	wooded	26	27
	water	1	
	residential (low)	20	
	residential (high)	5	
	pasture/grass	46	
	commercial/industrial	1	
	agricultural	1	
HB02	residential (high)	92	100
	commercial/industrial	8	
KB01	wooded	34	27
	residential (low)	26	
	residential (high)	1	
	pasture/grass	38	
KB03	wooded	90	8
	residential (low)	7	
	pasture/grass	2	
MB01	wooded	51	26
	water	1	
	residential (low)	24	
	pasture/grass	22	
	agricultural	2	
NF03	wooded	63	34
	residential (low)	26	
	residential (high)	8	
	pasture/grass	2	
TS01	wooded	19	6
	residential (low)	5	
	pasture/grass	75	
	agricultural	2	
WF01	wooded	45	14
	residential (low)	12	
	residential (high)	2	
	pasture/grass	41	
WF02	wooded	56	10
	residential (low)	10	
	pasture/grass	34	



Data Sources: Land cover and sub-basin outlines derived from Ogden 2000a. Streams derived from TVA 1978, TVA 1987a, TVA 1987b and TVA 1992.

Figure 4-8. Riparian Land Use



Data Sources: Land cover and sub-basin outlines derived from Ogden 2000a. Streams derived from TVA 1978, TVA 1987a, TVA 1987b and TVA 1992.

Figure 4-9. Simplified Riparian Land Use

negative relationship between the increasing riparian human use index and the degree of bank erosion documented by the SVAP bank stability scores ($\tau = -.41$, $n = 10$, $p < .05$), such that the prevalence of bank erosion increased as the proportion of human uses increased within the catchment area.

The human use index calculations excluded all pasture/grass from the "human" category. Because cows have been known to trample down stream banks and increase bank erosion in Beaver Creek (Parish and Young 2000), and because a Pacific Northwest study (May *et al.* 1997) found that stream degradation was linked to the proportion of "mature" riparian buffer (or the proportion of riparian buffer consisting of trees rather than other types of vegetation and built surfaces), I also examined the percentage of wooded riparian buffer within each catchment. Once again, the values ranged widely, from 0% wooded in catchment HB02 to 90% wooded in catchment KB03. As expected, there was a positive relationship between the amount of forested area and the SVAP bank stability scores ($\tau = .32$, $n = 10$, $p < .10$). No significant relationship was found with the excess shear stress measurements, however.

Discussion of Urbanization Metrics

In this chapter, I compared 10 approximations of urbanization to both sets of channel stability indicators (qualitative and quantitative) in an effort to establish a relationship between increasing development and accelerated channel erosion. Despite the small number of sites used in the statistical analysis, there appeared to be a good correlation ($p \leq .10$) between seven of the urbanization metrics and the qualitative SVAP bank stability scores and two of the urbanization metrics and the quantitative measurements of excess shear stress (**Table 4-7**). Both sets of channel stability indicators were correlated with the percentage of wooded area in each catchment. Neither set of

Table 4-7. Summary of Tests for Bivariate Correlation between Urbanization Metrics and Indicators of Bank Stability (10 Samples)

Urbanization Metric	SVAP Bank Stability Score		Excess Shear Stress	
	τ *	Significance **	τ *	Significance **
Percent Impervious Cover (AMEC)	-0.32	0.10	-0.11	Insignificant
Percent Impervious Cover (CDMcKee)	-0.37	0.07	-0.07	Insignificant
Percent Impervious Cover (ATtILA)	-0.37	0.07	-0.02	Insignificant
Human Use Index (U-index)	-0.37	0.07	-0.02	Insignificant
Percent Wooded	+0.51	0.02	-0.38	0.06
Road Density	+0.14	Insignificant	-0.11	Insignificant
Road/Stream Crossing Density	+0.09	Insignificant	+0.16	Insignificant
Population Density	+0.05	Insignificant	-0.38	0.06
Human Use Index of Riparian Buffer	-0.41	0.05	-0.02	Insignificant
Percent Wooded Riparian Buffer	+0.32	0.10	-0.20	Insignificant

* τ = Kendall rank correlation coefficient

** When the probability of a Type I error was determined to be $\leq$ 10% using a 1-tailed distribution, the relationship was considered to be significant.

channel stability indicators was related to the road density or road/stream crossing density of the contributing area.

It is possible that the lack of correlation with the road density and road/stream crossing density simply resulted from the road data being out of date or at a resolution too coarse for such a small study area. Since 1995, many new subdivisions have been built in the upper Beaver Creek watershed. If this study were to be expanded, I would suggest scanning in and digitizing the road maps contained in the recently published third edition of the *Knoxville and Knox County Street Guide Map* (The MiniTmap Company 2000). These large-scale street maps were invaluable during the fieldwork portion of this thesis, and they included nearly all of the new subdivision roads.

The majority of the analyses outlined in this chapter indicated that sub-basin-wide land use changes are indeed causing channels within the upper Beaver Creek watershed to become less stable, either through widening or incision. As further demonstration that there is a likely relationship between urbanization and channel stability within the upper Beaver Creek watershed, consider the comparison of sites KB03 and NF03. Both of these sites were located within upper tributary reaches with similar topography, and both were underlain by dolomite. Both streams had the same width of 5.5 m (18 ft), but NF03 was considerably deeper than KB03 (**Figure 4-10**). Whereas KB03 had a width-to-depth ratio of 11.7, NF03 had a width-to-depth ratio of 1.6, indicating that NF03 had been incised. While the topographic and geologic controls of both sites were nearly identical, the land use patterns within the catchments were not. The KB03 catchment was 83% wooded and had a 93% wooded riparian buffer. The NF03 catchment was only 43% wooded, with 15% high density residential land use and 1% commercial/industrial land use. Although its riparian buffer was 64% wooded, 15% of the 30-meter riparian zone was occupied by high density residential land use. Given

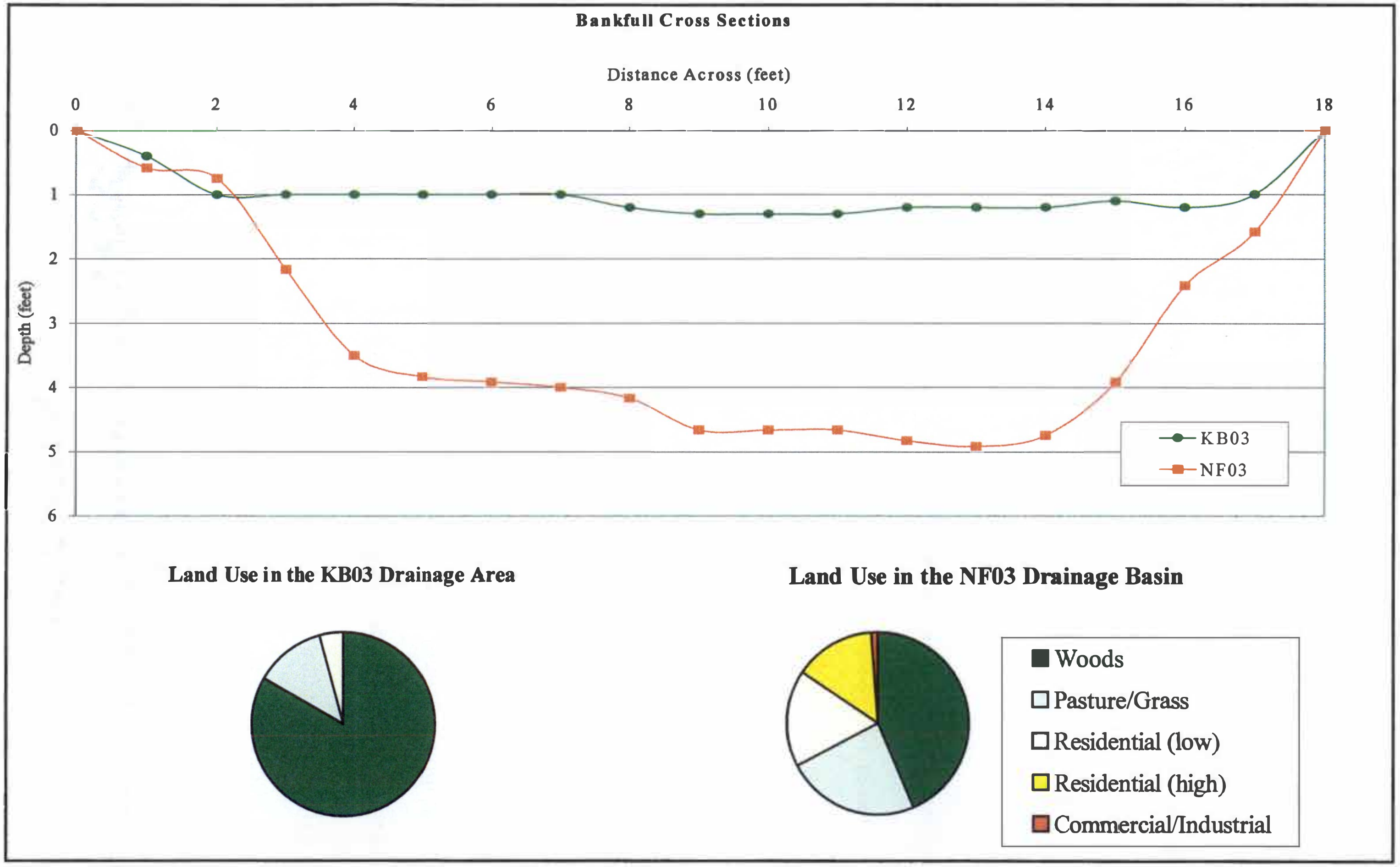


Figure 4-10. Case Study: KB03 versus NF03

the similarities of topography and geography, it seems likely that the differing land uses, either catchment-wide or within the riparian zone, caused the significant differences in the channel depths. Similar cases of incision due to urbanization have been noted in Indiana (Doyle *et al.* 2001) and in Connecticut (Jacobson *et al.* 2001).

Although several of the urbanization metrics discussed in this chapter related to channel instability, impervious cover is the measure most likely to be applied by land use planning agencies (Arnold and Gibbons 1996). I used the ATtILA imperviousness coefficients (Ebert *et al.* 2001) trend line from a plot of SVAP bank stability versus percent TIA (**Figure 4-4**), to find a range of impervious cover beyond which bank instability would be likely to occur in the upper Beaver Creek watershed. During the qualitative assessment of bank stability, the four most stable sites received scores between 8 and 10 and the five eroding sites received scores between 1 and 4 (although site BV05 was deemed stable, it only scored 5.5 and was really a borderline site). Thus, to calculate the lower threshold boundary of TIA, I set the SVAP bank stability score equal to 8, and to calculate the upper threshold boundary of TIA, I set the SVAP bank stability equal to 4. In this way, I determined that the channels within the upper Beaver Creek watershed tend to become unstable when urban development of the catchment exceeds 13-20% impervious cover. Using the same technique on a plot of wooded area versus SVAP bank stability scores, I determined that erosion will become more prevalent in Beaver Creek when the wooded area falls below 38-51% of the total catchment land use.

CHAPTER V
CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE STUDY

My hypothesis that there would be a positive relationship between the prevalence of bank instability, as erosion, and increased levels of urbanization within the upper Beaver Creek watershed was upheld by the results of this associative study. I selected 10 sites within eight adjacent sub-basins ranging from predominately rural to urban and used two different field methods to assess channel stability at those sites: (1) a visual, qualitative indicator of bank stability ranging from 1 (worst) to 10 (best) based on the USDA *Stream Visual Assessment Protocol* (1998); and (2) a calculated measure of excess shear stress based on channel geometry measurements and the median particle size at each site (Doyle *et al.* 2001). Both of the methods showed that five of the 10 sites were eroding substantially, and that the remaining five sites were either stable or aggrading. After quantifying urban development in 10 different ways (both on a catchment-wide scale and a 30-meter riparian buffer scale), I found that the qualitative indicators of channel stability correlated with seven of the 10 selected urbanization metrics and that both sets of bank stability indicators were significantly related to the wooded area of the contributing drainage area **(Table 4-7)**.

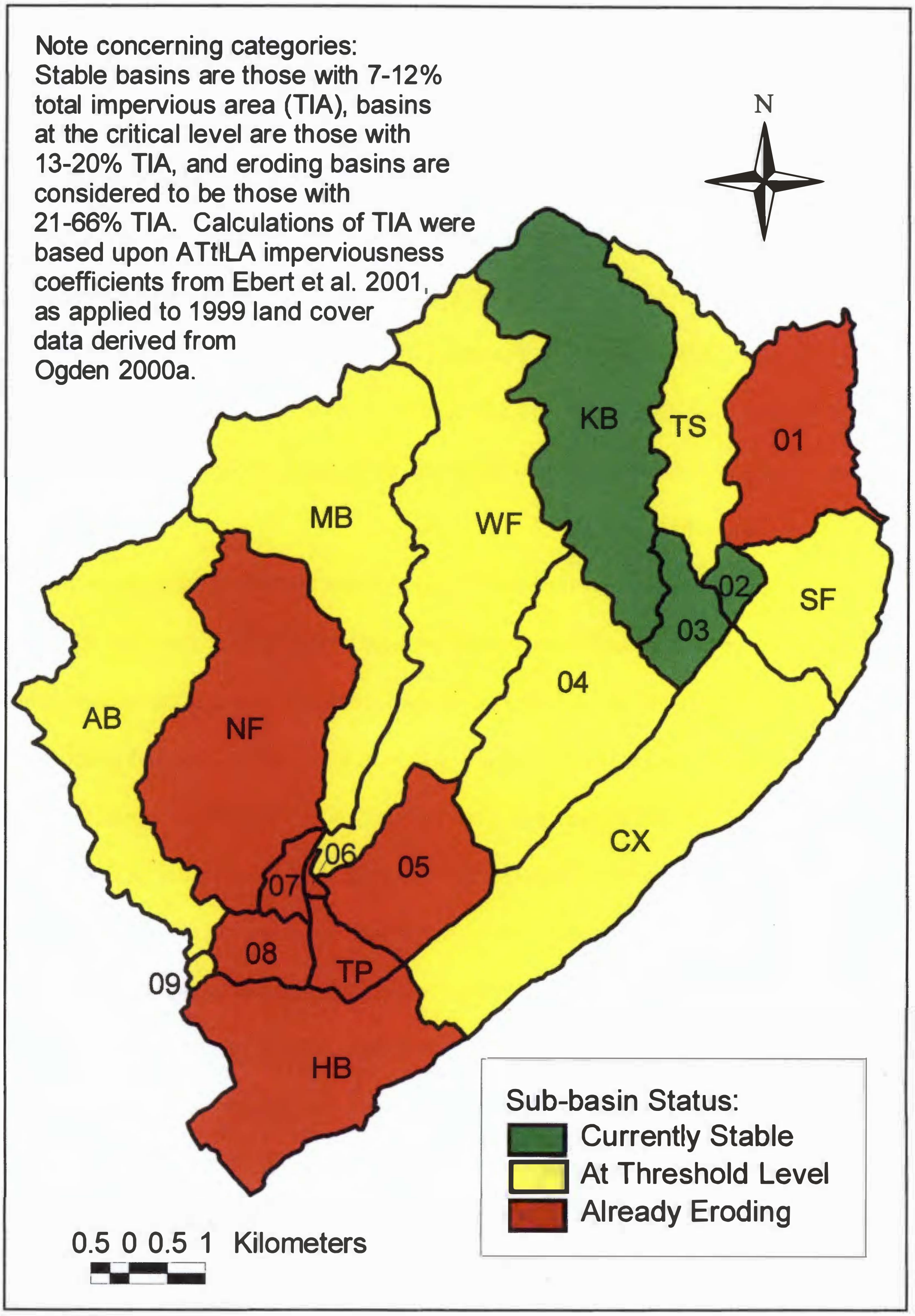
A central Michigan study recently found that there was a greater correlation between bedrock and channel morphology than there was between land use and channel morphology (Jacobson *et al.* 2001). While I found no such correlation between geology and channel erosion in my study area, I did find a correlation between decreasing slope and increasing channel erosion. I found even stronger relationships, however, between bank stability and urban development. Thus, this associative study has achieved its objective of being a coarse filter to test for potential relationships between land use change and channel morphology (Jacobson *et al.* 2001). An increase in the number of sites will likely strengthen these relationships and facilitate a greater distinction between catchment-wide land use change impacts and riparian land use change impacts on channel stability.

Because it is difficult to attain access to sites within the upper Beaver Creek watershed, it would take many more months to work out agreements with local residents to enable a researcher to take both sets of channel stability measurements on private property. Fortunately, the SVAP bank stability indicators ended up being more reliable than the excess shear stress measurements, and the qualitative protocol (USDA 1998) can generally be used without crossing fences at the water's edge. If more field work is to be conducted, then I would suggest that measurements be taken within more heavily developed catchments similar to HB02. There was a large jump in development between HB02 and the other nine catchments selected for analysis (*e.g.*, 45% impervious cover versus the next highest value of 24% impervious cover). While I assumed that there was a linear relationship between urbanization and channel stability (based on other studies relating impervious cover to runoff), it is also possible that more intense development over a sufficient length of time leads to a new equilibrium state (Jacobson*et al.* 2001).

Although there was a good correlation ($\tau = -.55$, $n = 10$, $p < .02$) between the qualitative and quantitative indicators of channel stability, the results from site TS01 revealed that there is an inherent limitation to the excess shear stress measurement method of quantifying bank stability: namely, the Wolman (1954) pebble count method used to approximate the particle size (D) used in the critical shear calculation is based upon the assumption that the bedload contains coarse gravel. Given the wide variations in topography, bedrock, and soil type throughout the upper Beaver Creek watershed, it is likely that other researchers attempting to quantify excess shear stress would find similar reaches with predominately fine-grained bedload. In such instances, D_{50} could be calculated in the laboratory by sieving and weighing dried bedload samples.

My data suggest that pronounced bank erosion, or channel instability, begins to occur at an 13-20% impervious cover, as calculated using the EPA coefficients of imperviousness (Ebert *et al.* 2001). Thus, my study agrees with a with a wide variety of studies from across the United States which have shown that potentially irreversible changes in stream structure and habitat begin at 10-20% impervious cover (Booth 1990, Schueler 1994, Bledsoe and Watson 2001). Because biological degradation of streams occurs more rapidly than physical degradation as the urbanization of a watershed increases (Barnes *et al.* 2000), these measurements of channel erosion should be seen as conservative measurements of stream habitat alteration. In addition to the potential impacts of channel erosion on stream health, inhabitants of the Beaver Creek watershed should be concerned about accelerated bank erosion because of its potential to fill in downstream water storage areas prematurely and exacerbate flooding. Further, we should all be concerned about bank erosion because it is a potentially significant contributor of nonpoint source pollution, the leading cause of water pollution in the United States (Booth 1990, Trimble 1997, Barnes *et al.* 2000, Jacobson *et al.* 2001).

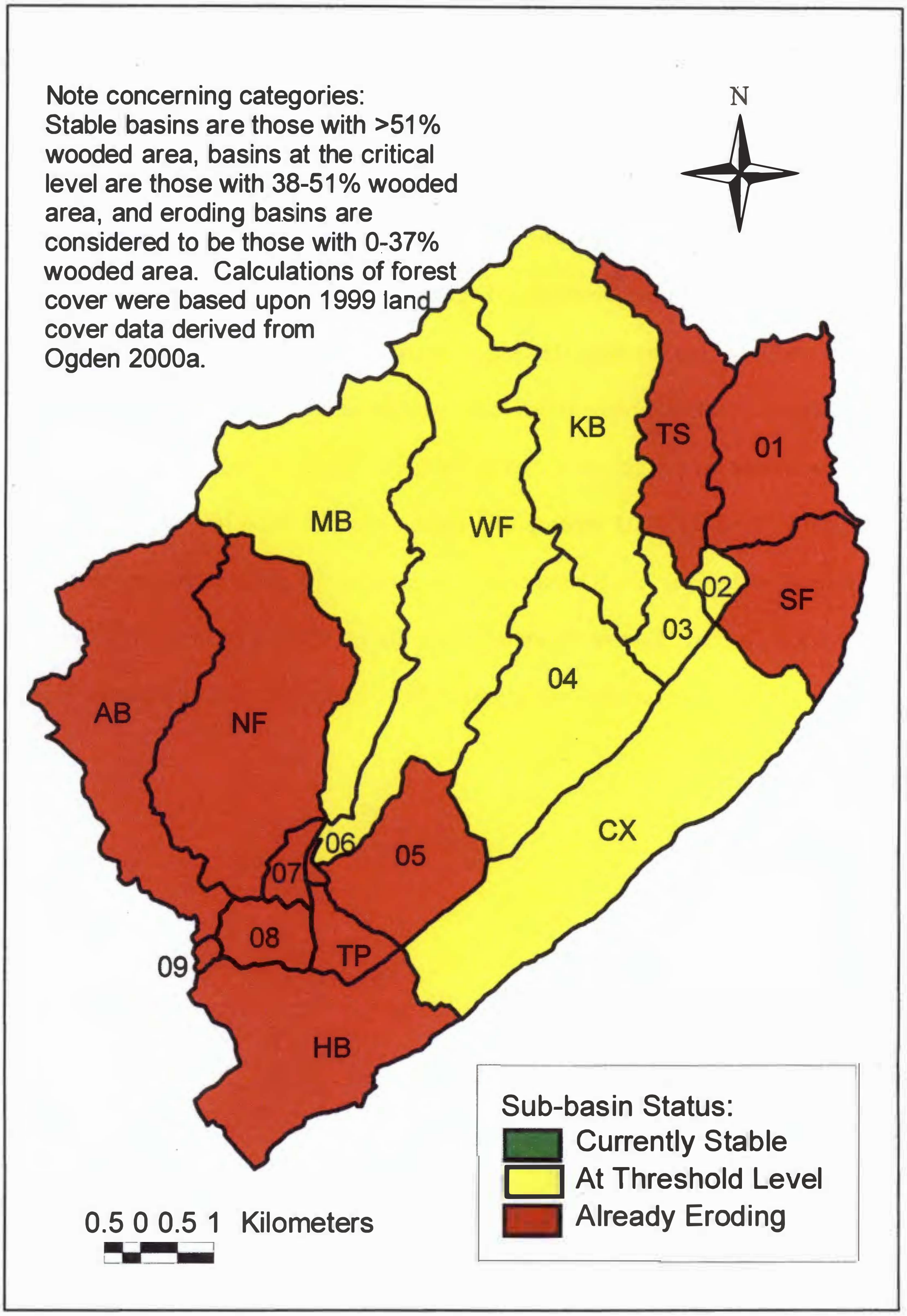
The Nonpoint Education for Municipals Officials (NEMO) Program at the University of Connecticut has developed a simple GIS interface that allows land use planners to test the effects of build out scenarios on stream degradation as based on impervious cover (Prisloe *et al.* 2001). Using a similar "traffic light" coloring scheme to illustrate the total impervious area of each sub-basin (**Figure 5-1**)— such that red implies that damage has already been done to the sub-basin's channels, yellow implies that the sub-basin's channels are on the verge of being severely eroded if nothing is changed, and green indicates that it will be a while before the sub-basin's channels become unstable—it



Note concerning categories: Stable basins are those with 7-12% total impervious area (TIA), basins at the critical level are those with 13-20% TIA, and eroding basins are considered to be those with 21-66% TIA. Calculations of TIA were based upon ATtILA imperviousness coefficients from Ebert et al. 2001, as applied to 1999 land cover data derived from Ogden 2000a.

Figure 5-1. Land Management Implications of Impervious Cover Calculation becomes apparent that seven of the 19 sub-basins of the upper Beaver Creek watershed are at a critical stage in development (namely Allen Branch, Mill Branch, Willow Fork, Thompson School Branch, Cox Creek, South Fork, and Sub-basin 04). A similar "traffic light" map based upon the percentage of wooded area within each sub-basin **(Figure 5-2)** indicates that Allen Branch, Thompson School Branch, and South Fork may have already exceeded the threshold level of development, and that Kerns Branch, Sub-basins 02 and 03 may not be as stable as they first appeared. Thus, I would recommend that Mill Branch, Willow Fork, Cox Creek, and Sub-basin 04 be examined immediately for ways to limit or mitigate the impacts of future urban development, followed closely by Kerns Branch and Sub-basins 02 and 03.

Because I found a positive correlation between the human use index of the riparian buffer, or the ratio of built to natural surfaces within the 30-meter area adjacent to each stream, and the degree of bank instability, I would suggest that the riparian zones in these three sub-basins be examined more closely in terms of the types and quantity of vegetation and the presence/absence of large woody debris. The effectiveness of water to erode banks is reduced by one to two orders of magnitude by the presence of flourishing vegetation (Grable 2000, Finkenbine 2000), and scientists and planners alike have now come to the conclusion that natural vegetated buffers are preferred to engineering methods when it comes to stabilizing banks. Leaving narrow strips of naturally vegetated land along the edges of streams in suburbanizing areas may preserve water quality and wildlife habitat, and serve as aesthetic greenways (Marsh 1997, Thibault 1997). As wooded riparian buffers are increased, however, the role of large woody debris in the watershed may need to be addressed (Jacobson *et al.* 2001). Other ways of minimizing future development impacts might include restricting the size of shopping center parking lots, which are typically built to a capacity estimated upon the two biggest shopping days



Note concerning categories: Stable basins are those with >51% wooded area, basins at the critical level are those with 38-51% wooded area, and eroding basins are considered to be those with 0-37% wooded area. Calculations of forest cover were based upon 1999 land cover data derived from Ogden 2000a.

Figure 5-2. Land Management Implications of Wooded Area Calculation per year rather than daily shopping needs, or clustering new residential housing areas (Barnes *et al.* 2000).

The qualitative assessment protocol used in this study (USDA 1998) only categorized eroding sites as "unstable," but in actuality, a disturbed stream system may erode in some areas while aggrading in others (Jacobson *et al.* 2001). More work needs to be done to allow for the incorporation of aggrading sites into aerial characterizations of channel stability. For example, it would be interesting to do a sediment budget of the entire Beaver Creek watershed to determine whether or not the eroding banks in the upper watershed are, in fact, prematurely filling downstream storage areas.

On March 18, 2002, the local news media reported that a 100-year flood had hit the Knox County area. It will be interesting to see if the channels in the upper Beaver Creek watershed have been impacted by the significant storm event and/or if the channel geometry and bedload particles will return to the size documented during November and December of 2001.

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APPENDIX

USDA

NRCS Stream Visual Assessment Protocol

Owner's Name ____________________ Evaluator's Name ___________________ Date _______________

Stream Name _________________________________ Waterbody ID Number ___________________

Reach Location ____

____

Ecoregion _______________________ Drainage Area __________________ Gradient _______________

Applicable Reference Site ____

Land Use within Drainage (%): Row crop ___ Hayland ___ Grazing/pasture ___ Forest ___ Residential ___

Confined Animal Feeding Operations ___ Cons. Reserve ___ Industrial ___ Other: ____________

Weather Conditions - Today _____________________ Past 2-5 Days ______________________________

Active Channel Width _____________ Dominant Substrate: boulder ___ gravel ___ sand ___ silt ___ mud ___

Site Diagram

Figure A-1. Field Data Sheet Used to Perform Qualitative Assessments

Assessment Scores

Channel Condition ☐

Hydrologic Alteration ☐

Riparian Zone ☐

Bank Stability ☐

Water Appearance ☐

Nutrient Enrichment ☐

Barriers to Fish Movement ☐

Instream Fish Cover ☐

Pools ☐

Invertebrate Habitat ☐

Score only if applicable

Canopy Cover ☐

Manure Presence ☐

Salinity ☐

Riffle Embeddedness ☐

Macroinvertebrates Observed (optional) ☐

Overall Score
(Total divided by number scored) ______

≤ 6.0	POOR
6.1 - 7.4	FAIR
7.5 - 8.9	GOOD
≥ 9.0	EXCELLENT

Suspected Causes of Observed Problems: ______________________________________

____

____

____

Recommendations: ____

____

____

Figure A-1. Continued

Table A-1. Baseflow Measurements

Site	Cross Sectional Area (m^2)	Wetted Perimeter (m)	Hydraulic Radius (m)	Roughness Value (n)	Bed Slope	Velocity* (m/s)	Discharge (m^3/s)
BV05	0.72	3.43	0.21	0.025	0.001	0.12	0.083
CX01	1.55	6.74	0.23	0.055	0.003	0.03	0.043
HB02	0.06	1.27	0.05	0.040	0.010	0.10	0.006
KB01	0.12	1.28	0.09	0.030	0.008	0.27	0.032
KB03	0.13	2.74	0.05	0.050	0.029	0.10	0.013
NF03	0.10	1.53	0.06	0.045	0.014	0.15	0.015
TS01	0.35	2.29	0.15	0.030	0.006	0.11	0.039
WF01	0.33	2.24	0.15	0.025	0.001	0.20	0.063
WF02	0.17	1.68	0.10	0.035	0.010	0.33	0.056

* Site MB01 has been excluded from the baseflow measurements table because it did not have flowing water at the time of observation. Per Dunne and Leopold (1978), I measured baseflow velocity at each site by conducting five float tests along the length of the reach (or over as long a section as possible, given low-flow conditions and obstructions). While I stood at the upstream end of the reach and dropped small twigs into the water at the imaginary line between flags 1 and 2 (see **Figure 3-3**), my assistant held a timer and stood at the downstream end of the reach waiting for the twig to cross the imaginary line between flags 3 and 4. My assistant recorded the amount of time that it took each twig to travel the length of the reach. If a twig got caught on an obstruction along the way, we discarded its results and conducted a new trial. I attempted to use uniform lengths of a single stick so that the twigs would have approximately the same weight.

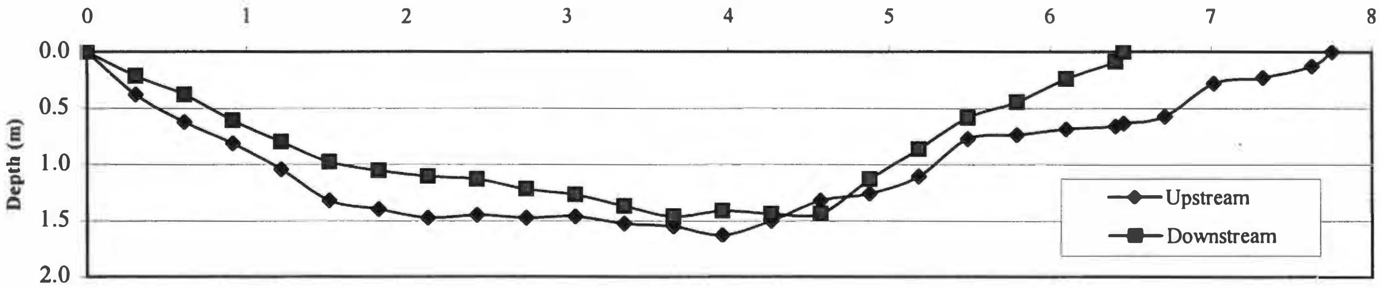
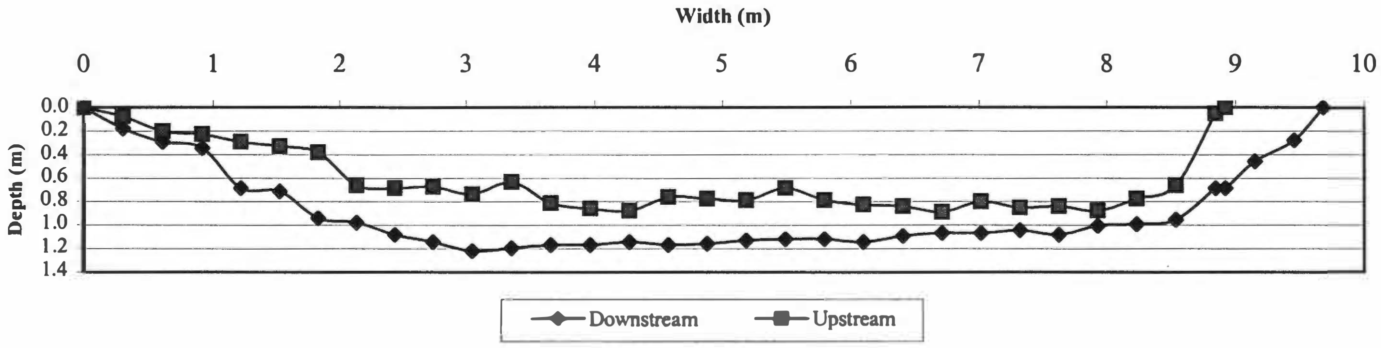

BV05: Sub-basin 05

Figure A-2. Bankfull Cross Sections



CX01: Lower Cox Creek

Figure A-2. Continued

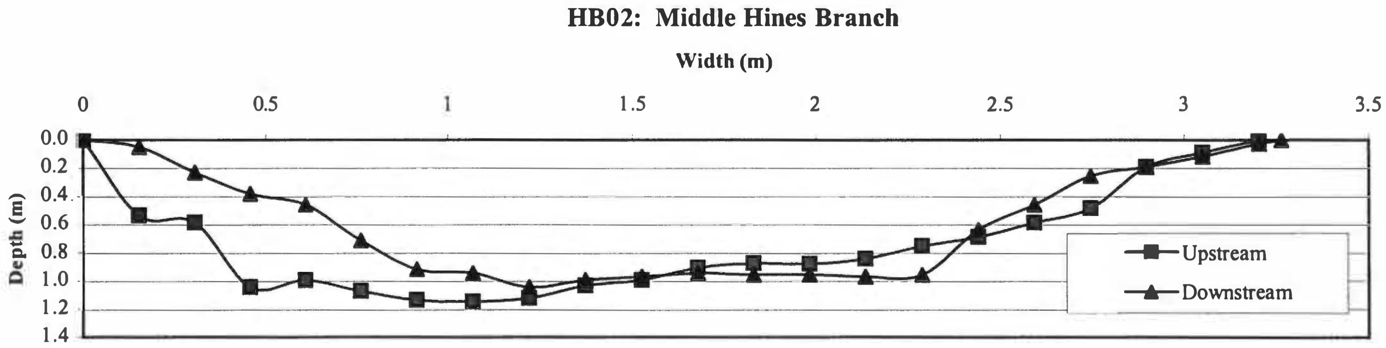


Figure A-2. Continued

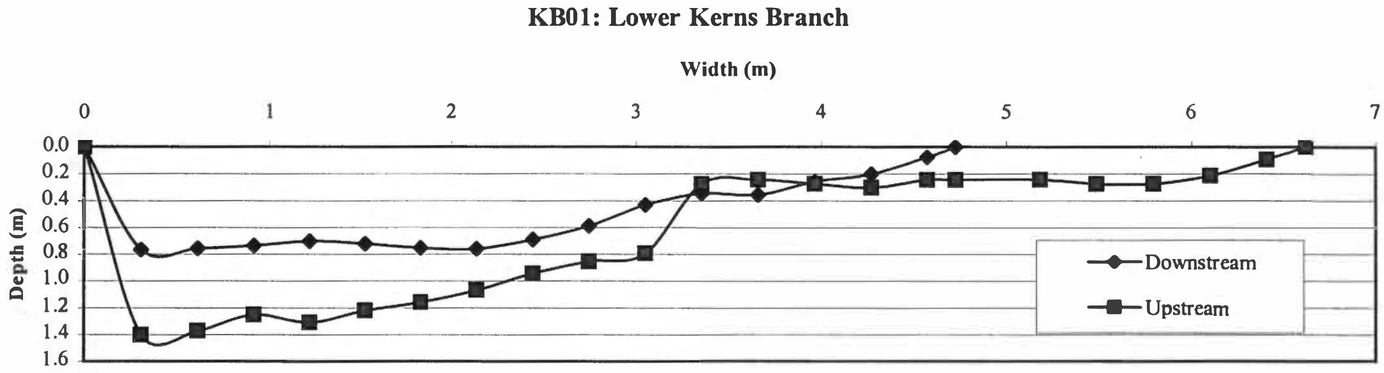


Figure A-2. Continued

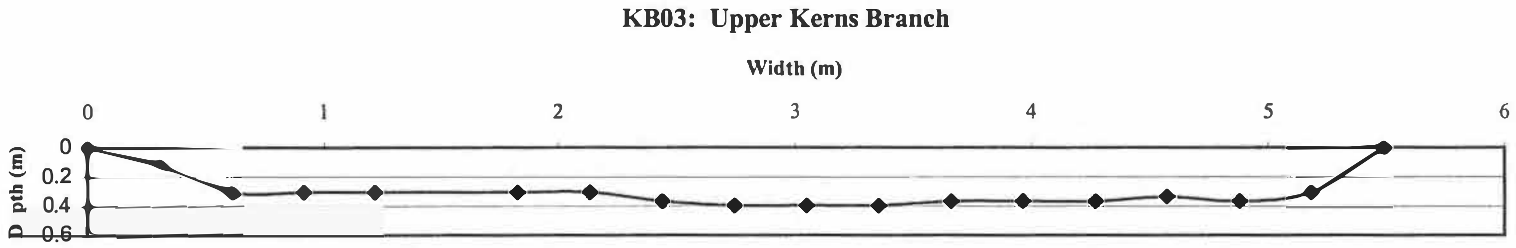


Figure A-2. Continued

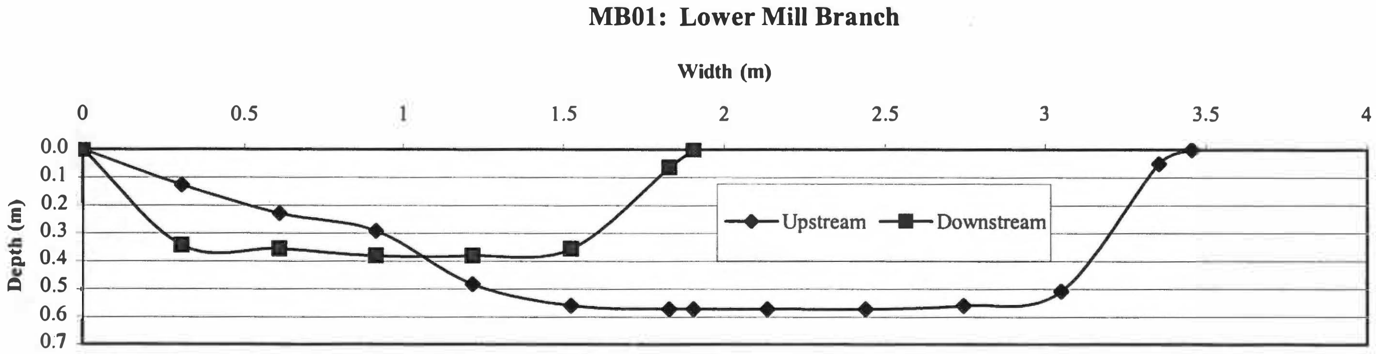
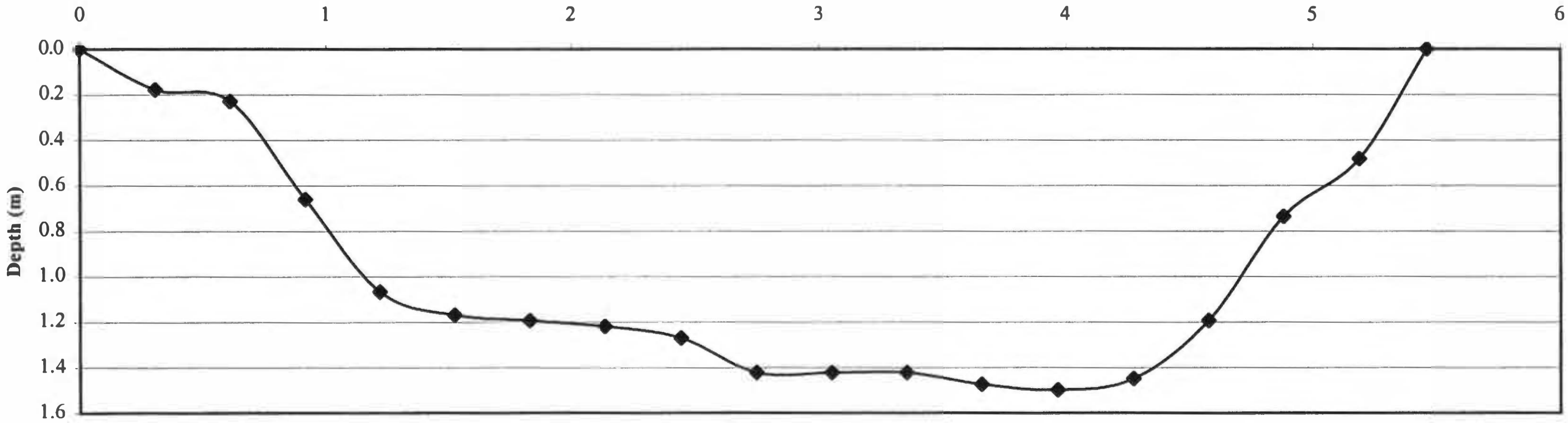


Figure A-2. Continued



NF03: Upper North Fork

Figure A-2. Continued

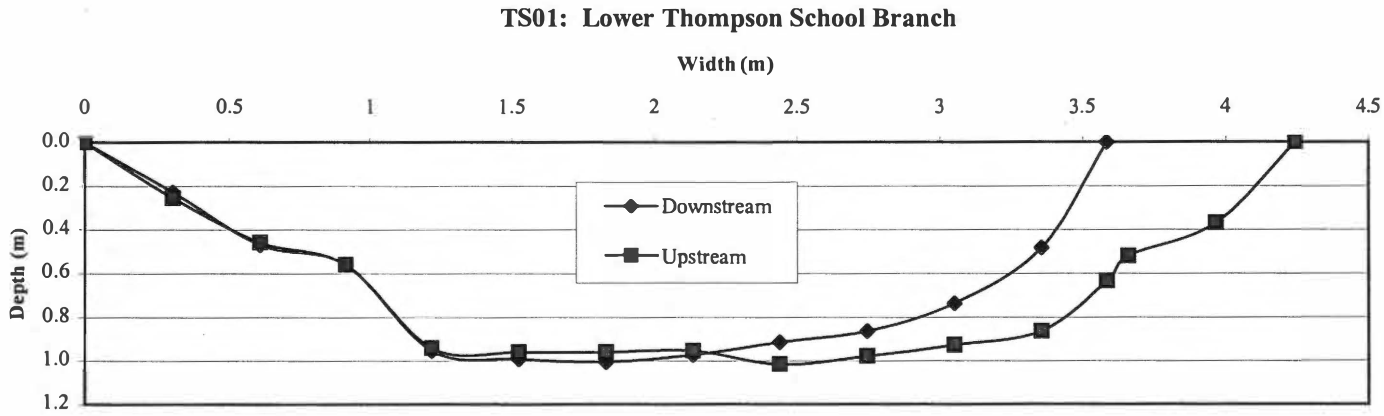
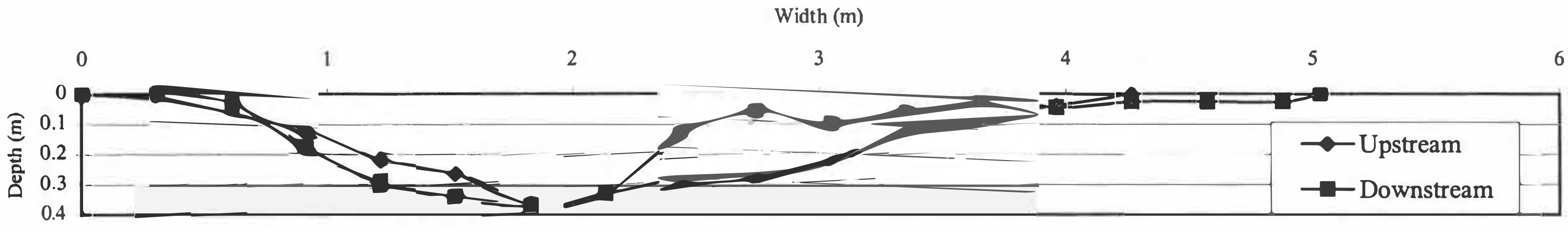

TS01: Lower Thompson School Branch

Figure A-2. Continued



WF01: Lower Willow Fork

Figure A-2. Continued

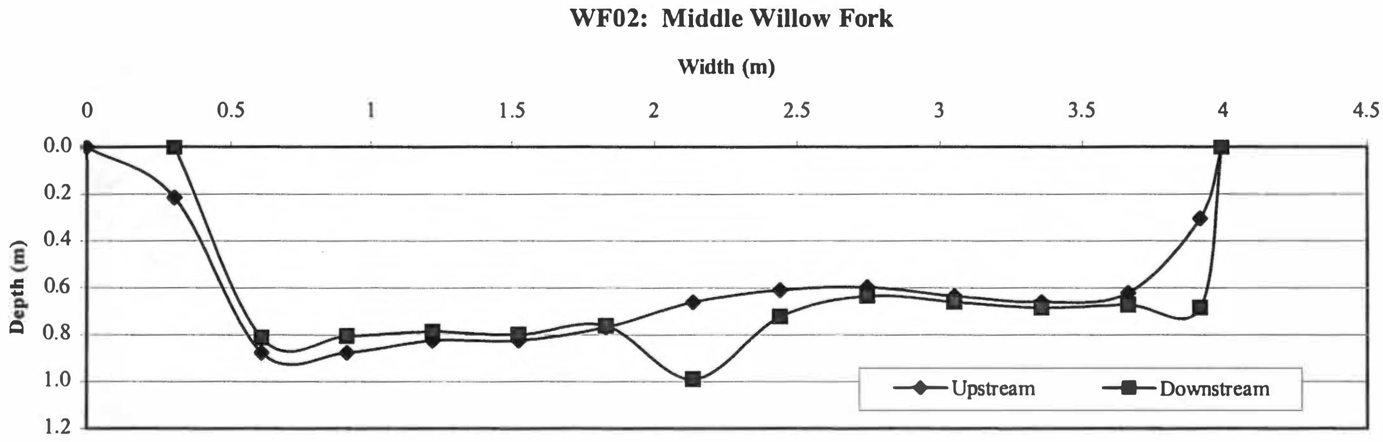


Figure A-2. Continued

VITA

Esther Marie Sullivan was born in Toccoa, Georgia on February 11, 1972. She began elementary school in Manila, Philippines, finished second grade in Watertown, Massachusetts, and completed the remainder of her grade school and high school education at public schools in Chicago, Illinois. Esther graduated as Valedictorian from Kenwood Academy in 1990. She earned a B.S. in Geology and Geophysics from Yale University in New Haven, Connecticut in May of 1994.

Immediately following college graduation, Esther spent a year working in the Oklahoma oil field as an engineer with Schlumberger Wireline and Testing. Over the next five years, she worked as an environmental consultant for two Oak Ridge, Tennessee firms—PAI Corporation and DPRA Inc.—and became a specialist on the Department of Energy's Pollution Prevention Program.

In the Spring of 2000, Esther began her work toward a Master's degree in Geography at the University of Tennessee. For three semesters, she worked as a Graduate Teaching Assistant, helping first with Introductory Cartography and then with Introductory Physical Geography. In July 2001, Esther began an environmental GIS internship with the TVA Public Power Institute in Norris, Tennessee.

Esther was married in October 2000 and currently lives with her husband, Brad Parish, and their Black Lab, Pepper, in Kingston, Tennessee.