12-2003

Effects of Urbanization on a Small Perennial Stream: Second Creek in Knoxville, Tennessee

Judith Laing Grable
University of Tennessee - Knoxville

To the Graduate Council:

I am submitting herewith a dissertation written by Judith Laing Grable entitled "Effects of Urbanization on a Small Perennial Stream: Second Creek in Knoxville, Tennessee." I have examined the final electronic copy of this dissertation for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, with a major in Geography.

Carol P. Harden, Major Professor

We have read this dissertation and recommend its acceptance:

Kenneth H. Orvis, Theodore H. Schmudde, G. Michael Clark

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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Anne Mayhew
Vice Provost and
Dean of Graduate Studies

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EFFECTS OF URBANIZATION ON A SMALL PERENNIAL STREAM: SECOND CREEK IN KNOXVILLE, TENNESSEE

A Dissertation
Presented for the
Doctor of Philosophy
Degree
The University of Tennessee, Knoxville

Judith Laing Grable
December 2003

DEDICATION

This dissertation is dedicated to my late husband

Earl Edgar Grable

with heartfelt thanks for his encouragement and support,
and deep sorrow that he never saw it finished.

ACKNOWLEDGMENTS

Many people helped me with this project. I would like to thank the members of the Dissertation Committee, Dr. Kenneth Orvis, Dr. G. Michael Clark, and Dr. Theodore Schmudde, for their guidance. I am particularly grateful to my advisor, Dr. Carol Harden, for her advice, help, patience, and the use of her lab facilities and field equipment. Thanks, in addition, to Dr. Sally Horn, who let me use her lab equipment, and to Bradley Brian of the Water Resources Division of the U.S. Geological Survey, for the use of stream discharge and suspended sediment-measuring equipment.

Thanks to all of the following people who assisted me with field work: Ed Grable, Joe Katz, Leah Manos, Marty Arford, Phillip Young, Brad Kreps, Lisa Boulton, and Don Kemp. I could not have done it alone.

There are other people whose assistance was valuable. I want to thank Tim Gangaware of the Water Resources Research Center for ideas and resources; Steve Allen and Steve Amick from the TVA for historical photographs and information; Paul Stodola of the Tennessee Department of Environment and Conservation for information on sediment in runoff; Nathan Hargrove and others at the NRCS in Knoxville for old aerial photographs and information on the new, unpublished soil survey of Knox County; David Hagerman, and Don Daily at Knoxville City Engineering for stream discharge monitoring information and maps; Dr. Terry Gilhua at the Knoxville Metropolitan Planning Commission for historical information about Knoxville; Don Horton at McCarty-Holsaple-McCarty for blueprints; and Wesley Wright at UT Agricultural Engineering for precipitation data.

I am very grateful for the support of Dr. Ed Chatelain, Dr. Frank Flaherty, and Dr. Mary Fares of Valdosta State University, and Carolyn Koroa of the TVA in Knoxville. Thanks also to Hurricane Isabel for you-know-what. Last, but certainly not least, I want thank my friend Dr. Cecilia Barnbaum for all her work with illustrations, help with computer matters, and her unfailing support through the latter stages of this project.

ABSTRACT

Little is known about the coarse load carried by streams in urban areas or the length of time needed for stream channel adjustments to urban conditions. In this study, I examine the history of urbanization in the basin of Second Creek, the status of the channel, and the sediment load of the creek in recent years.

Second Creek is a small perennial stream whose 18.6 km^2 drainage basin is almost entirely contained within the City of Knoxville, Tennessee. Almost all of the drainage basin was developed more than 40 years ago, and is now urban and suburban in character.

For this study, I inspected the channel of Second Creek, measured its dimensions in many places, and recorded the types of materials present and evidence of recent deposition and erosion. My analysis of channel materials included measuring the sizes of more than 100 coarse particles on the streambed at each of several locations. In addition, I measured stream discharge and suspended sediment load near the mouth of the stream during several low and high flows, measured suspended load for a year using rising stage samplers, and estimated bedload by calculating the volume of sediment deposited at the mouth of the stream. Data made available as a result of this study include suspended sediment concentrations from rising stage samplers at five locations for a year of record (October 1998 to October 1999), discharge measurements and suspended sediment concentrations from nine storm events, bedload particle sizes from eight sites, and cross-sectional surveys from 18 sites.

If a stream channel is adjusted to present-day hydrologic and sediment load regimes, little net deposition or erosion is expected to take place, yet my examination of the channel of Second Creek reveals that both deposition and erosion have occurred in recent decades. Sediment deposits in box culverts and concrete-lined channel reaches cannot be more than 30 years old, but I found few signs of present-day deposition. Rather than deposition, much of the channel (where not lined with concrete or thick riprap) shows signs of recent erosion. Therefore, channel erosion appears to have replaced deposition as the dominant process in the last few years. This suggests that Second Creek has not adjusted to the urban conditions of its drainage basin, and that channel enlargement is occurring in many places.

Impervious surfaces and lawns cover most potentially erodible soil in the drainage basin, so the suspended load is expected to be low, yet measurements show it to be high. Channel erosion is likely to be contributing suspended sediment and coarse particles to the stream. Existing basin models generally used for water quality analysis do not include streambanks as sediment sources, and would thus significantly underestimate sediment load in Second Creek and other streams experiencing rapid streambank erosion.

Coarse particles are common in the streambed alluvium, yet my calculations of the volume of sediment in the reservoir at the stream outlet indicate the amount of bedload

carried by the creek in the last 50 years to be low. The numbers and/or sizes of coarse anthropogenic particles are sufficient at some sites to alter mean particle diameters and, therefore, stream dynamics. Such particles should not be ignored in fluvial studies.

Urbanization has not been a single, discrete event in the drainage basin of Second Creek. The results of this study demonstrate that a stream in a basin where urbanization began more than 200 years ago and essentially ended 40 years ago is not static, but is continuing to respond to major changes made decades ago and to smaller, more recent changes.

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CHAPTER 1

INTRODUCTION

PURPOSE OF STUDY

The purpose of this study is to extend our understanding of short- to medium-term (years to decades) processes and responses of streams in older urban areas. I examine Second Creek, a small perennial stream that flows within Knoxville, Tennessee, where most land has been developed for at least 30 years, in order to 1) aquire baseline data for detection of future changes in sediment load and stream channel configuration and condition, and 2) discover the state of adjustment of the channel to urban conditions. To address the second objective, I look for answers to the following questions: Does the stream have a low sediment load, as expected in a post-development setting? Has the stream channel adjusted to post-development levels of sediment input and water discharge, as signified by a relatively stable channel, or are there active areas of deposition or erosion of material in the channel (other than local scour and fill)? If recent changes have occurred in the channel, what is the extent of the deposition or erosion, and what may have caused or is causing it?

STREAM RESPONSE TO URBANIZATION

Streams and their channels are integral and dynamic components of drainage basin systems. Whether the result of natural processes or human actions, changes in basin hydrology or sediment delivery to streams will trigger complex responses in stream and sediment dynamics. The responses include changes in channel morphology (Leopold et al., 1964; Schumm, 1977; Gregory, 1987; Lane and Richards, 1997).

The hydrology of streams in urban areas changes as the land surface is paved and built over and as ditches, drains, pipes, and culverts are installed to handle storm water. Increased amounts of impervious land surface result in increased runoff water from storms, and the runoff is delivered rapidly to urban streams through storm water drainage systems instead of moving slowly over and around the irregularities inherent in natural landscapes. Fast delivery of increased amounts of runoff produces greater peak flows and more frequent high flows in streams (Leopold, 1968; Hollis, 1975).

Sediment delivery to streams is also altered in urban settings. As vegetative cover and the soil surface are disturbed during the construction activities of land development, the amount of sediment delivered to nearby streams increases greatly, unless effective sediment management practices are employed (Wolman and Schick, 1967; Hammer, 1972; Graf, 1975; Neller, 1988; Booth, 1990). The immediate result is stream aggradation, manifested by accumulations of fine sediment in the channel. Once an area has become urbanized, that is, when most of it is covered with buildings, lawns, parking lots, and roads, the amount of sediment eroded and delivered to streams should drop to very low levels (Wolman, 1967). With less energy expended in sediment transport, an urban stream would have more energy available to do geomorphic work. In addition, more geomorphic work can be accomplished by the stream because of the more frequent high flows with their higher water velocities. The geomorphic work accomplished by this "extra" energy typically results in stream channel enlargement. The soon-after-development channel enlarging effect has been shown to occur in urban areas in many different geographic locations (e.g.,Wolman and Schick, 1967; Hammer, 1972; Graf, 1975; Neller, 1988; Ebisemiju, 1989).

Much less well known is the response of urban streams to discharge and sediment regimes during the years and decades following post-urbanization channel enlargement. Most researchers think stream channels will become adjusted to new hydrologic and sediment regimes at some point in time following the urbanization process, but estimates of the time required vary widely, from 5 years or less (Hammer, 1972; Ebisemiju, 1989) to several decades (Henshaw and Booth, 2000), to indefinitely (Wolman, 1967; Arnold et al., 1982). In addition to uncertainty over channel restabilization, very little has been reported about changes in the sizes or quantities of sediment delivered to streams some years after urbanization of the drainage basin, or about the types and timing of stream system responses to post-urbanization changes imposed on stream courses and bank and bed materials. As Graf (2001) points out, much more attention has been paid to collecting water quality and discharge data than to collecting data on the physical aspects of stream channels.

PREVIOUS STUDIES IN KNOXVILLE AND SECOND CREEK

There have been several studies of the hydrology of drainage basins in Knoxville. In 1976, Betson published a study of urban hydrology in the city. This was followed by a comprehensive study by Kung (1980) that also compiled information about many of the landscape characteristics that influence drainage basin hydrology. In 1987, Kung and McCabe used water budgets for a hydrologic analysis of drainage basins in Knoxville. They mentioned Second Creek, but did not include it in their analysis because of a lack of runoff data for the creek. More recently, Potter (1999) tested methods of estimating runoff in two small subbasins in the upper part of the Second Creek drainage basin. Storm-by-storm rainfall and runoff data are presented in Potter's report.

In the early 1980s, the Nationwide Urban Runoff Program (NURP) included parts of First and Second Creeks in a study of urban water issues. In the basin of Second Creek, researchers tested water quality in two residential subbasins and a strip commercial area.

They also studied the effects of carbonate geology on stormwater runoff transport in two subbasins containing sinkholes (TVA, 1984).

The City of Knoxville National Pollutant Discharge Elimination System (NPDES) Stormwater Permit Application (City of Knoxville, 1993) presented land use, impervious surface, one-year rainfall and runoff, and water quality data for each of the drainage basins in the city and surrounding area. A similar report in 2000 – 2001 presented updated information of the same types.

No previous field-based study has examined the sediment dynamics of Second Creek.

OVERVIEW OF THIS STUDY

Chapter 2 describes the physical setting and the history of urbanization within the drainage basin of Second Creek, as well as specific changes made to Second Creek at different times. In Chapter 3, Channel Status, I present the locations of recent erosion, deposition, and areas of stability along the length of Second Creek, and analyze the most pronounced areas of recent change. Chapter 4, which focuses upon the fine portion of the sediment load in Second Creek, contains the results of several methods of measurement of suspended sediment and estimations of the yearly sediment load in Second Creek. In the following chapter, Chapter 5, which focuses on the coarse portion of the sediment load in Second Creek, I present size distributions of coarse particles in the bed of the creek, and discuss the contribution of natural versus anthropogenic particles. Also included in this chapter is a study of the amount of sediment that has collected in the reservoir at the outlet of Second Creek. The conclusions I draw from this study of Second Creek and suggestions for further research are found in Chapter 6.

CHAPTER 2

THE STUDY AREA

LOCATION

Second Creek is one of several small perennial streams that flow through Knoxville, a city located in the eastern part of the state of Tennessee (Figure 2.1). Second Creek and most of the other streams that drain the city of Knoxville flow into Fort Loudoun Lake, a reservoir formed on the Tennessee River. The Hydrologic Unit Code (HUC) of the portion of the Tennessee River drainage area containing Second Creek is 06010201.

PHYSIOGRAPHY

Knoxville is located in the Ridge and Valley Physiographic Province (Fenneman, 1938), in an area known locally as the Great Valley of East Tennessee. The Cumberland Plateau lies to the west of this area, and the Blue Ridge Mountains to the east (Figure 2.2).

Landforms in the drainage basin of Second Creek consist primarily of the southwest-northeast trending ridges and valleys characteristic of Ridge and Valley physiography, as well as a few sinkholes. Most of the land within the 18.6 km^2 (7.1 mi^2) drainage basin is gently rolling or hilly, with slopes less than 12%, but Sharp's Ridge and some areas adjacent to Second Creek have predominantly steep slopes, greater than 25% (Figure 2.3).

Second Creek and the long axis of its drainage basin lie directly across the trend of the ridges and valleys (Figure 2.4). The creek flows in a southeasterly direction for most of its 8.4 km (5.3 mi) length. About one-third of the way from its headwaters to its outlet, Second Creek encounters what now appears to be a wind gap through Sharp Ridge (locally called "Sharp's" Ridge), a prominent ridge cutting through the area. The gap is a water gap, but Second Creek has been re-routed to flow underground, beneath the interstate highway that now occupies the gap.

Elevation in the drainage basin of Second Creek ranges from 248 m (813 ft) to slightly more than 427 m (1400 ft), thus relief in the basin is approximately 179 m (587 ft). The point of greatest elevation is, somewhat curiously, not located on a divide near the headwaters of the stream, where the highest elevation is 415 m (1360 ft), but rather on Sharp Ridge at the location of the WATE television tower. The lowest elevation in the basin, given as 248 m (813 ft) in this report, actually fluctuates with the water level in Fort Loudoun Lake. The lake is a reservoir, one of a series of impoundments of the Tennessee River and its tributaries (Figure 2.5). Normal pool level of the reservoir at Knoxville is 248 m (813 ft) (TVA, 1958).

Figure 2.1. Location of Knoxville, Tennessee. (ESRIData CD, 2003)

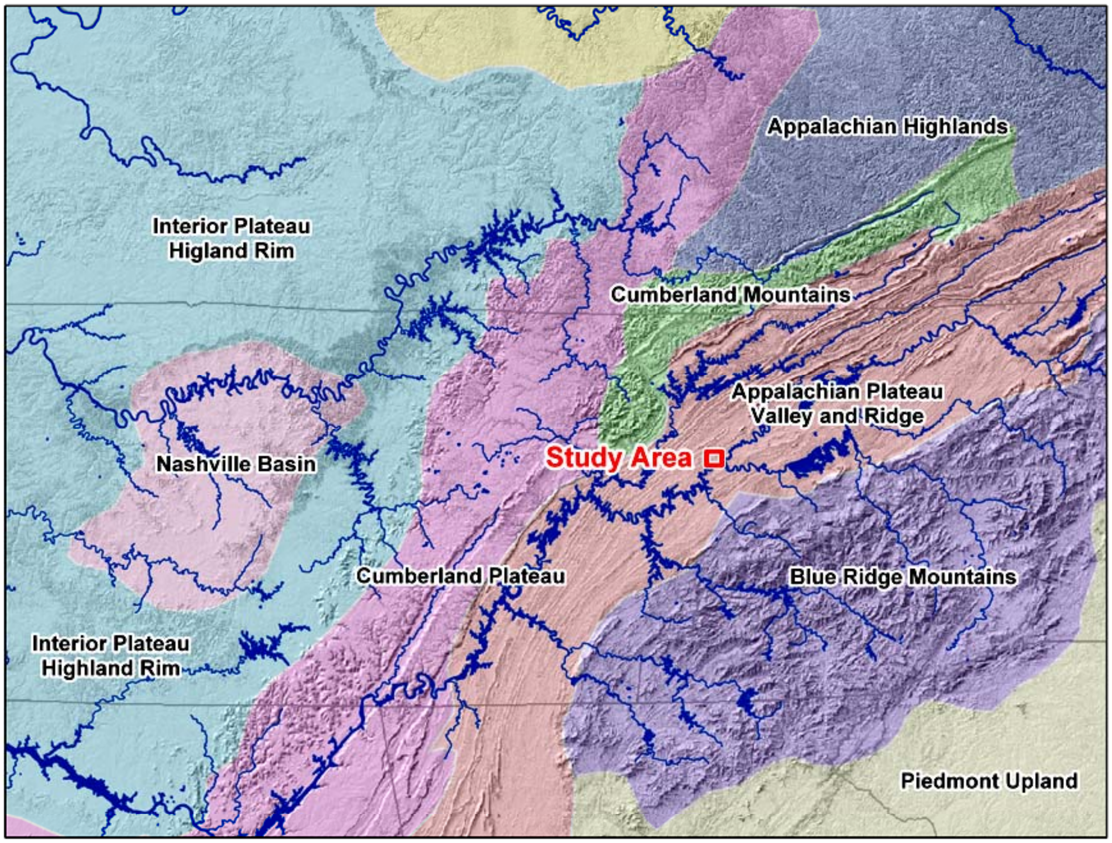

Figure 2.2. Physiography of the region around Knoxville. (USGS National Geologic Map Database.)

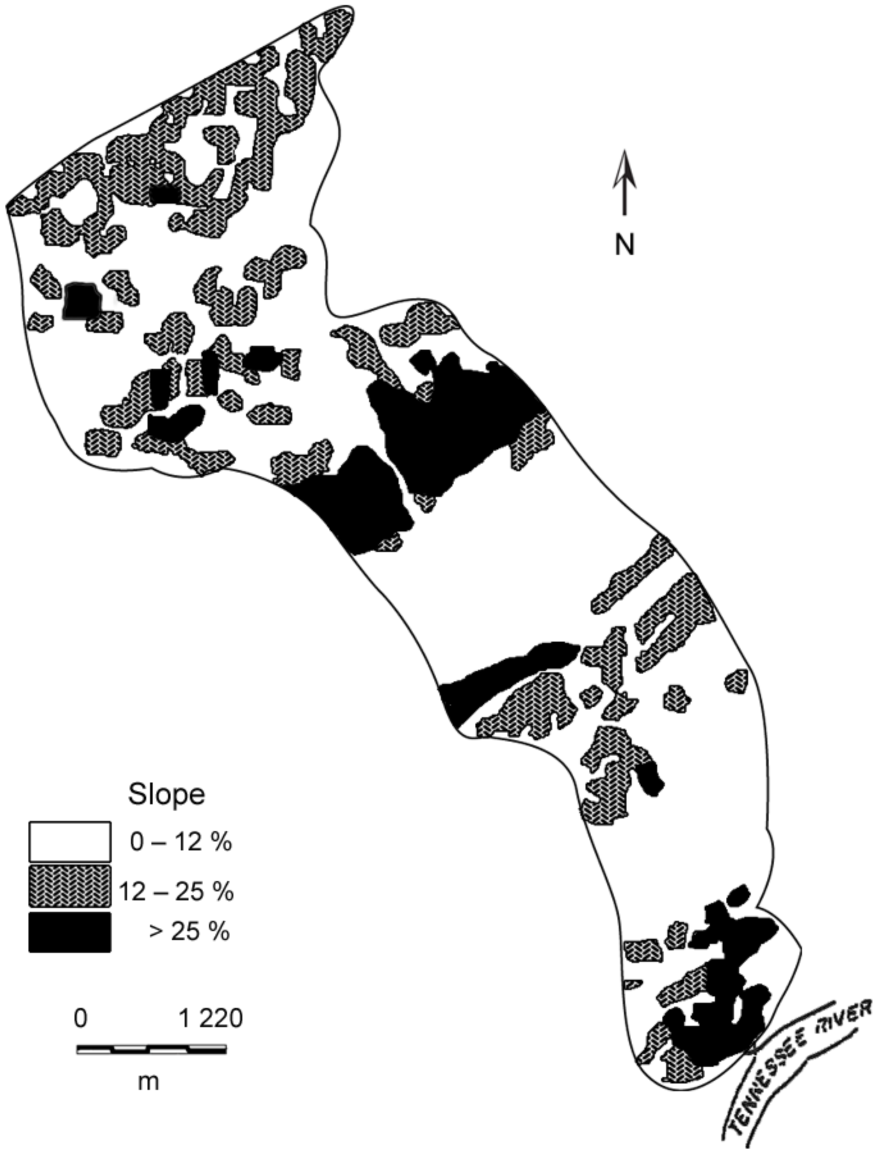

Figure 2.3. Slope in the drainage basin of Second Creek.
(Adapted from Kung, 1980.)

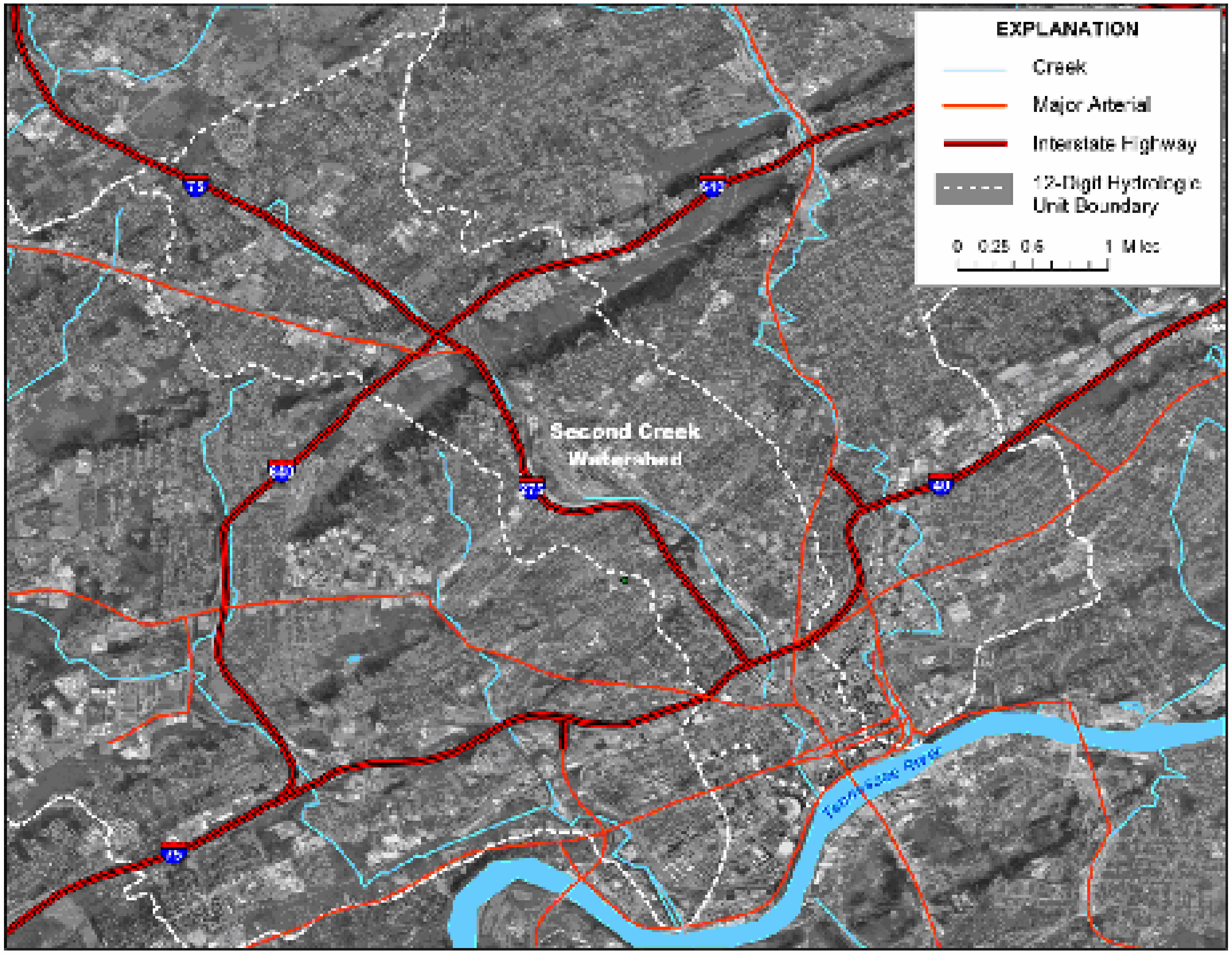

Figure 2.4. The drainage basin of Second Creek. Sharp Ridge, which is forested, is clearly visible in this view. All of Second Creek lies within the City of Knoxville. 1 mile = 0.6 km. (USGS Digital Ortho Quad).

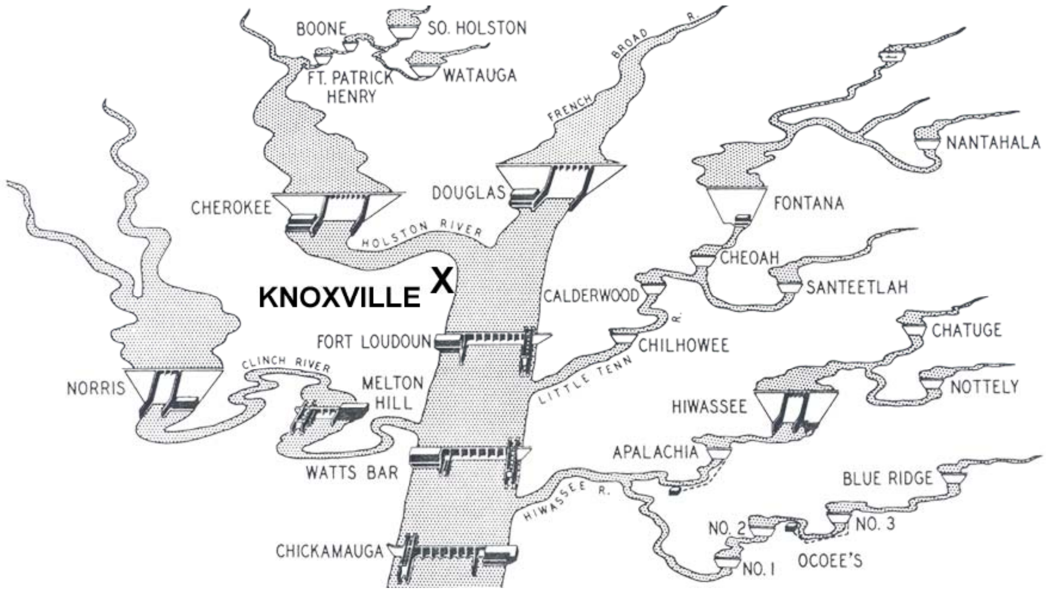

Figure 2.5. Reservoirs on the Tennessee River and its tributaries. A small part of Knoxville lies across the Tennessee River from the "X" shown in this schematic. (Adapted from TVA, 1963.)

GEOLOGY

The northeast-southwest trending ridges and valleys in the Knoxville area were created by folding and thrust faulting of early Paleozoic sedimentary strata during the late Paleozoic Alleghanian Orogeny (Henry and Mossa, 1995). In the drainage basin of Second Creek, these deformed strata are composed primarily of carbonate rocks, both limestone and dolostone, with subordinate amounts of shale, siltstone, and sandstone (Cattermole, 1958 and 1966). Subsequent weathering and erosion have resulted in valleys where less resistant rocks, typically limestones and thin-bedded calcareous shales, are located; and ridges where more resistant rock types occur. Sinkholes and cavern development occur in the carbonate rocks, especially the Holston Formation and the more soluble units of the Knox Group (Moore, 1973). Bedrock is mantled by sand, silt, and clay regolith in most places. Consequently, exposures of bedrock in the drainage basin are rare, typically occurring only in road cuts and in the channel of Second Creek.

Geologic maps of the study area, contained within the area covered by the Knoxville and Fountain City Quadrangles (Cattermole, 1958 and 1966), show the sub-parallel bands created by the northeast-southwest striking Cambrian and Ordovician rock units (Figure 2.6). Second Creek flows essentially perpendicular to the direction of strike of the rocks. A geologic cross-section along the trend of the creek (Figure 2.7) reveals how thrust faults and eroded folds in the strata have caused the same rock units to appear at several different locations along the course of the stream. The perennial portion of Second Creek, even though it is only 8.4 km (5.3 mi) long, crosses many of the same rock units three times. It crosses one unit, the Chepultepec Dolomite, four times between stream headwaters and the outlet of the stream at Fort Loudoun Lake.

SOILS

Knox County soils were mapped and described in 1942 (SCS, 1955). A new survey of Knox County soils is underway, and preliminary maps for the parts of the county containing Second Creek are available (Hargrove, 2003).

Most soils in the drainage basin of Second Creek are silt loams or silty clay loams, with minor amounts of loam, clay loam, sandy loam, and cherty silt loam (SCS, 1955). Soil depths range from 0 to more than 1.8 m (6 ft) (Figure 2.8). Permeability of the soil near the surface is generally rated as moderate to moderately rapid, while subsoil permeability is moderately slow. Hydrologic ratings for most soils in the basin are B and C (SCS 1955). Figure 2.9 shows the spatial distribution of soil permeability in the drainage basin of Second Creek.

The SCS (1955) points out that accelerated erosion caused losses of the uppermost layers of what used to be silt loams and loams and left silty clay loam and clay loam soils in their place. It also notes that construction activities were responsible for creating areas of severely disturbed land, labeled "made land," in the survey. This disturbed land is mostly located along the lower portion of Second Creek and in the former Coster railroad yard

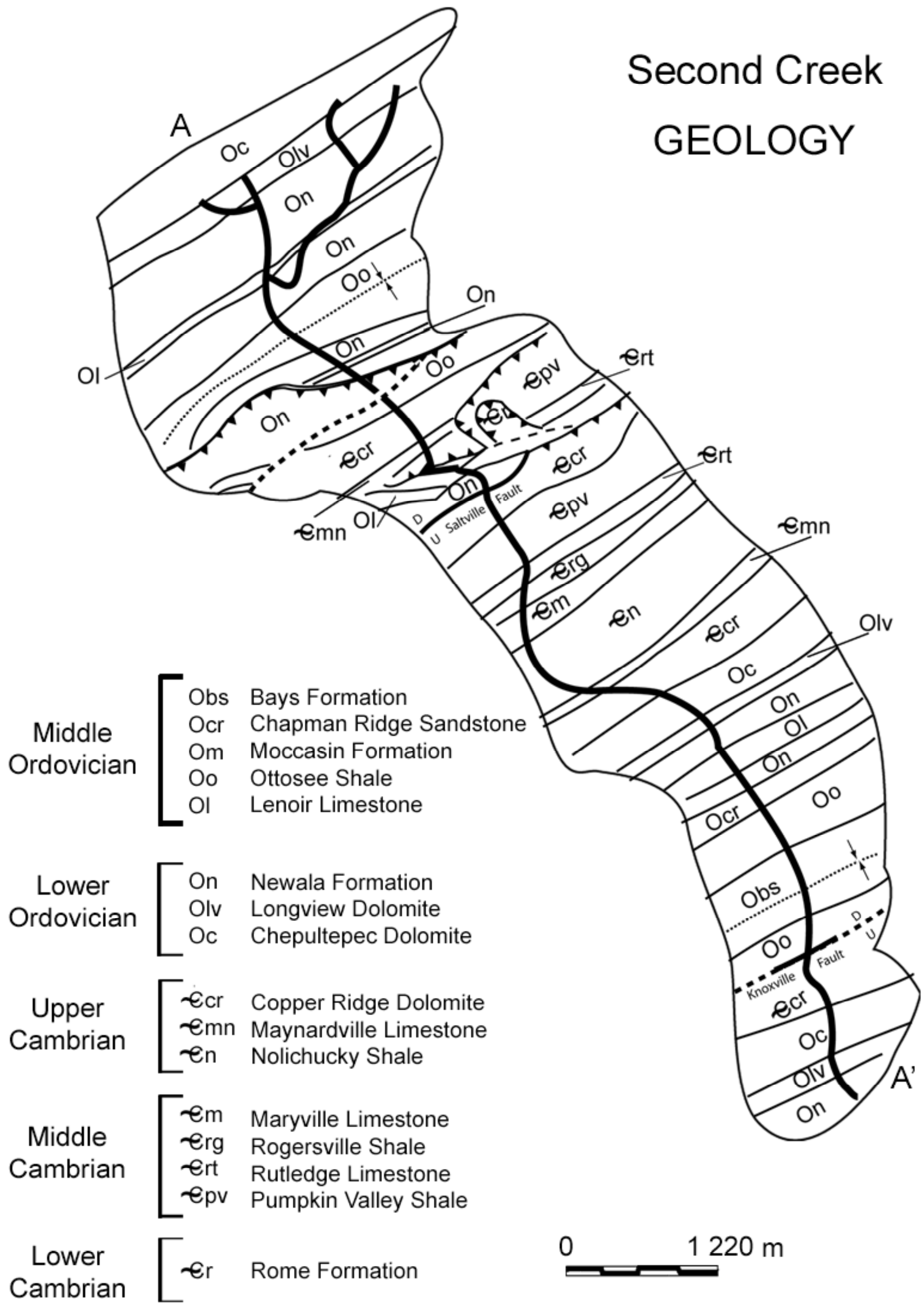

Figure 2.6. Geology of the drainage basin of Second Creek. (Adapted from Kung, 1980.)

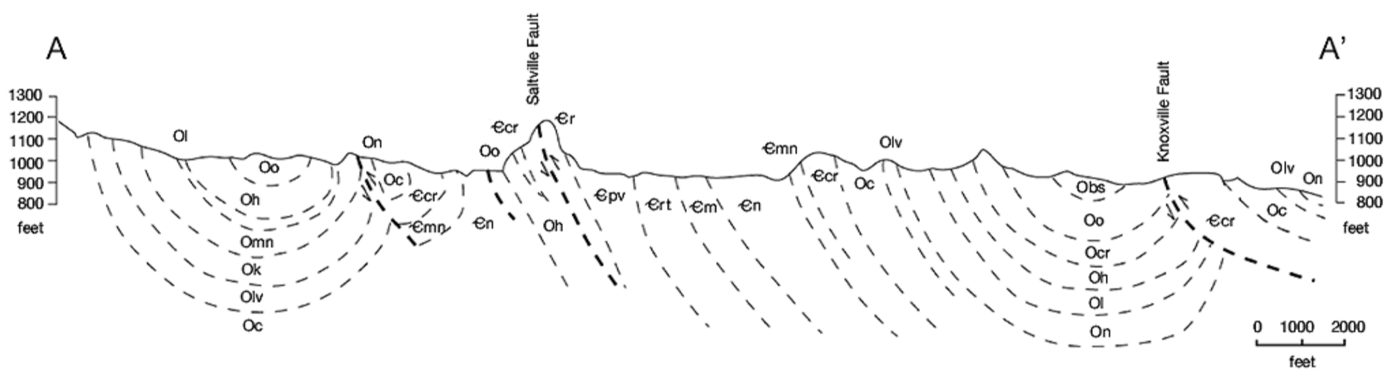

Figure 2.7. Geologic cross-section along the trend of Second Creek. Scales are shown in feet, as they appeared on the original map (1 meter = 3.28 ft).
(Adapted from Cattermole, 1958 and 1966).

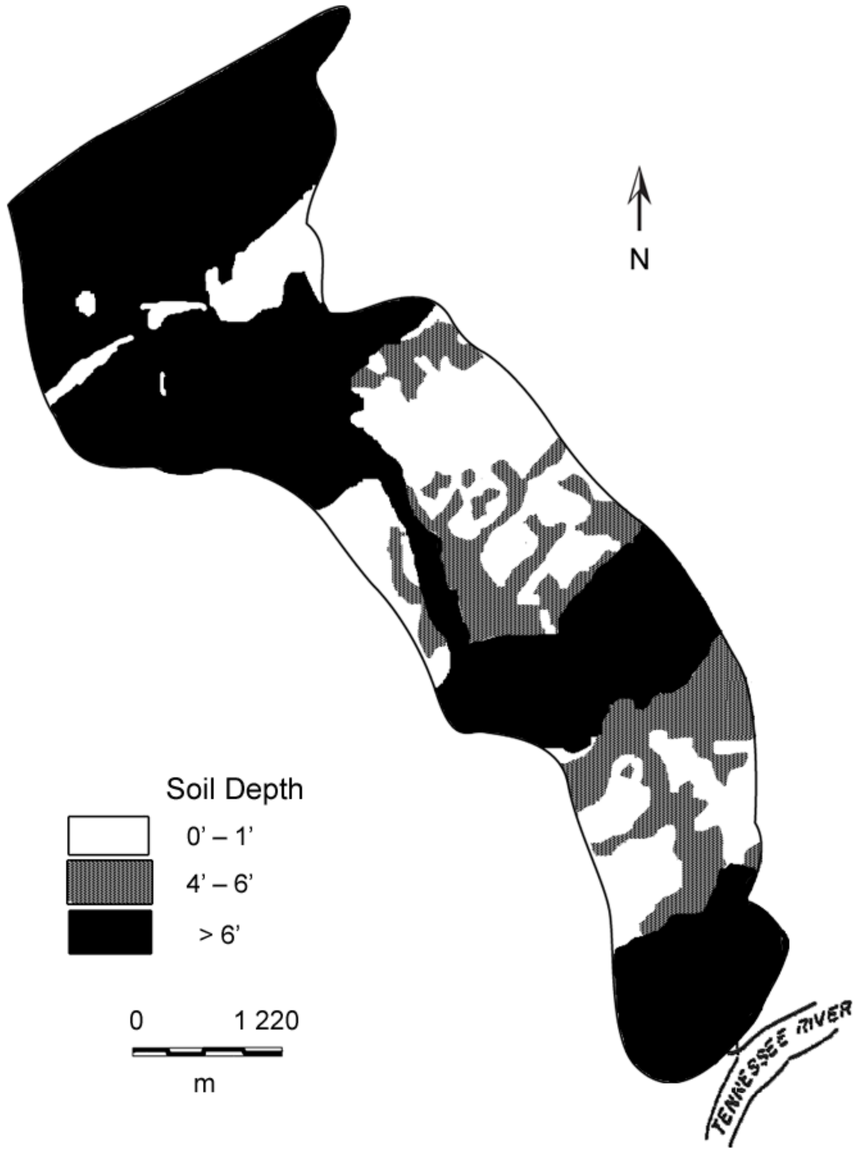

Figure 2.8. Soil depth in the drainage basin of Second Creek. 1 foot = 0.3048 m. (Adapted from Kung, 1980.)

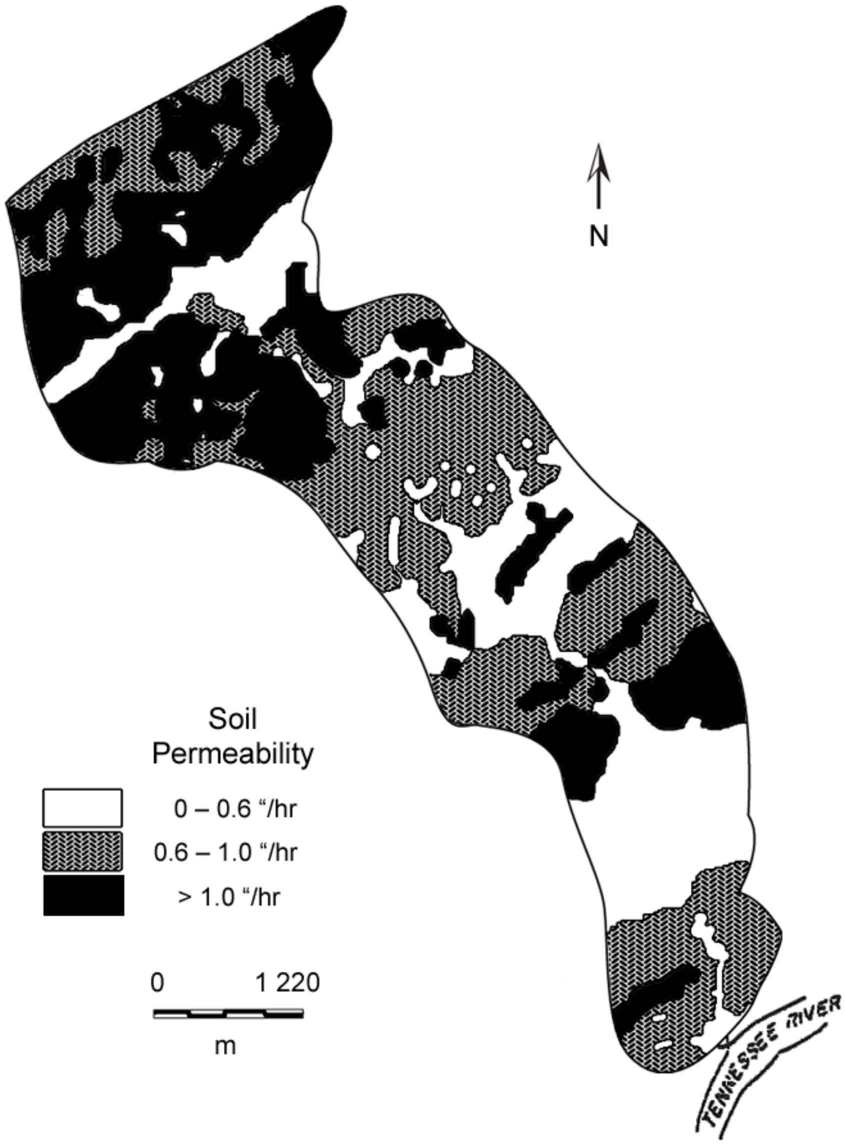

Figure 2.9. Soil permeability in the drainage basin of Second Creek. 1 inch = 2.54 mm. (Adapted from Kung, 1980.)

area (Figure 2.10). Because considerable land in the upper part of the drainage basin (northwest of Sharp Ridge) was only lightly urbanized in the late 1930s, but is now almost entirely urbanized, the amount of "made land" along the upper portion of Second Creek is now more extensive than it was when the cited soil survey map was created. It is somewhat difficult to directly compare older and newer maps, as categories of land classification on the newer maps no longer include "made land", but rather include the categories "urban land" and "Urban land-Udorthents complex."

WEATHER AND CLIMATE

Knoxville, at 36° N latitude, has a humid subtropical climate, with warm summers and cool winters. The average annual temperature is 14.2° C (57.6° F). Average monthly temperatures range from 2.2° C (36.0° F) in January to 24.8° C (76.6° F) in July (Wood, 1996).

Mean annual precipitation in Knoxville is 1207.3 mm (47.53 in), based on 1961 to 1990 data (Wood, 1996). Precipitation is distributed fairly evenly throughout the year, with the greatest amount usually occurring in winter and another lesser peak in late spring and summer. Autumn is usually the driest part of the year (Wood, 1996). Approximately 305 mm (12 in) falls as snow during the winter in storms that usually leave less than 102 mm (4 in) on the ground. The ground is typically bare of snow during most of the winter, as melting is often complete within a week after snowfall (Wood, 1996). The amount and timing of precipitation in Knoxville are sufficient to support numerous perennial streams (Figure 2.11), including Second Creek, the focus of this study.

Annual precipitation was slightly greater during earlier decades (1935 – 1974), when the mean was 1218.7 mm (47.98 in) (U.S. Weather Bureau, as cited in TVA, 1984). Table 2.1 lists mean monthly precipitation and the wettest months in recent decades in Knoxville, and Table 2.2 gives the wettest months for the entire period of record.

Wetter and drier years often occur in groups, as shown in Figure 2.12. Wetter than normal conditions occurred in 1996 through 1999, although the amount of precipitation above the mean was modest in comparison with the wet years in the early 1970s. Wet periods are important to this study because they promote higher volumes of rainfall runoff, higher energy flows, and more opportunities for sediment movement.

Infiltration rates typically decline during storms as the length of time with rainfall increases, and runoff increases when less water infiltrates. Therefore, intense rainfall occurring near the end of a long storm is likely to produce more runoff than the same rainfall early in the storm. The amount of storm runoff controls sediment dynamics, a major factor in shaping the channel of Second Creek.

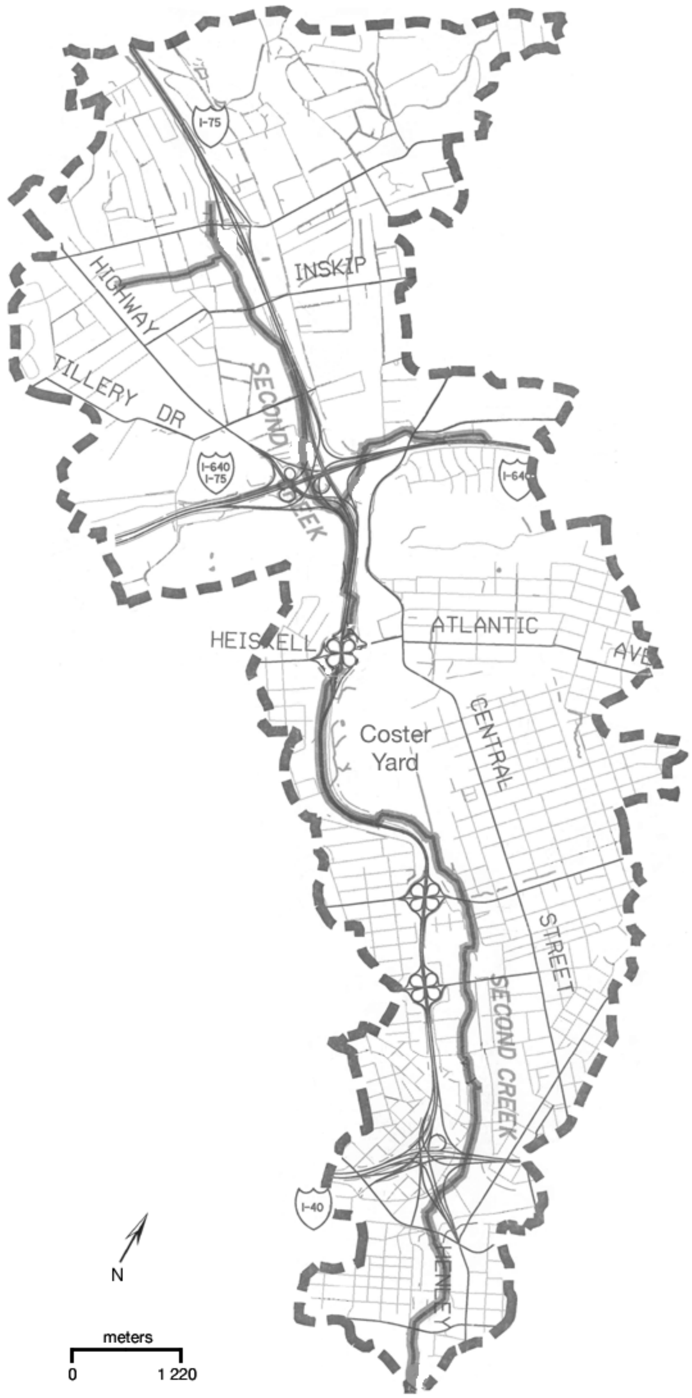

Figure 2.10. Location of Coster Yard and the lower part of Second Creek. (Base map from KGIS, Knoxville, TN.)

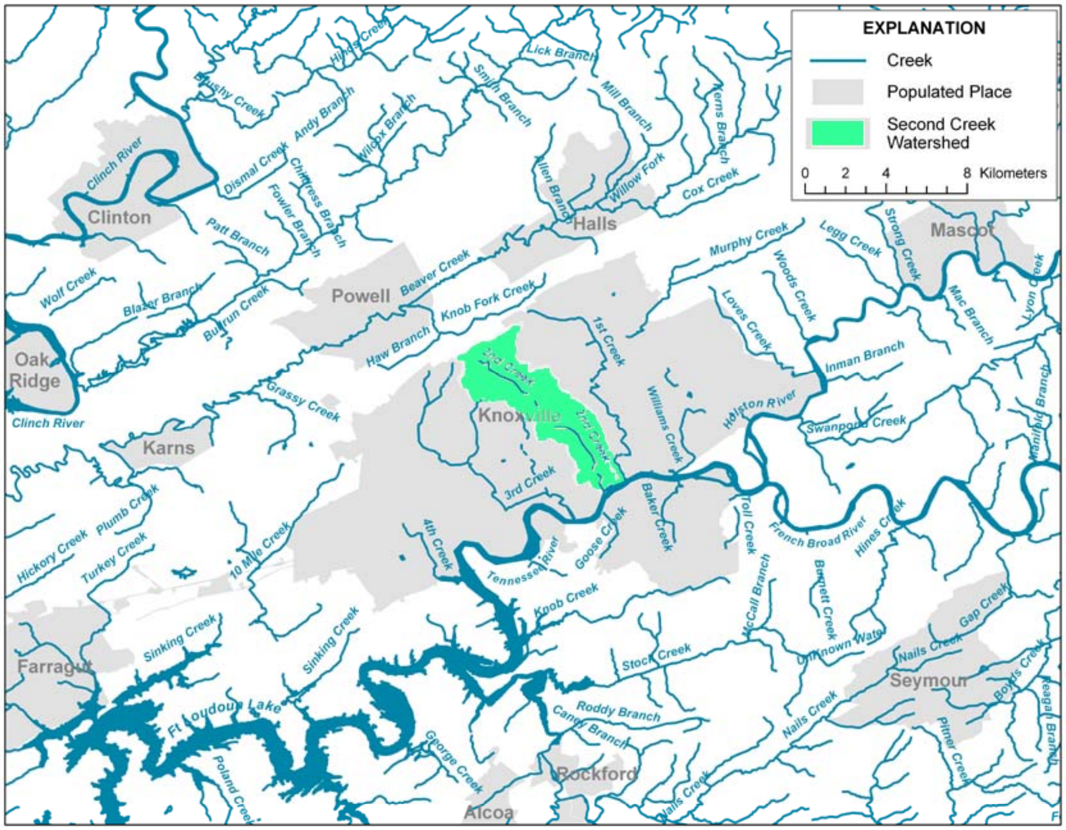

Figure 2.11. Streams in and near Knoxville, Tennessee. (EPA River Reach File 3)

Table 2.1. Precipitation means and extremes in Knoxville, 1941 to 1992[1].

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Av. Precip. (mm)	106	103	129	94	105	101	119	80	78	72	95	115
Max. Precip.	298	238	265	183	279	209	256	226	233	169	263	295
Year	1954	1944	1975	1970	1974	1989	1967	1942	1989	1949	1948	1961
Max. in 24 hrs.	99	87	123	93	86	91	119	83	129	62	103	124
Year	1946	1991	1973	1977	1984	1972	1942	1959	1944	1961	1948	1969

[1] Data from Wood, 1996.

Table 2.2. Wettest months in Knoxville, Tennessee.[1]

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Precip. (mm)	431	318	339	440	279	300	334	288	233	242	263	313
Year	1882	1873	1917	1874	1974	1928	1917	1920	1989	1925	1948	1901

[1] Data from NCDC, 2003.

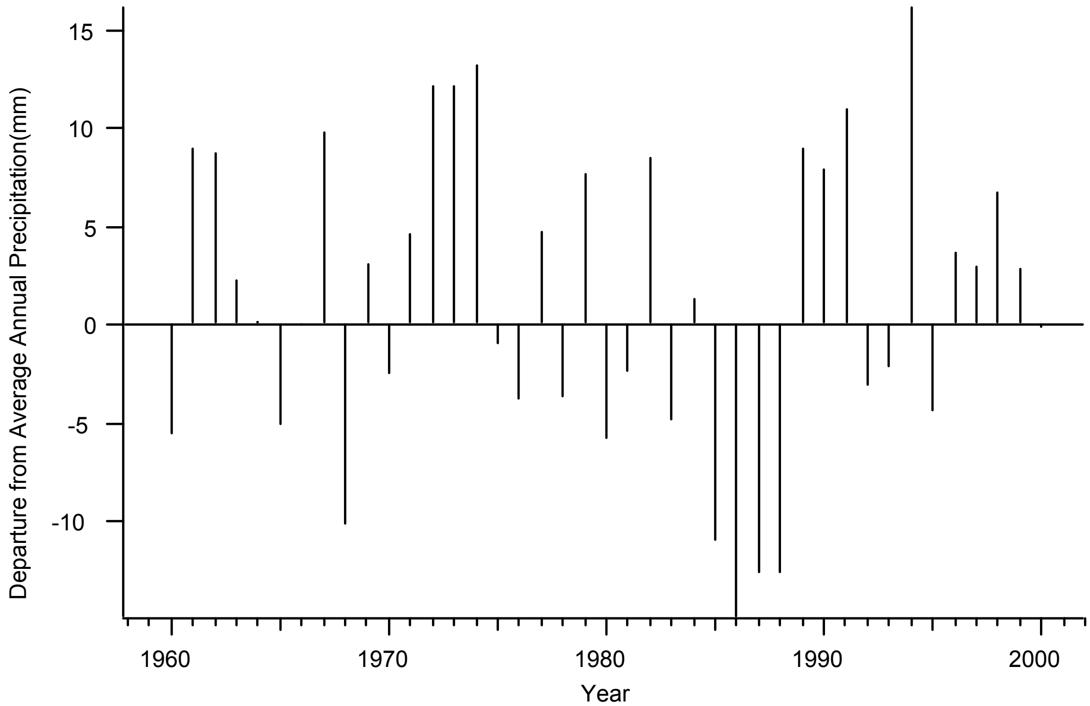

Figure 2.12 Wetter and drier years in Knoxville. (Data from the National Climatic Data Center, NCDC, 2003).

During urbanization, the amount of impervious land surface increases, and runoff increases in response. If an area usually experiences storms in which the most intense rainfall occurs early in the storms, increases in runoff from newly impervious land are greater than if the most intense rainfall occurs late in the storms. The timing of intense rainfall makes little difference during winter and early spring in Knoxville, times when the soil is usually saturated. The amount of increase in runoff in places with increasing amounts of impervious cover, therefore, is partly controlled by the timing of the most intense rainfall in each storm. The amount of impervious surface in the basin of Second Creek has increased in recent years (City of Knoxville, 1993 and 2000 – 2001). Most storms in Knoxville in 1997 – 1998 did not have intense rainfall early in the storms (see Appendix A). If these data are typical of longer spans of time, increases in runoff in the urbanizing areas of Knoxville have not been as great as they would have been had most storms been characterized by intense rainfall early in the storms.

VEGETATION

Braun (1950) described the natural vegetation in the Knoxville area as Oak-Chestnut forest, but noted that little of the primary forest remained at that time. Zon (1924) gave a more detailed description of the natural vegetation, noting that the area fell within the chestnut-chestnut oak-yellow poplar belt of the Eastern forest hardwoods and mixed hardwoods and pines vegetation region. He listed the dominant tree species as "...chestnut, chestnut oak, white, red, and post oaks, hickory, ash, elm, maple, gum, beech, holly, white poplar, yellow poplar, and yellow pine" (Zon, 1924). Chestnut trees, once plentiful, were essentially gone from the region by 1940, following the rapid spread of a chestnut blight disease (Starr and Taggart, 1995). Some native tree species can still be found in Knoxville, but, as I have noticed during my travels within the city, much of the present-day vegetation consists of plants imported for landscaping purposes from a wide variety of source areas or a mix of native and exotic urban pioneer species.

HISTORY OF LAND USE IN THE BASIN OF SECOND CREEK

Knoxville was settled by Europeans in 1791. The initial settlement was located near the confluence of the Tennessee River and First Creek, roughly 900 m east of Second Creek.

The population of Knoxville grew from 387 persons in 1800 to 1,115 in 1820 (Deaderick, 1976). By the mid-1820s, Second Creek formed the western boundary of the hamlet of Knoxville. In 1826, East Tennessee College, later to become the University of Tennessee, moved from Knoxville to a hill on the west side of Second Creek in what was then the open countryside (EERC, 2001). One of the attractions of the new college location was the water provided by Second Creek and "two or three springs" adjacent to the hill (EERC, 2001). These springs are not in evidence at this time, but at least one of them was still there when a person who was described as "older" in 1957 was a child. In talking of her childhood in Knoxville, she remembered "…a large spring at the foot of Cumberland Street just beyond Second Creek" that was used to supply water to the ice factory (Knoxville News-Sentinel, 1957). Second Creek now flows underground in a large double concrete box culvert at this location.

Much of the forest in the Knoxville area had been cut by the mid 1800s (or earlier), as shown in drawings and photographs of the area at that time. In 1850, the population of the town was 2,076 (U.S. Bureau of the Census, 1850). A map of the city drawn five years later shows most of the town still located east of Second Creek, though it extended north to Gray Cemetery (Figure 2.13). Exceptions were the college and an urban area of about 12 blocks located north of Clinch Street. Both these features were west of Second Creek. Several railroads ran through the area, and tracks ran adjacent to and crossed over Second Creek in several places (Plan of the City, 1855).

The census of 1860 gives the population of Knoxville as 5,300 persons. A photograph (Figure 2.14) taken several years later, during the Civil War, reveals an almost treeless landscape in the vicinity of Second Creek. Not visible in the photograph are the trenches and earthen walls on hills west of Second Creek and College Hill. The western extent of the trenches was the place now occupied by Melrose Hall on the University of Tennessee campus. The trenches were defenses created by Union soldiers during the Civil War (Burnside, 1865). On November 20th, 1863, the lower parts of both First and Second Creeks were dammed by the Union forces to create barriers intended to impede the progress of Confederate soldiers (Burnside, 1865). There is no published mention of when free flow was restored to the streams.

After the Civil War the population of Knoxville continued to grow (Table 2.3), as did the size of the urban area. A drawing of the City in 1886 shows the lower third of the drainage basin of Second Creek was mostly urban in character at that time (Figure 2.15). Various industries, including a cotton mill, marble works, iron company, button factory, bucket factory, and an ice company were located adjacent to Second Creek (Map of Knoxville, 1886).

By the late 1930s, almost all of the drainage basin of Second Creek downstream from Sharp Ridge was developed. Land on the upstream side (northwest) of the ridge was primarily used for agriculture, although there were a few residential areas (Figure 2.16) (SCS, 1939). Less than 15 years later (in 1953), the amount of land in the upper basin used for agriculture had greatly diminished. The predominant land use had become residential, with some churches, a few businesses, some agricultural land, and many more roads present (USGS, 1953).

A city freeway was built right along the lower course of Second Creek in the 1960s. This highway became interstate highway (I-275/75) in the early 1970s, and the construction of Interstate Highway 640 followed soon thereafter. The latter is a roughly semicircular bypass around the northern part of Knoxville (see Figure 2.4). I-640 crosses the drainage

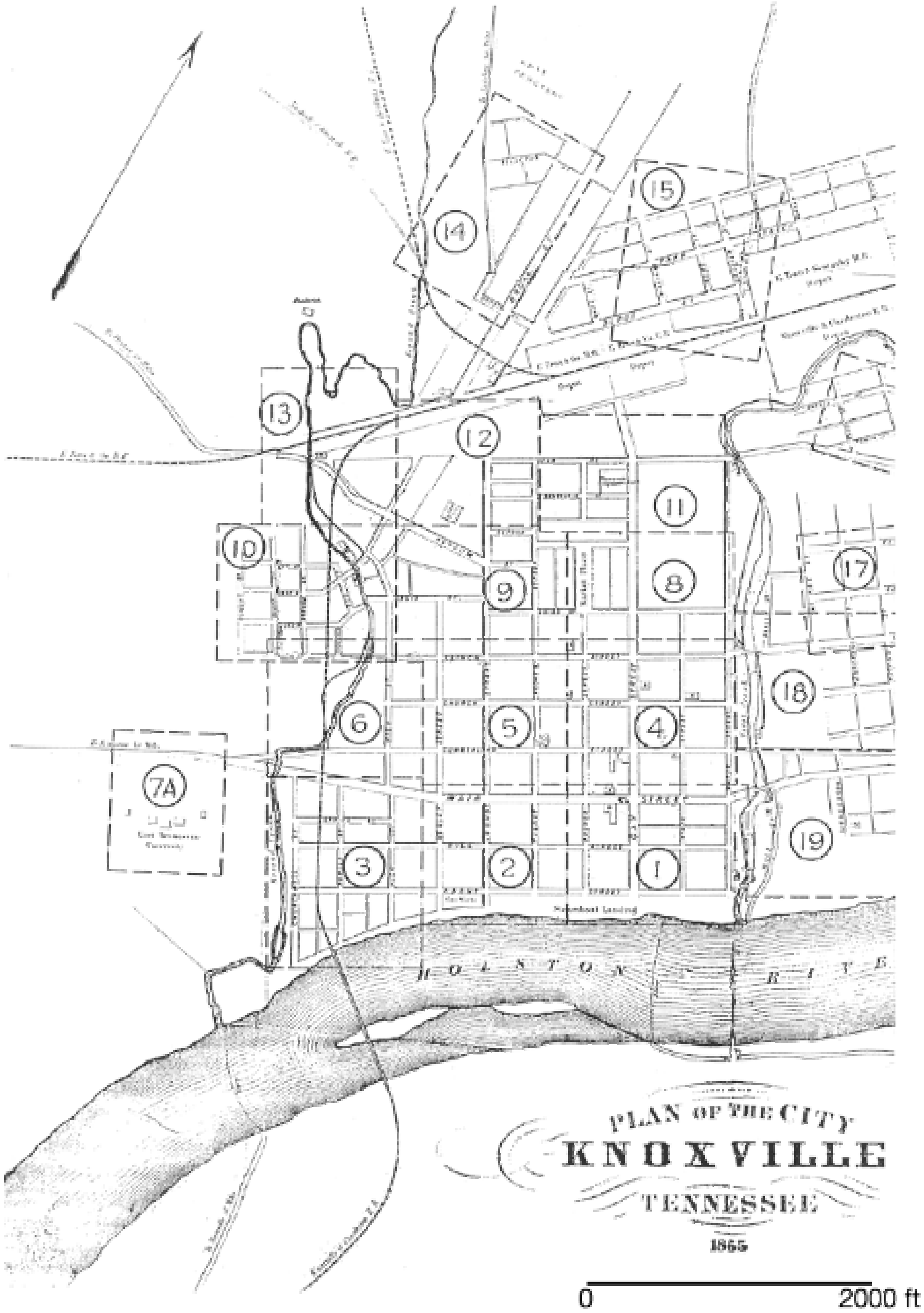

Figure 2.13. Map of Knoxville in 1855. Second Creek forms much of the southwestern boundary of the town at this time. (East Tennessee Historical Society, Knoxville, TN.)

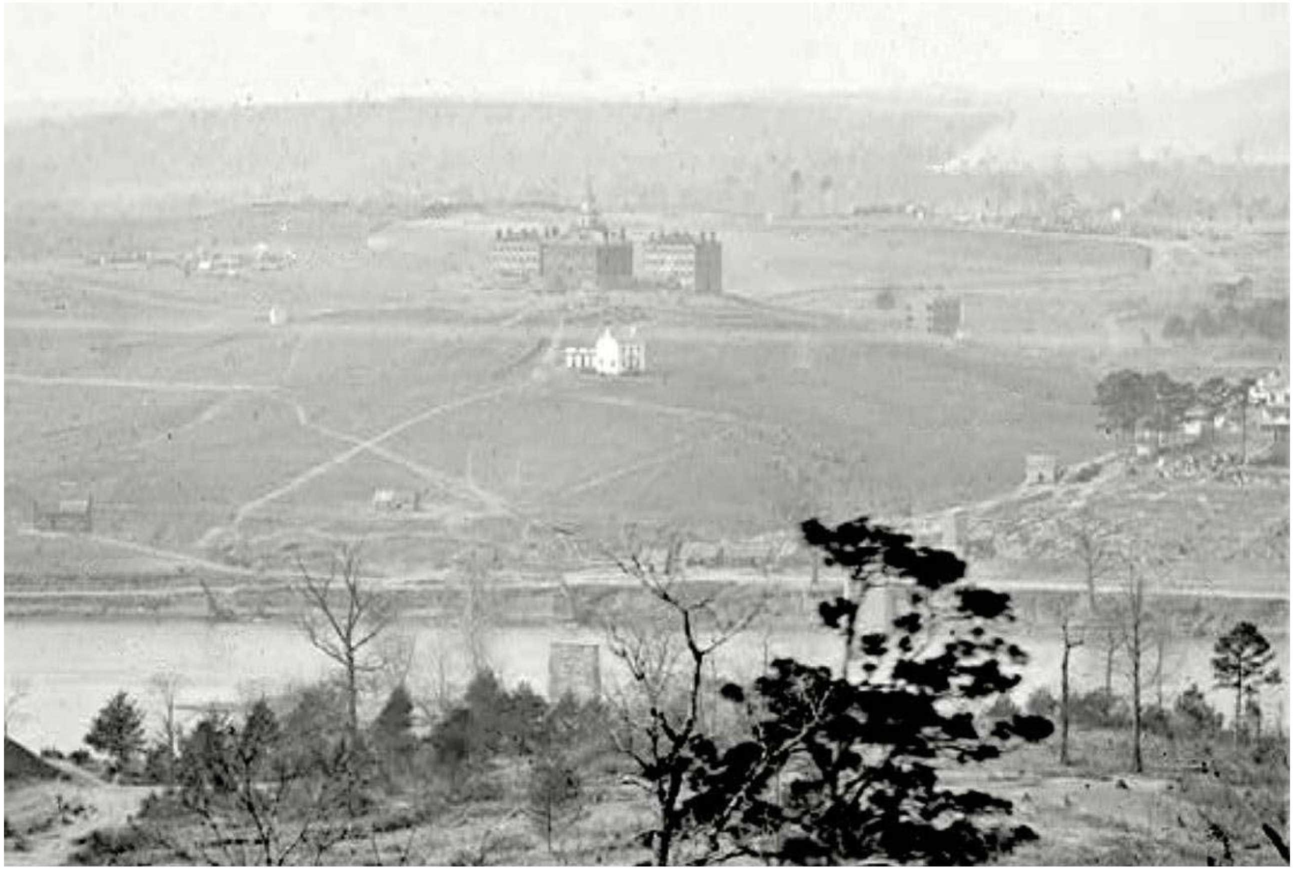

Figure 2.14. Photograph of College Hill. This was the view looking northward across the Tennessee River in 1862. Second Creek is near the right edge of the picture, the large buildings are on top of College Hill. Most of Knoxville lies beyond the right side of the picture. Note the lack of trees in the area. (East Tennessee Historical Society, Knoxville, TN)

Table 2.3. Population of Knoxville, 1870 to 1940.[1]

Year	Population
1870	8,682
1880	9,693
1890	22,535
1900	32,637
1910	36,346
1920	77,818
1930	105,802
1940	111,580

[1] Data from U.S. Bureau of the Census

Figure 2.15. Oblique view of Knoxville in 1886. Various industries, including a cotton mill, marble works, iron company, button factory, bucket factory, and an ice company were located adjacent to Second Creek (Map of Knoxville, 1886).

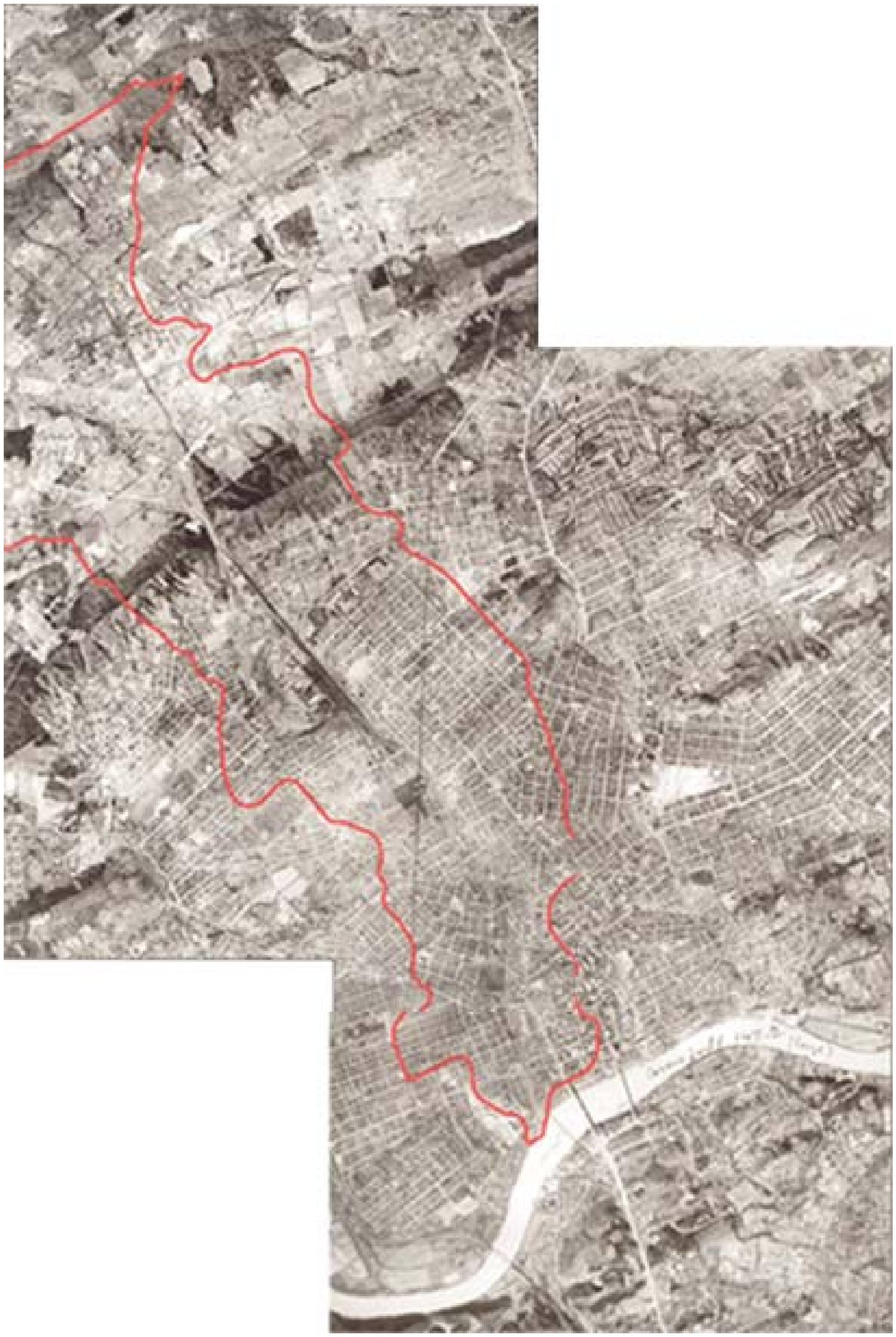

Figure 2.16. Aerial photographs of Knoxville in 1939. Unfortunately, photographs covering the northwestern side of the drainage basin were not available. (SCS 1939)

basin and I-75 north of Sharp Ridge. A major interchange between the two interstate highways and Clinton Highway was built northwest (upstream) of the gap in Sharp Ridge, and Second Creek re-routed to flow underground beneath them. The course of the creek was altered in several other places during and soon after interstate highway construction.

Land use in part of the lower drainage basin changed again in the early 1980s, due to the 1982 World's Fair. Knoxville bought 29 ha (72 ac), much of which had been a railroad yard, along the creek and began construction for the Fair in 1980 (Knoxville News-Sentinel Staff, 2002). The water of Second Creek was too polluted to supply water to a lake planned for the Fair site, so a long box culvert was built to convey the creek under that part of the future fairgrounds and under Cumberland Avenue (TVA, 1984) (Figures 2.17 and 2.18). Farther downstream, one of the pavilions for the Fair was built over Second Creek, and a dock was constructed in Fort Loudoun Lake at the mouth of the creek.

Land use in the drainage basin continued to change during the 1990s even though most land in the basin had been developed for at least four decades. The percentage of land used for single-family residences declined, and the amount of land used for roads and highways increased (City of Knoxville, 1993 and 2000 – 2001). As a result of these and other changes in land use, the amount of impervious land surface increased from 26% in 1980 (Kung, 1980) to 41% early in the 1990s (City of Knoxville, 1993) to almost 53% by the end of the decade (City of Knoxville, 2000 – 2001). Some of the recent increase in impervious surface area may be an artifact of changing methods used for the calculation of land use types, as the Metropolitan Planning Commission switched to using digital imagery and Geographic Information System (GIS) techniques to update land use data.

Major construction projects within the drainage basin of Second Creek continued into the twenty-first century. In a project that began in 1999, the City of Knoxville built a convention center at the former World's Fair site. The project included extensive landscaping over much of the old Fair grounds. The new convention center opened in July 2002. Farther upstream along Second Creek, buildings were demolished and polluted debris and soil removed from the site of the old Southern Railway Coster Shop in 2001 and early 2002 (City of Knoxville, 2000 – 2001; Barker, 2003). The area was a state Superfund (Comprehensive Environmental Response, Compensation and Liability Act, or CERCLA) site because of the metals and other hazardous waste in the soil at this former railroad maintenance facility. Soils mixed with debris from Coster Yard that were moved to other locations in Knox County, were later found to be contaminated with arsenic, lead, polychlorinated biphenyls (PCBs), and diesel fuel (Barker, 2003). The cleaned-up Coster Yard area is now being promoted as the I-275 Business Park by the city as a "Brownfield Redevelopment" project (City of Knoxville, 2003).Second Creek is on the EPA's 303(d) list of impaired streams because of excess metals, nutrients, pathogens, and siltation (USEPA, 2003). Because of the pathogens (as indicated by fecal coliform bacteria), there is a water contact advisory in effect for Second Creek.

Figure 2.17. Second Creek upstream of Cumberland Avenue in 1979. This part of the creek now flows underground in a large box culvert. *Top*: looking upstream. *Bottom*: looking downstream. (Photographs from TVA Archives, Knoxville, TN.)

Figure 2.18. Construction in the channel of Second Creek upstream of Cumberland Avenue. These photographs were taken in 1980. (Photographs from TVA Archives, Knoxville, TN.)

Extraordinary efforts have been made by many concerned people to improve water quality and conditions in general in Second Creek and other local streams. Some of this interest has undoubtedly been generated by National Pollutant Discharge Elimination System (NPDES) requirements. The Water Quality Forum of Knox County is an organization whose goals include educating the public about streams, collecting data on the status of local streams, and planning and carrying out stream cleanup and restoration projects. The following are partners in the Water Quality Forum:

1) The Tennessee Valley Authority (TVA)
2) Ijams Nature Center
3) Knox County Stormwater Department
4) University of Tennessee Knoxville Water Resources Research Center (UTK WRRC)
5) The Town of Farragut
6) Knoxville Geographic Information Systems Department (KGIS)
7) Knox County Soil Conservation District
8) Knoxville Stormwater Department

Others who are involved with local streams and often with the Water Quality Forum include professors and students from several different departments at the University of Tennessee, researchers from Oak Ridge National Laboratories, personnel from the Tennessee Department of Environment and Conservation (TDEC), the Knoxville Utility Board (KUB), and volunteers with the Community Action Committee's AmeriCorps. Second Creek was the focus of attention of a group called the Second Creek Task Force, a subgroup of the Water Quality Forum, for several years in the 1990s. The Task Force used portions of Second Creek to demonstrate how improvements can be made in urban streams in Knoxville.

CHANGES IN SECOND CREEK

During the changes in land use through the years in the drainage basin of Second Creek, the course of the stream was changed more in some places than in others by human actions. Figure 2.19 shows the location of the lower part of Second Creek in 1855 superimposed on a modern map. This part of the creek is considerably shorter now than it was. In 1855, the length of the creek from its mouth to Fifth Avenue was about 2940 m, but now it is approximately 1980 m. Much of the difference in length occurred from changes in the course of the creek in two locations: the area where the creek enters the Tennessee River, and under the present-day Henley Street/I-275/I-40 interchange.

In earlier times, Second Creek made a sharp bend and reached the present-day location of Neyland Stadium before it made another right-angle turn and joined the Tennessee River. The location of this outlet was approximately 195 m downstream from the present mouth of the creek. The creek lost about 260 m in length when it was re-routed to the new outlet, an event that occurred sometime between the years of 1948 and 1951, according to maps of those dates. Much more length, about 630 m, was lost when the meanders

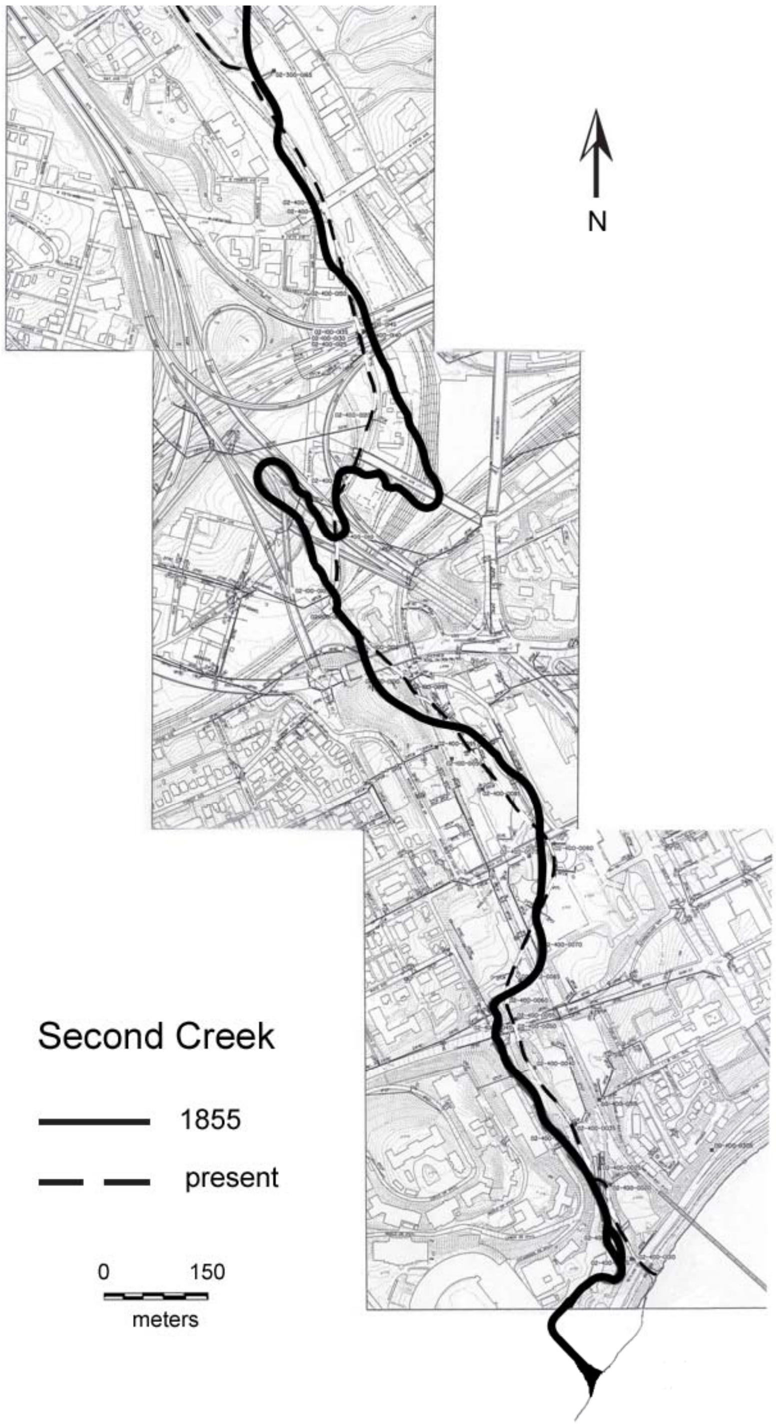

Figure 2.19. Old and new courses of the lower part of Second Creek. (Base map from City of Knoxville Stormwater Engineering, Knoxville, TN.)

upstream of Grand Avenue and the east-west railroad tracks were straightened. This occurred between 1886 and 1895, as shown by maps of those dates.

Farther upstream, most of the course of Second Creek is in approximately the same place it was in 1942, in spite of all the interstate highway construction close to the creek. An exception to this occurred near Merchant Drive, where intermittently flowing headwaters used to join the perennial part of the creek. Before I-75 was built, a channel went through the place now occupied by the interchange between Merchant Drive and I-75. The creek was re-routed, and now goes northwest in a ditch, joins other tributary channels, passes under the interstate in a large concrete box culvert north of Merchant Drive, bends back towards the southeast, and then goes beneath an extensive parking lot in a large corrugated metal culvert. This change in course added approximately 122 m to the length of the stream.

Between 1964 and 1966, the City of Knoxville widened and deepened the channel of Second Creek "...where needed from a point about 800 feet [244 m] north of Western Avenue to a point about 300 feet [91 m] south of Woodland Avenue" (Knoxville News-Sentinel, 1966). The article explained that there had been flooding problems near Van Street and Baxter Avenue, where the channel was "...narrow and about three feet [0.9 m] deep..." before they altered it. They made it 6 – 8 feet (1.8 – 2.4 m) deep, and wider than it had been. A profile of the creek made in 1958 (Figure 2.20) shows the creek in that area had a lower slope than areas upstream and downstream from it before the alterations were made (TVA, 1958).

In summary, the drainage basin of Second Creek has become increasing populated and urbanized since its initial settlement. The channel has been altered at different times to greater or lesser degrees over its entire length. Some alterations were intended, such as the redirection of the stream into concrete-lined channel segments. Others were unintentional, such as channel erosion due to increased stormwater runoff.

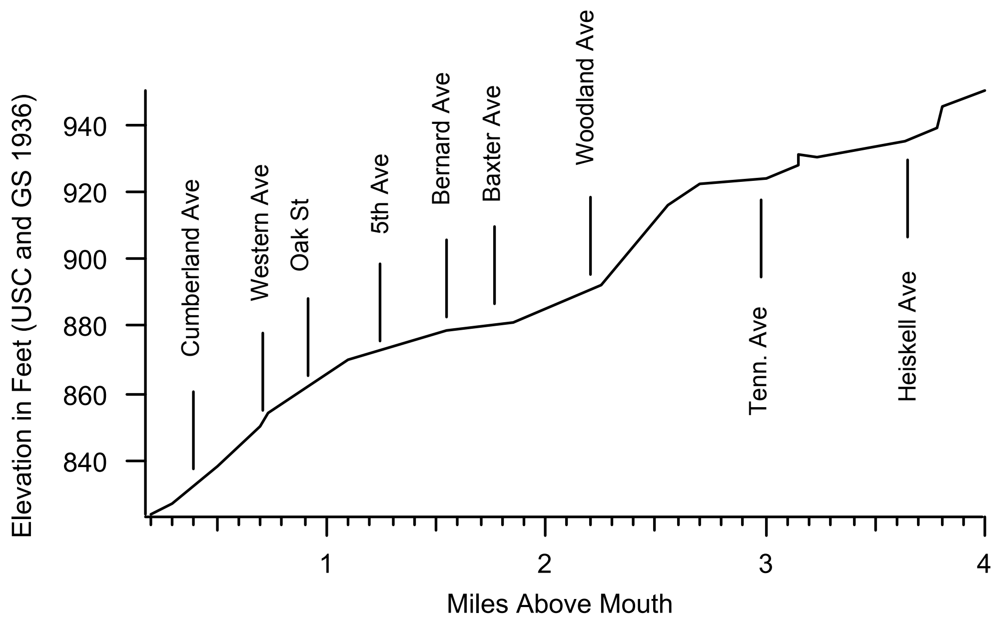

Figure 2.20. 1958 profile of Second Creek downstream from Sharp Ridge. Scales are shown in feet and miles, as they appeared on the original profile (1 meter = 3.28 ft and 1 km = 0.6 mi). (Adapted from TVA, 1958.)

CHAPTER 3

CHANNEL STATUS

INTRODUCTION

Rapid changes in stream channel shape and size may not be noticed or thought important if they occur in natural areas, but in urban areas, where streamside property is valuable and bridges are common, changes in stream channel configuration can result in hazardous conditions and property loss or damage. Bridge supports may be undermined and valuable riparian property eroded if rapid channel enlargement occurs. If contaminated sediment has accumulated in a channel, it may be eroded and spread downstream. Under other conditions, sediment may accumulate in channels, reducing their depth. Flooding often becomes more common in such places, and clearances below bridge decks may be inadequate during high water events.

Rills, gullies, and stream channels are carved by the energy of moving water as it flows downhill. They become deeper and wider as flow pathways converge towards lower places in the landscape. During periods of storm runoff, channels convey water that has not evaporated or soaked into the ground, along with whatever materials have become entrained in the flow. These drainage systems can become constricted if materials are deposited in them, but unlike manufactured gutters, natural channels have the capability of becoming deeper or wider in response to increased amounts of water or decreased amounts of sediment moving through the system (Figure 3.1).

Channels may become adjusted to a range of water discharges and sediment loads, and change size and shape only slightly and slowly over periods of time, a condition described as "quasi-equilibrium" (Leopold and Maddock, 1953; Wolman, 1955; Langbein and Leopold, 1964), or "graded" (Mackin, 1948). They may also change rapidly if significant changes in stream discharge or sediment load occur (Schumm, 1977; Robbins and Simon, 1983; Booth, 1990).

Stream channels in areas becoming urbanized typically go through a series of changes in response to changing conditions of the land in the drainage basins. Wolman (1967) described several distinct stages (Table 3.1) based primarily on data from the Middle Atlantic region of the United States. In the first stage, before major construction begins, the area to be developed often contains a mixture of agricultural and idle land. During this phase, sediment input to streams is generally low, and stream channels are relatively stable. The next phase occurs in response to construction activities. During this time, when vegetation is removed and the land surface disturbed, the amount of sediment delivered to stream channels increases dramatically unless effective measures are taken to prevent it. Aggradation results when more sediment is delivered to streams than they can carry, and the excess is deposited in the channels (Wolman and Schick 1967; Graf, 1975).

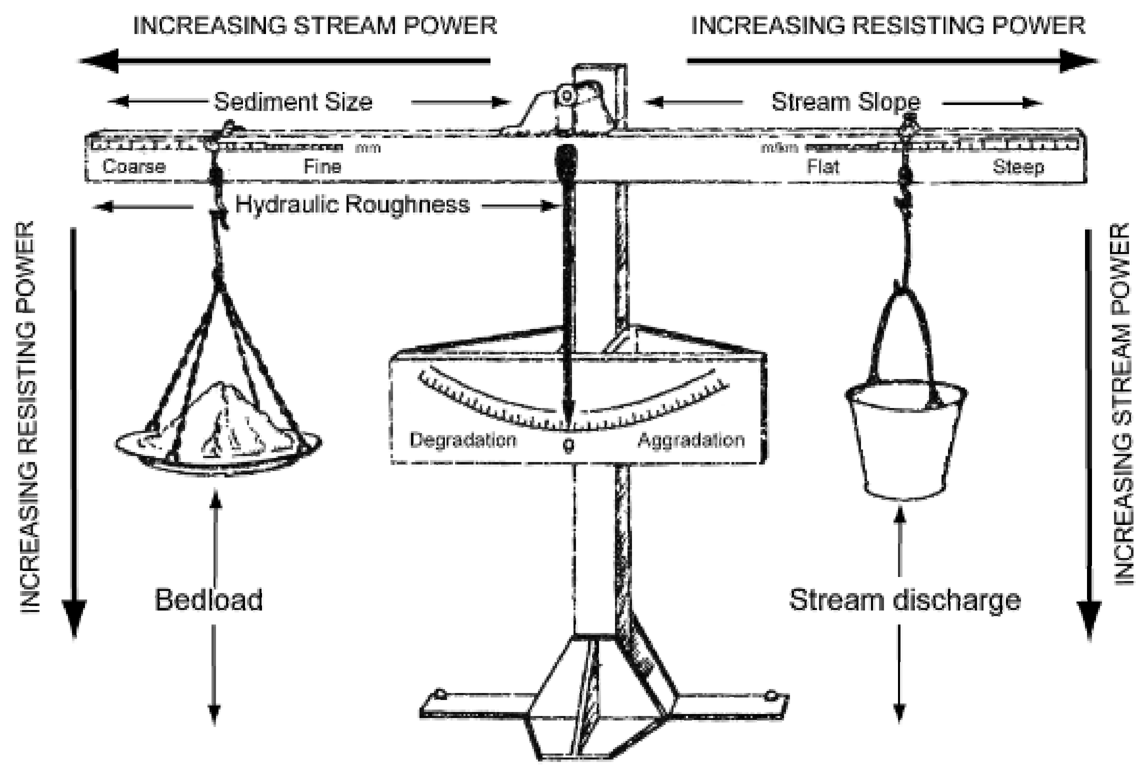

Figure 3.1. The stream balance. Stream channel aggradation or degradation may result from changes in bedload volume and caliber, from changes in stream slope, and by alterations in stream discharge in the manner shown in this diagram. (Adapted from Lane, 1955.)

Table 3.1. Channel changes due to changing land use.[1, 2]

Land Use	Forest	Cropping (Agriculture)	Woods and Grazing	Construction	Urban
Sediment Input to Streams	Low	Greater	Somewhat less	Huge increase	Low, similar to before farming
Channel Condition	Stable	Aggradation	Scour, then stable	Aggradation	Scour, bank erosion

[1] Source: Wolman, 1967.
[2] Time progresses from left to right in this typical sequence of land use changes and channel responses

The third stage occurs soon after development, as greater areas of impervious and compacted land surface cause more stormwater runoff. The runoff is rapidly conveyed to streams through drainage ditches and culverts, resulting in greater and more frequent high flows in the streams. At the same time, sediment input is greatly reduced because bare ground has been covered with pavement, buildings, or lawns and other landscaping. Channel degradation results from the "flashy" stream discharge and low sediment load.

Many researchers have confirmed that channel enlargement follows urban development (e.g., Hammer, 1972; Leopold, 1973; Morisawa and LaFlure, 1979), but much less is known about the re-attainment of a state of quasi-equilibrium. Wolman (1967) professed doubt that urban streams would be able to establish a new state of relative stability, and Arnold et al. (1982) predicted an indefinite period of instability following urbanization. Several studies (Hammer, 1972; Ebisemiju, 1989; Gregory et al., 1992) suggest a state of quasi-equilibrium will be regained within a time frame of years to a few decades. Trimble (1995) hints that decades might be needed for streams to reacquire a state of quasi-equilibrium. More recently, Henshaw and Booth (2000) searched the coastal lowlands of Washington for streams that had restabilized after urbanization. They found that one of the two post-development streams they studied in detail appeared to have stabilized and the other had not. They also examined several streams draining areas with transitional (less developed) land use. They concluded that it is typical, but not universal, for channel restabilization to occur within a decade or two if land use in the drainage basin is constant.

At least part of the reason for the sparse data on stream restabilization is that, as Graf (2001) points out, much more attention has been paid in recent decades to water quality than to the physical condition of stream channels. The present study is intended to provide information on the physical state of Second Creek that may be used to help predict and recognize future changes.

Almost all of the land in the basin of Second Creek has been urban for at least 40 years, and about 20 years have passed since the last construction project impinged directly upon the stream. In addition, Second Creek drains a relatively small area, so stream channel responses to changes in the basin occur more quickly than they would in a stream draining a larger area, where lag times are longer. This makes Second Creek a good place to study post-urbanization stream channel adjustment. My examination of the creek focused on the following questions:

1) What is the status of the channel of Second Creek with respect to degradation or aggradation of the channel?
    a. If there is evidence of aggradation or degradation, how extensive is it and where is it located?
    b. If there has been recent degradation or aggradation, is it stabilizing or ongoing, and what factors may have caused or are causing it?
2) How much of the channel of Second Creek is armored or has been hardened, so that no channel enlargement can occur (at least in the short term)?

METHODS

Between June and November 2000, I walked in or along almost all of Second Creek, and conducted a systematic visual survey of the channel, noting the materials in the banks and bed of the stream and the locations and severity of any evident erosion or deposition. Where channel depth or thickness of riparian vegetation prevented the use of landmarks outside the channel for location purposes, I used a 100 m fiberglass tape to measure distances up- or downstream from easily recognizable objects such as large box culverts, bridge piers, or trestles.

For evidence of recent erosion, I used the presence of exposed roots of trees, shrubs, and/or grasses in stream banks. Undermined fence posts, utility poles, culverts and pipes, and road shoulders also gave evidence of recent bank erosion. The slumping of stream bank material and the presence of cracks in the ground close to the bank, indicating imminent collapse, were also used as evidence of erosion. Evidence for streambed incision included the exposure of the bases of old walls or foundations above the present bed of the stream. I recorded stream bank erosion severity in the following categories:

Slight is > 0 to 0.05 m
Moderate is 0.06 to 0.2 m
Severe is > 0.2 m.

Where erosion varied over a short distance, I combined categories, using designations such as "slight to moderate."

To measure the volume of material lost from small areas of erosion, such as small gullies, I used a chain, tape measure, and rod or meter stick. Data points in such areas were collected on a 1 m grid, and results recorded in centimeters.

The occurrence of sediment within concrete or other constructed segments of the channel, and accumulations of fine sediment in the bottom of the otherwise gravel- and cobble-dominated streambed provide evidence of recent deposition. To ascertain the volume of sediment within channel segments, I used one of two methods, depending on the length of channel to be assessed. For segments less than 200 m long, I used a surveyor's level and rod to measure the height of points on a grid. Spacing of the points was 2 m apart along the length of the channel and 1 m apart across the channel. The results were recorded in centimeters. A computer program (ArcView Spatial Analyst) was employed to construct contour maps and calculate the volume of the sediment deposits from the data. For longer stream segments, I measured distances along the length of the stream, and estimated width and depth of sediment deposits. Occasionally, I measured the dimensions of the deposits as "calibration" for estimates.

Stream channels responding to urbanization in their watershed typically become larger. There are no previously published cross-sections of the channel of Second Creek, so comparisons with earlier channel sizes are not possible. I measured cross-sections at locations I judged to be representative of different parts of Second Creek to provide a record of the size and shape of the channel, and to be able to compare cross-sectional geometry in different parts of Second Creek. I used a fiberglass tape stretched horizontally across the channel, in combination with either a meter stick or a surveyor's rod (for deeper channel locations) to measure channel depth from bankfull level at 1 m intervals across the channel. In places where channel banks or bed were exceptionally uneven, I used 0.5 m intervals. Depths were recorded in centimeters. The location of bankfull discharge was often difficult to discern in Second Creek. This is a common problem in stream studies, as noted by many researchers (Williams, 1978; Gordon et al., 1992; Harrelson et al., 1994; Johnson and Heil, 1996; Scholz and Booth, 2001). I used changes in vegetation, breaks in slope, and sometimes stain lines as indicators of bankfull level.

One way to better understand the factors affecting the present status of the channel of Second Creek is to examine individual reaches/sites in detail. At the scale of individual reaches or cross-sections, it becomes possible to measure volumes gained and lost and seek evidence to identify the controlling factors. Therefore, after observing the entire stream, I divided it into segments based primarily on the materials forming or covering the banks and bed of the channel. The materials forming the channel perimeter affect erosion rates and, therefore, the dynamics and appearance of the channel. In addition, anthropogenic changes in channel materials, and the changes in channel shape and size that often accompany them, may encourage deposition or erosion at or near the altered sites. In dividing the stream into segments, I also considered the preponderance of evidence for erosion, deposition, or relative stability in each portion of the stream.

RESULTS

Figure 3.2 shows the divisions of Second Creek into segments based on the criteria given above. I discuss each segment, some in a general fashion and some, if they are places with evidence of significant recent deposition or erosion, in more detail. An overview of Second Creek appears at the end of this section. Cross-sections of the channel are presented in Appendix B. "Left" and "right" banks of the stream always refer to the left and right of an observer standing in the stream and facing downstream. I will use the term "regolith" in the manner of Gale (1992), to refer to all unconsolidated material, whether it is alluvium, colluvium, soil, or anthropogenic fill. I will not follow this convention with streambed material, which I will call "bedrock" or "alluvium."

Segment 1: UT

This 450 m long segment of Second Creek is located from the upstream end of the box culvert under Neyland Drive to the downstream end of the box culvert under Cumberland Avenue. The lower portion of the segment is characterized by mature trees and shrubs on the banks and alluvium containing much coarse material on the surface of the bed. Most of the banks are steep and tall and composed of regolith. There are bridge piers and trestles in the stream in several locations. A large midchannel bar covered with coarse alluvium (including many bricks) is located on the downstream side of a bridge pier supporting the first bridge upstream from Neyland Drive. About 30 m upstream from the bridge, deep pools (about 1.5 m deep during low water) have formed around the large, square supports left in the stream after the World's Fair in 1982. About 40 m upstream from the pools, the stream makes several sharp bends as it flows under side-by-side bridges that used to carry railroad tracks over the stream. Large pieces of rock and concrete have been placed along the banks on the outside of these curves, most likely to protect them from erosion. There is a shaped-rock wall on the inside of the curve, under the bridges and extending about 20 m upstream along the left bank. Some of the upstream part of this wall has fallen apart and the exposed bank has been eroding.

In the upstream portion of this segment, the vegetation on the banks consists primarily of scattered trees and mowed grass. There is a 90 m long patio covered with loose paving stones on the right bank (when looking downstream) between two footbridges. The patio floods regularly, as it is only slightly higher than the bankfull elevation of the stream. One post of the wooden railing was hanging in the air due to erosion of the bank under it, and some paving stones from the patio were in the creek at the time of this survey.

Most of the banks in the upstream 100 m or so of this segment have been lined with rock walls or large riprap. The right bank is lined with a low shaped-rock wall for about 70 m. The wall has fallen apart at the upstream end (close to the Cumberland Avenue box culvert) and in a 20 m long area located approximately 60 m downstream of the culvert. This wall and rocks in the stream that appear to be from riprap on the opposite bank can be seen in Figure 3.3.

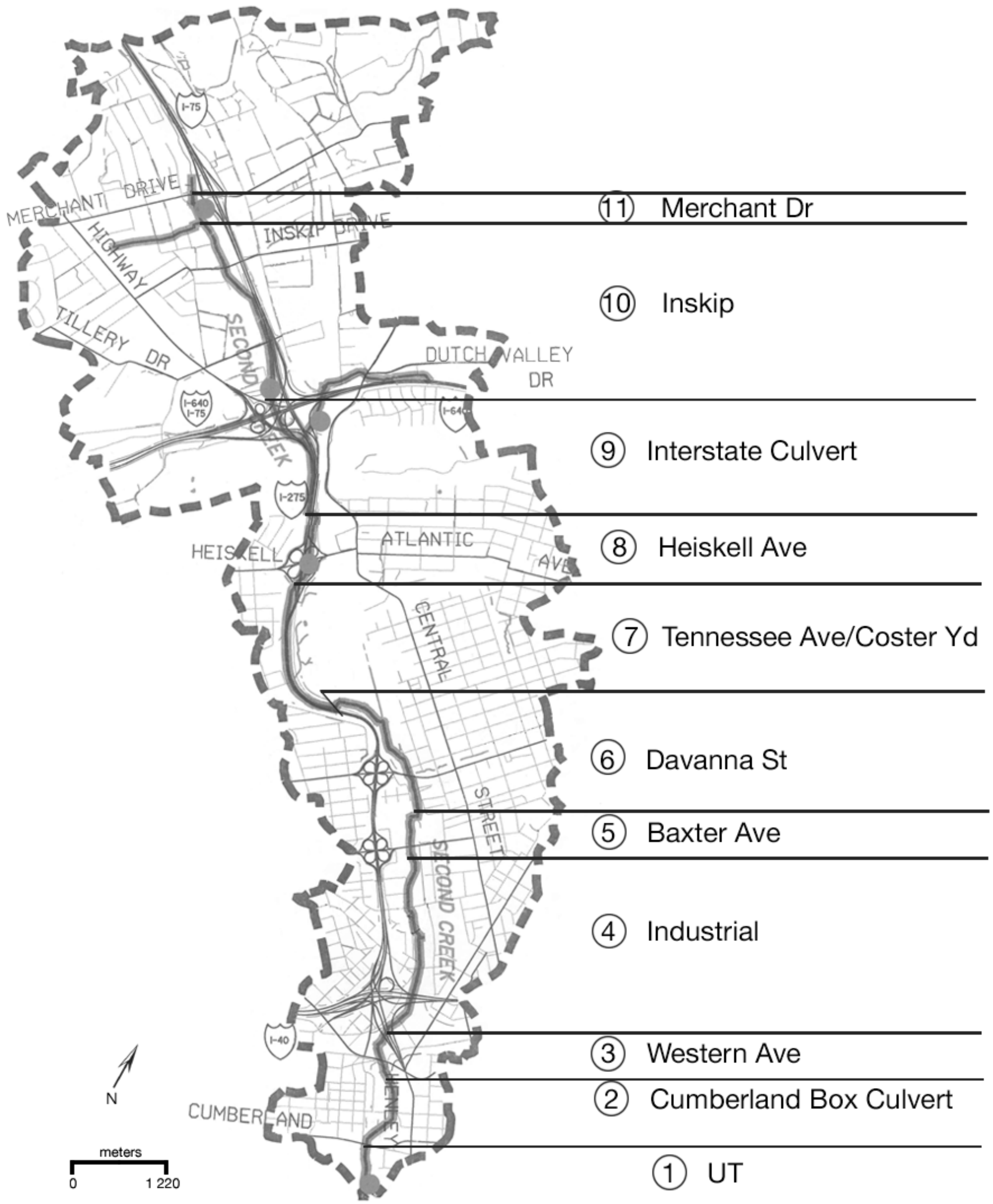

Figure 3.2. Division of Second Creek into segments. (Base map from KGIS, Knoxville, TN.)

Figure 3.3. Erosion in the upper part of the Cumberland segment. *Top*: Looking upstream towards the Cumberland Avenue box culvert. *Bottom*: The left bank of the stream between two footbridges. A tree was undermined and fell into the stream at this location. (Photographs by the author.)

In spite of the measures taken to prevent it, much of the channel in this segment shows signs of recent erosion on both banks. In many places, the lower parts of the streambanks are vertical or nearly so, and tree, shrub, and/or grass roots hang in the air. A tree that was growing on the slope above the left bank became undermined and fell into the stream in 2000. A sewer line access structure high on the left bank between the two footbridges provides evidence of erosion and slumping of the streambank (Figure 3.3). Most of the slumping visible in the photograph occurred between 1996 and 2000. Downstream of the location between the footbridges shown in Figure 3.3, a portion of an old rock wall is now poised to slide to the bottom of the left streambank (Figure 3.4). More places with severe erosion occur along the left bank than the right in this segment of the stream.

Considerable erosion has occurred around the end of the box culvert on the downstream (south) side of Cumberland Avenue. A portion of concrete wall about 7 m long on the right side of the stream has been undermined and fallen into the channel, and regolith high on both sides of the end of the culvert have eroded back more than 3 m. An extension of the culvert was built in the early 1980s, so all of the erosion around its terminus has occurred since that time.

Incision of the streambed has also occurred. A metal pipe about 0.35 m in diameter is exposed in the bed of the channel 76.5 m downstream from the box culvert. The pipe, which was probably under the streambed in the past, forms a knickpoint in the stream, with sediment against its upstream side and a drop of 0.35 m on its downstream side (in 2000, when surveyed). The trestles 260 m downstream from the Cumberland Avenue culvert, which lie near the left bank at site U, are undermined, but it is unclear whether this is further evidence of streambed incision or evidence of a shift in the course of the stream.

The predominant process in recent decades in this segment has been erosion. Both banks show evidence of erosion along much of their length, indicating widening of the stream channel in this area.

Segment 2: Cumberland Box Culvert

This part of Second Creek extends from 25 m south of the center of Cumberland Avenue to 110 m southeast of the center of Western Avenue. The southern end of this 650 m long reinforced concrete box culvert was lengthened in 1980 to run under land used for the 1982 World's Fair (now the site of the Knoxville Convention Center). Technicians who collect water quality data near the downstream end of the culvert for the City of Knoxville Stormwater Engineering Department report that the culvert is usually free of sediment, although occasional gravel- or cobble-sized clasts are present. There are signs of abrasion on the floor of the culvert, further evidence that coarse clasts move through this part of Second Creek. The predominant process in this stream segment is the transportation of sediment, rather than erosion or deposition.

Figure 3.4. Part of an old wall poised to slide into the stream. This location is between sites U and UT on the east side of lower Second Creek. Large rocks at the base of the banks, as seen here, are common in this segment of the stream. The water flows from left to right in the picture. (Photograph by the author.)

Segment 3: Western Avenue

This part of Second Creek extends from the upstream end of the Cumberland Box Culvert to directly beneath the Henley Street onramp to I-275 N. The lower part of this 390 m long segment, which lies downstream (south) of a metal culvert under railroad tracks, is characterized by hardened walls of rock, concrete, or riprap. Bedrock is exposed in much of the bed of the stream (Figure 3.5). There are small amounts of alluvium in some places in the bed, and some rocks that used to be part of a covering of riprap now lie on the bed at the base of the slope covered with that material.

As can be seen in the photograph in Figure 3.5, some erosion has occurred behind the low concrete-lined bank on the right side of the stream. Other signs of erosion in this part of the segment are the collapse of part of a rock wall on the left bank just downstream of the railroad culvert, and apparent incision of the bedrock streambed where the base of an old stone wall is exposed about 152 mm (6 in) above the bed of the stream.

The upper part of this segment has banks of regolith, with trees, shrubs, and some grass growing on most of them. Ledges of bedrock outcrop intermittently in the bed of the stream in this part of the segment. Deep (up to 1.3 m) pools with sparse coarse alluvium on the bed occur between bedrock ledges.

Just upstream from the railroad culvert, efforts have been made to re-establish vegetation on the formerly eroded right bank. Large (approximately 1 m) boulders and pieces of concrete and smaller rocks have been placed along the base of the banks on both sides of the stream, although they are spaced such that they rarely touch each other. In spite of the protection of the rocks, moderate erosion has recently exposed tree roots on both sides of the stream in this area.

Although minor amounts of erosion have apparently occurred recently in the lower part of this segment, transportation of sediment has been the primary process in this segment. In the upper part of the segment, erosion has been the dominant process in recent decades.

Segment 4: Industrial

This segment is located from under the Henley Street – I-275 onramp to the downstream end of the box culvert under Baxter Avenue. It is 1,420 m long. The bed is covered with alluvium over almost the entire length of the segment. The banks, where not lined with concrete or rock walls, are composed of fine-grained regolith. There are shrubs and trees on the upper parts of the banks along most of this segment.

Signs of moderate to severe bank erosion are common in the downstream part of this segment between places where the banks are hardened. In one place, between Oak Avenue and the onramp to I-40 East, a section of concrete bank material has collapsed

Figure 3.5. The channel near Western Avenue. The channel banks along this part of the stream are lined with concrete, shaped rock, or riprap. This view is looking downstream. World's Fair Park Drive crosses Second Creek in the upper left part of the picture. (Photograph by the author.)

into the stream, where it now forms a gently sloping lower bank and bed. Between I-40 and Fifth Avenue, where old railroad tracks hang out of the left bank and tree roots are exposed, there appears to have been 2 to 3 m of erosion. A concrete wall approximately 180 m long covers the right bank for most of the distance between I-40 and Fifth Avenue.

There is generally less evidence of moderate to severe erosion in the upstream direction, but the trend is not entirely consistent. About 150 m upstream from the Fifth Avenue Bridge are signs of bank erosion on both banks, but erosion is slight to moderate in extent on the left bank. The right bank has suffered more severe erosion, as shown by exposed roots and trees leaning over the stream. Less erosion occurs upstream from this location. Some deposition has occurred in the bed in this part of the stream. From this location upstream to the culvert-fed tributary that enters Second Creek about halfway between Fifth and Bernard Avenues, sediment has accumulated on the bed to form a low midchannel bar. This bar extends about 40 m downstream from where the tributary enters the creek.

Rock walls line both banks downstream of Bernard Avenue. The downstream wall on the left bank (east side) of the stream extends 210 m downstream from the center of the street. The downstream end of the rock wall is located only 40 m upstream from the tributary mentioned above. Sediment has accumulated against the base of the downstream 15 m of wall, but from that point upstream the stream is located against the wall until it gets close to the railroad bridge south of Bernard Avenue (Figure 3.6). There is low sediment on both sides of the stream at the sharp bend just downstream from the railroad bridge. The rock wall on the left bank is visible for only a short distance south (downstream) of the railroad bridge south of Bernard Avenue, where the wall disappears into an accumulation of regolith (probably alluvium). No signs of recent erosion are evident in this part of the channel.

North of Bernard Avenue, the right bank consists of a tall, vertical concrete wall that extends about 100 m upstream (Figure 3.6). Adjoining the concrete on the upstream end is an exposure of almost vertically dipping, competent bedrock. The rocks form a nearly vertical wall that extends upstream about 50 m. Upstream from the rock, the banks are tall and steep, and composed of regolith. Mature trees grow on most of the slopes, and recent erosion is evident along much of the low bank. The roots of many mature trees are exposed along the channel and several trees appear ready to topple into the channel.

Railroad tracks lie on the top of the left bank of the creek in the 300 m north of Bernard Avenue. Much of this part left bank is surfaced with gravel and riprap, with sparse low vegetation. In 2000, the time of this survey, there were several recently repaired places where erosion had threatened to undermine the tracks. Farther upstream, where the railroad tracks angle away from the creek, mature trees and shrubs line the banks and

Figure 3.6. Rock and concrete walls downstream and upstream of Bernard Avenue. *Top*: Looking downstream from close to Bernard Avenue. A railroad bridge can be seen at the right side of the picture. *Bottom*: Looking upstream. (Photographs by the author.)

riparian corridor. Tree roots are exposed along most of the lower parts of the left bank in this part of the stream, providing evidence of recent moderate to severe erosion.

A large tree has fallen into the creek from the right bank about 150 m downstream from the center of Baxter Avenue, but some of its roots are still in the bank and it has stayed alive. Woody and other debris have collected against the obstruction it creates (Figure 3.7). A pool has developed on the upstream side of the debris dam and under the tree. Approximately 2 m downstream from the tree, a 10 m long ridge of sediment that is exposed at low water has formed. A bar of alluvium also extends out from the right bank into the debris trapped by the tree trunk.

In summary, the lower 200 m or so of this segment has experienced deposition, the 100 m length next upstream shows little evidence of recent deposition or erosion, and most of the remainder of the segment has experienced recent erosion of one or both banks. There are a few places where sediment has accumulated into low bars in the upper part of the segment.

Segment 5: Baxter Avenue

This part of the stream is 270 m long. It is located from the downstream end of the box culvert under Baxter Avenue upstream to the right-angled bend near a railroad bridge close to Oklahoma Avenue. The downstream part of the segment consists of a reinforced concrete double box culvert that runs under Baxter Avenue and a parking lot on the downstream (south) side of the road. No sediment was visible in either end of the culvert in 2000.

On the upstream side of Baxter Avenue, Second Creek is contained within vertical rock, brick and concrete walls that are 5.9 m apart (Figure 3.8). A few parts of the wall have collapsed, and the exposed materials in those places have eroded as much as 2 m back from the former position of the wall. The bed is covered with alluvium in this part of the stream. I excavated down about 0.5 m and did not hit a hard surface, so I am assuming the bed is not lined with concrete under a veneer of alluvium.

The distance between the walls becomes greater and the walls lower about 115 to 120 m upstream from the center of Baxter Avenue. The wall on the left side (looking downstream) increasingly disappears into regolith that is covered with shrubs, vines, and young trees as distance upstream increases, until the wall is no longer visible. The right bank is composed of regolith with vegetation in places. This bank is hardened with timbers or "pillows" of stacked cement sacks in many places. The active channel meanders between small point bars in this segment of the stream. In one location where the stream flows against the cement wall, it undermined the wall, and a piece of it about 3 m long broke off and fell into the channel. In spite of this minor amount of erosion, and deposition of the material forming the bars, transport of sediment through this segment, rather than erosion or deposition, seems to have been the predominant process in recent decades.

Figure 3.7. A woody debris dam between Bernard and Baxter Avenues. This view is looking upstream. (Photograph by the author.)

Figure 3.8. Brick and concrete walls upstream from Baxter Avenue. Even in 1979, at the time of these photographs, parts of the walls were falling into the creek. More damage had occurred by 2001. *Top*: Looking downstream at the culvert under Baxter Avenue. *Bottom*: Looking upstream from Baxter Avenue. (Photographs by the author.)

Segment 6: Davanna Street

This portion of Second Creek is 1,140 m long. It lies between the railroad bridge near Oklahoma Avenue and the triple box culvert under I-275 south of Coster Yard. In the 300 m lying downstream of Woodland Avenue, most of the left bank is tall and steep. There are mature trees and some shrubs on the banks, and the bed is covered with alluvium in this area. The right bank is lower and more gently sloping than the left bank. Exposed roots and the almost vertical lower part of the left bank provide evidence of moderate to severe erosion in recent decades. Some deposition has occurred along the right bank in this part of the stream.

In between the areas of deposition, there has been slight to moderate erosion of the right bank from the downstream end of the segment to 80 m upstream of that location. The left bank has also been experiencing erosion, indicating channel widening in this portion of the channel. Farther upstream, erosion on the right side is slight to moderate, but erosion on the left bank remains severe. One piece of evidence of the erosion occurs about 100 m upstream of the starting point of this segment, where a cement pipe protrudes into the channel from the left bank. A 1.5 m long piece of pipe has broken off, and is lying at the base of the bank.

Bedrock appears in the bed about 120 m upstream in this segment, and it appears more frequently upstream from that location. It is also exposed in some places in the right bank. In places, it forms a series of pools and small waterfalls.

At a location 190 m above the downstream end of this segment, a 0.25 m (O.D.) pipe crosses the stream. In the center of the channel, the pipe is 0.2 m above the bed. This appears to be evidence of streambed incision. Bank erosion is moderate to severe on both sides of the channel in this area, and evidence of the same is found in the upstream direction.

The Oldham Avenue Bridge lies 354 m upstream from the downstream end of this segment. Immediately upstream from the bridge, Davanna Street lies close to the stream. Erosion of the outside of the bend along the stream threatens to undermine the street and an adjacent utility pole (Figure 3.9). Most of the creek upstream of the Oldham Avenue Bridge is characterized by frequent exposures of steeply-dipping bedrock (mostly dolostone) in the channel, and mature trees along both banks for most of its length (Figure 3.10). Roughly two-thirds of the length of the left bank in this part of the stream are armored or partially armored with large blocks of concrete rubble or, in limited places, concrete walls (Figure 3.10 and Figure 3.11). About 43% of the right bank is anthropogenically armored or partly armored in a similar manner to the left bank, and there are some outcrops of bedrock in the right bank. Between the areas of protected bank, exposed tree roots and undermined trees provide evidence of recent erosion along much of this segment (Figure 3.10). Approximately 40% of the channel in this segment is becoming wider rather rapidly, although widening has occurred at discrete sites rather

Figure 3.9. Severe erosion upstream of the Oldham Avenue Bridge. The eroding streambank threatens a utility pole and part of Davanna Street. *Top*: Looking toward Davanna Street. *Bottom*: Looking upstream. Devanna Street is visible on the right. (Photographs by the author.)

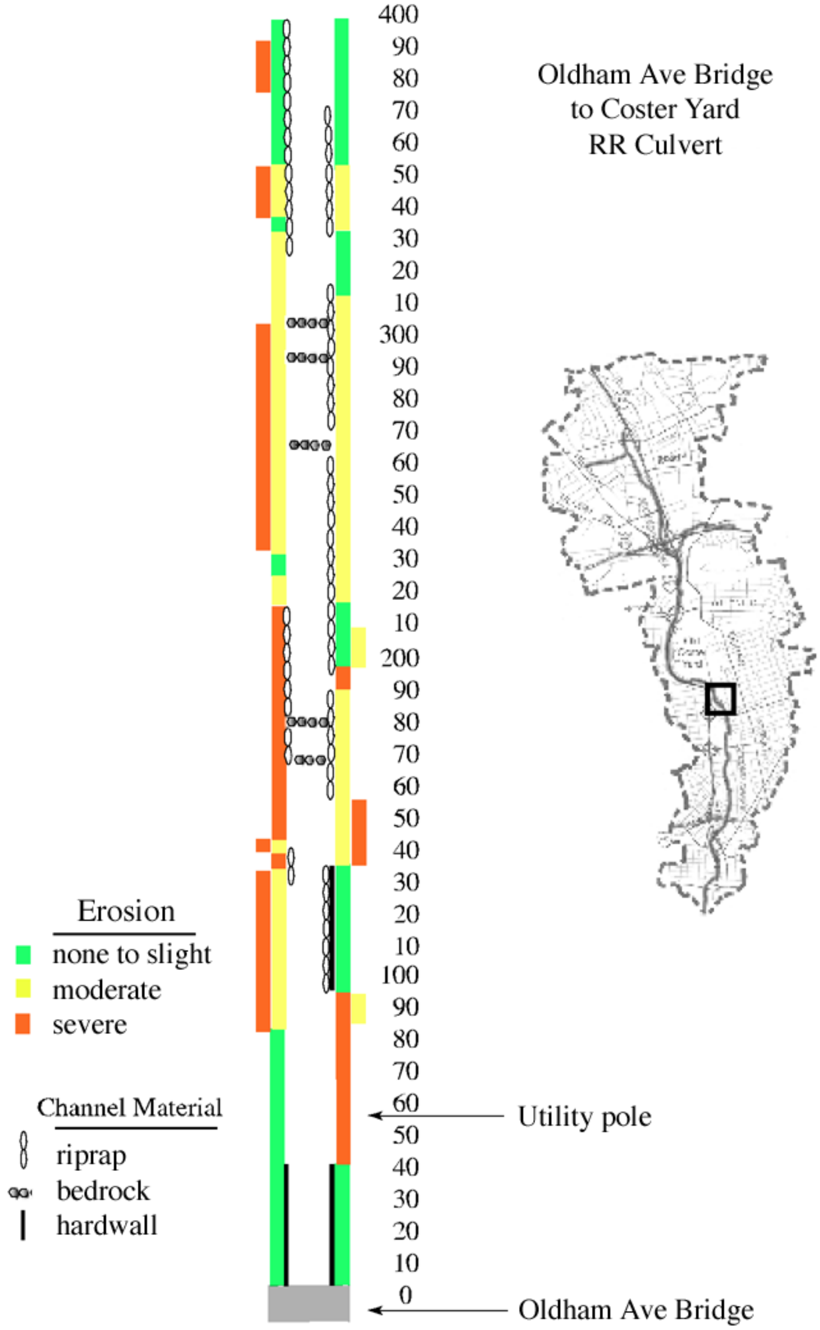

Figure 3.10. Status of the channel north of Oldham Avenue Bridge. Two colors along the edge of the channel indicate both categories of erosion are present. (Base map for locator map by KGIS, Knoxville, TN.)

Figure 3.11. Typical scenes in the upstream half of the Davanna segment. *Top*: Bedrock dams form pools in some locations. *Bottom*: Exposed roots and undermined trees are common in this segment. (Photographs by the author.)

than in one continuous area. There are three distinct locations of pronounced channel widening, and each contains exposures of bedrock in the bed of the channel. Much of the remainder of the channel segment downstream of the metal railroad culverts has been experiencing erosion on one side and deposition of alluvium against the other, an indication of incipient channel meandering.

Upstream from the 37 m long double metal culverts under the railroad tracks, the channel banks are tall and steep. Mature trees grow on most of them, with minor amounts of shrubs and saplings. The exposure of tree roots and the presence of undermined trees on the lower banks provides evidence of moderate to severe erosion in most of this part of the stream.

Overall, this segment shows the most pronounced bank erosion in Second Creek.

Segment 7: Tennessee Avenue/Coster Yard

This portion of the stream lies between the downstream end of a triple box culvert under I-275 and the downstream end of the triple box culvert passing under I-275 near Heiskell Avenue. Most of this segment is characterized by a trapezoidal-shaped concrete channel that contains Second Creek as it flows around the old Coster Yard area (Figure 3.12). The trapezoidal channel bounded on both ends by triple box culverts is 840 m long. I consider the downstream culvert to be part of this segment. This culvert is about 240 m long. The left-hand box (looking downstream) contains alluvium 0.4 – 0.5 m deep. I did not walk through the culvert to see how far this deposit extends, but there is sediment of almost the same depth at the downstream end of the same box, suggesting that it extends through the culvert.

The trapezoidal channel runs parallel to the highway, but the highway sits on fill material, about 12 m higher than the channel. The steep slope from the highway down to the concrete-lined channel is almost entirely covered with riprap (Figure 3.13). I estimate the average diameter of the rocks comprising the riprap as about 200 mm, although the rocks are not all the same size. Some rocks are considerably larger, and many are smaller.

The stream channel is 9.1 m wide at the base, and has walls that slope outward at a 45^{o} angle. The walls will contain a flow 1.4 m deep. Some parts of the channel are free of sediment, but many places are not. Vegetation, including occasional small trees, grows on almost all sediment accumulations deep enough to be above water at low (base) flow of the stream (Figure 3.13). Much of the sediment that has collected in this concrete-lined channel is fine-grained, but there is some gravel, as well as occasional cobble and boulder-sized clasts. The cobbles and boulders are similar in size and appearance to rocks comprising the riprap on the slope above the left stream bank.

Deeper (0.4 – 0.7 m) sediment has accumulated along the banks, but not along the entire length of this concrete-lined channel segment. The longest continuous accumulation of

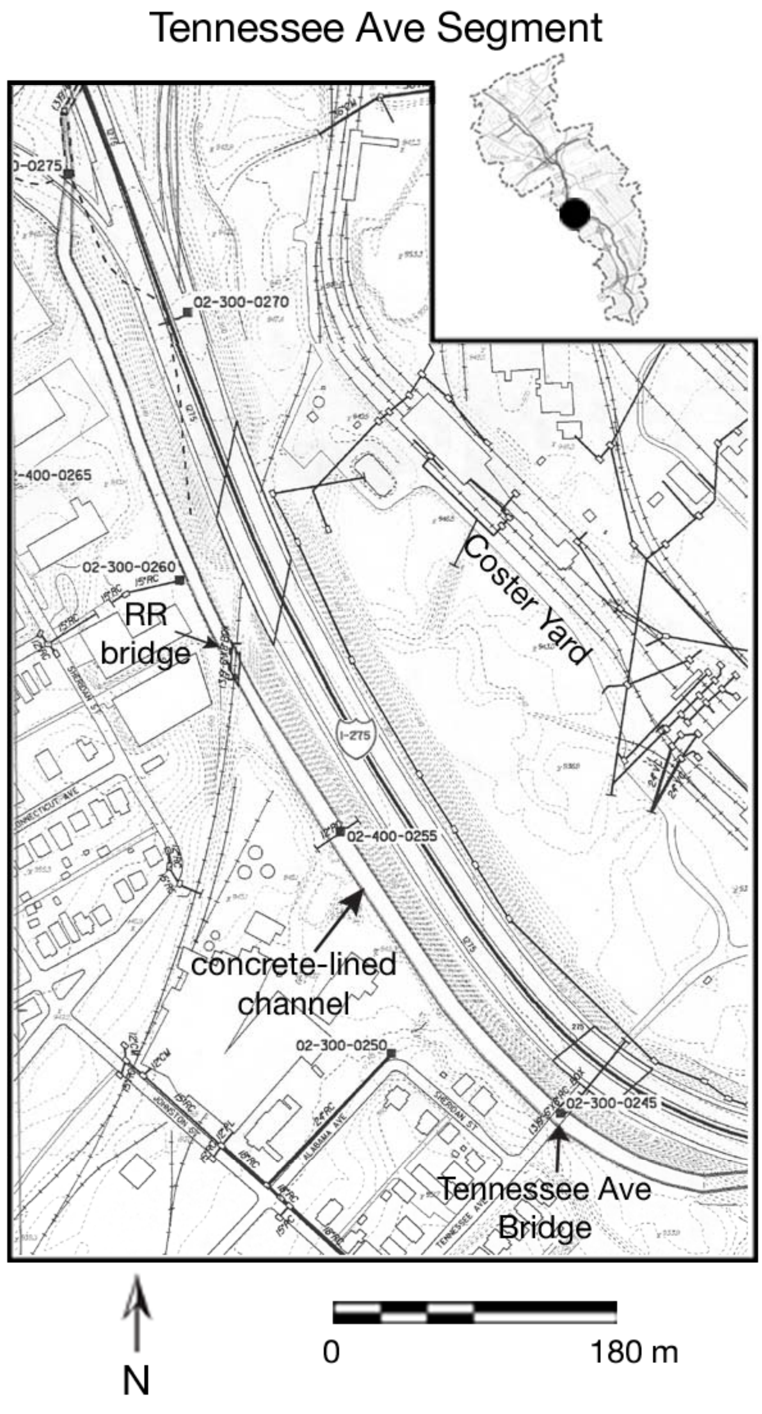

Figure 3.12. Map of the Tennessee Avenue segment. Second Creek flows from the upper left to the lower right in this map view of the channel. (Base map from City of Knoxville Stormwater Engineering, Knoxville, TN.)

Figure 3.13. Riprap above and vegetation in the channel. *Top*: Looking upstream from the Tennessee Avenue Bridge. I-275 is at the top of the riprap-covered slope. *Bottom*: Looking downstream near the upper end of this channelized segment of the stream. Plants grow on most sediment in the channel. (Photographs by the author.)

sediment along the left bank, which is the inner side of the curving channel, occurs in the downstream part of the segment. This deposit along the left bank extends 280 m upstream from the culverts at the downstream end of the Tennessee Avenue/Coster Yard segment.

The width of the deposit along the bank varies from about 1.5 to 5.2 m, but I estimate its average as 2 m. Assuming an average depth of 0.55 m, there are approximately 308 m^3 of sediment stored along the bank in this part of the channel. Farther upstream, accumulations along the left bank range in length from 2.5 to 109 m. The longest continuous distance with no sediment accumulation along the left bank is 25 m. I estimate the volume of the remainder of the left bank deposits as 97 m^3. Thus, total estimated deposition along the left bank of the trapezoidal channel amounts to 405 m^3.

Sediment has also been deposited in many places along the right bank of the stream. The longest continuous accumulation begins over 230 m upstream of the culverts, and continues for 170 m against the bank in the upstream direction. This deposit is located the farthest downstream of all the right-bank deposits except for one small (12.7 m long) accumulation of alluvium just downstream of the Tennessee Avenue Bridge. Other areas of deposition along the right bank range in length from 1.5 to 98 m. The longest continuous length with no sediment along the right bank is 90 m, located at the downstream end of the segment. Another place where bare concrete is exposed for almost the same length (88 m) along the right bank is located less than 100 m from the upstream end of the Tennessee Avenue/Coster Yard segment. I estimate the total volume of the various deposits along the right bank as 224 m^3.

This is not all the sediment in the channel segment. The entire floor of the channel is covered with alluvium close to and under the Tennessee Avenue Bridge across Second Creek. A mixture of fine-grained, gravel, and cobble-sized particles make up this deposit. Much of it forms a shallow layer over the concrete, but a substantial mid-channel bar extends from 14 m upstream to 22.5 m downstream of the Tennessee Avenue Bridge. Sediment in this bar, also a mixture of fines, gravel, and cobbles, is about 0.3 m deep. I estimate the bar to be about 35 m^3 in volume, and the shallower, more extensive sediment about 20 m^3. Using these figures, the total sediment accumulation is 55 m^3 in a 26.5 m length at the Tennessee Avenue Bridge. This total does not include the deposits along the banks.

Six other locations contain sediment deposited in the middle of the channel. Two of them are located downstream of the railroad bridge over the creek, and four are upstream of that bridge. The deposits range in width from 2 to 6 m, and in length from 2 to 37 m. I estimate these six mid-channel bar areas to contain about 110 m^3 of alluvium in total.

Combining all the figures above gives a total volume of approximately 800 m^3 of sediment that is stored in the 840 m long Tennessee Avenue/Coster Yard channel. Some of this sediment may contain high levels of metals or other pollutants, as drainage from part of the Coster Yard area enters Second Creek in this segment.

Segment 8: Heiskell Avenue

This segment extends 607 m, from the upstream end of a triple-box culvert under I-275 to the downstream end of a triple-box culvert north of Heiskell Avenue (Figure 3.14). The downstream triple-box culvert under I-275 is 170 m long. There is sediment more than 1 m deep in the right-hand box, looking downstream. The other two boxes are clear of sediment. Bedrock is exposed in part of the streambed downstream of the Heiskell Avenue Overpass. A low bench of primarily fine-grained regolith (probably alluvium) lies along the right bank in this 100 m long part of the segment. Grass, herbs, shrubs, and saplings grow on this bank and bench. Some recent erosion of this bank has occurred, but most of it is slight or slight to moderate in character. The left bank is taller and steeper and is well-vegetated. It has undergone more erosion than the right bank, but the severity ranges from slight to severe. Most erosion of this bank was slight to moderate, and some places showed no evidence of recent erosion.

North of the overpass, Second Creek flows through two 2.9 m by 2.4 m triple box culverts under the interstate highway on- and off-ramps upstream of Heiskell Avenue (see Figure 3.14). Between the culverts, the channel has vertical concrete walls that are 2.85 m tall. There is a footer, or small ledge of concrete at the base of the walls, but the remainder of the bed of the channel between the concrete walls is formed of regolith. Sediment has accumulated within some of the culverts and in the area between the sets of box culverts. Vegetation is growing on much of the sediment located between culverts and just inside the ends of culverts, but none grows on deposits farther within the culverts. The distribution of sediment in the segment of stream containing vertical concrete walls and box culverts under the on-ramp and off-ramp upstream of Heiskell

Avenue is shown in Figure 3.15. Culvert volumes occupied by sediment are shown in Table 3.2. Detailed contour maps of each culvert and the areas between them are presented in Appendix C for use in detection of future changes in sediment volume.

It can be seen from Table 3.2 that even though individual box culverts contain different amounts of alluvium, the total sediment-filled volume of each set of triple boxes is almost the same, between 16 and 17 percent. I estimate that sediment volume stored in the entire 84 meter long segment with vertical concrete walls, including the culverts, is 231 m^3. Sight to moderate erosion of part of the edge of the active channel is shown by vertical banks and exposed grass roots.

Upstream from the culverts under the on- and off-ramps, both banks of the stream show signs of erosion. Erosion ranges from none to severe, but moderate to severe erosion was most common along this part of the segment. At the upstream end of the segment, the wing-walls attached to the downstream end of the triple-box culvert are undermined as much as 1 m on the left side. The stream curves to the right after leaving the culvert. The left bank is protected by a curving concrete wall, but there is evidence of severe erosion beyond the end of the wall. Moderate to severe erosion continues along the left

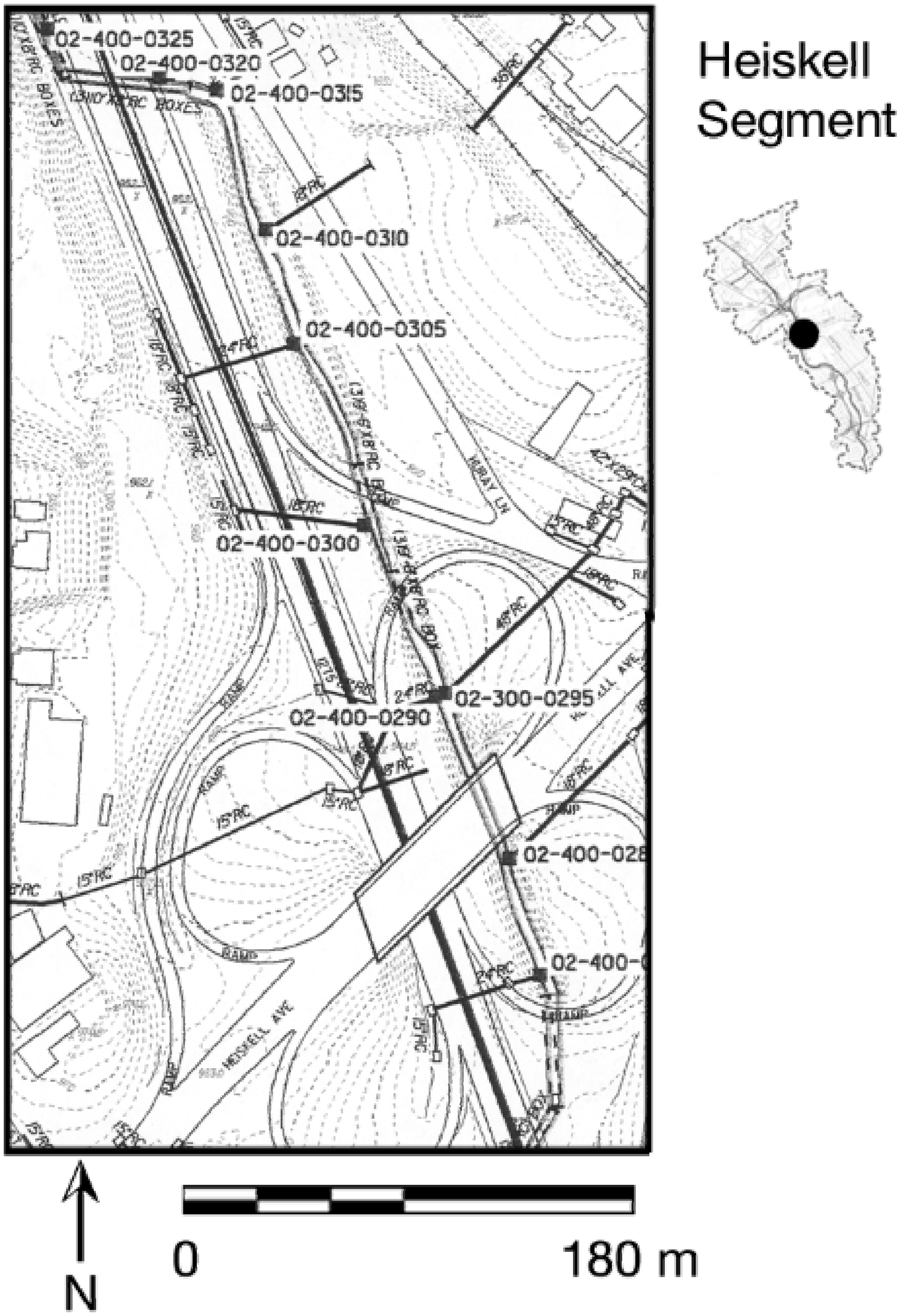

Figure 3.14. Map of the Heiskell Avenue area. Sediment has accumulated in the triple box culverts under the on- and off-ramps north of Heiskell Avenue. (Base map from City of Knoxville Stormwater Engineering, Knoxville, TN.)

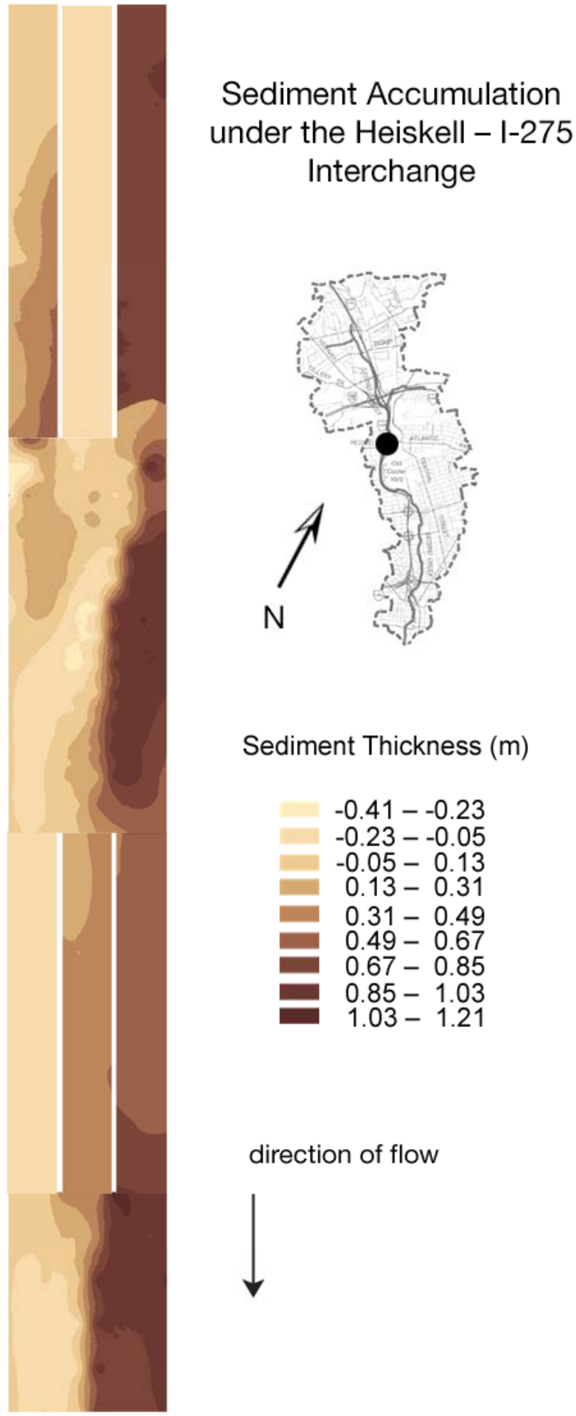

Figure 3.15. Contour map of sediment in the concrete-walled portion of the channel. Negative sediment thickness is shown for locations lower than bottom in culverts. See Appendix C for detailed maps of each section shown combined above. The channel shown in this diagram is 10 m wide and 81 m long. (GIS-generated maps from data collected by the author.)

Table 3.2. Sediment in culverts near Heiskell Avenue.[1]

Location	Measured Sediment Volume (m^3)	Percent culvert filled
On-ramp, west box	57.6	39
" center box	0	0
" east box	16.2	11
" all boxes	73.8	16.6
Off-ramp, west box	0	0
" center box	21.4	18
" east box	37.6	31
" all boxes	59.0	16.3

[1] The triple box culverts are located upstream of the Heiskell Avenue overpass, under the on-ramp and off-ramp connecting northbound I-275 and Heiskell Avenue.

bank in the downstream direction. On the right bank, there is a deposit of alluvium near the outfall of the culvert, but evidence of bank erosion begins to appear less than 15 m downstream from the culvert. Much of the right bank shows signs of moderate to severe erosion downstream to the triple box culverts under the on-ramp to I-275 N.

In summary, the Heiskell Avenue segment shows signs of slight to moderate recent erosion in its downstream part, recent but stabilized deposition in the center part with some erosion of the older deposits, and moderate to severe erosion in much of the upstream part of the segment.

Segment 9: Interstate Culvert

This system of large box culverts is approximately 1,070 m long. It extends from the downstream end of the box culverts near Heiskell Avenue to upstream of the I-75/I-640 interchange. A box culvert containing the tributary from the Dutch Valley area north and of Sharp Ridge and east of Second Creek joins the creek under the interchange. All boxes were clear of sediment near their ends at the time of the survey for this report.

Segment 10: Inskip

This 1,455 m long segment extends from the upstream end of the Interchange Culverts to the tributary on the upstream side of the Inskip Ball Park. Site C, the Clinton Site, where I measured suspended sediment with rising stage samplers, lies at the downstream end of the segment (Figure 3.16). An active gully is located on the right bank of Second Creek, about 3 m upstream from the infall (upstream end) of the double box culvert under the interchange of I-75 and I-640. The floor of the gully at the gully/stream junction is approximately the same height as the water surface at low flow. The gully is 11 m long, and is approximately elliptical in shape. Its widest dimension is 5.5 m, and maximum depth is 0.95 m. There is a step of 0.5 m in the bottom of the gully about 4 m away from the gully outlet. I observed a small flow of water emerging from the base of the step. Debris (rocks, wood, trash, minor amounts of concrete) has been dumped into the head of the gully in an obvious attempt to stop or slow headward expansion. Using estimated average width, length, and depth, I estimate the total volume of material eroded from the gully at the time I measured it (February, 2001) as about 28 m3.

The stream channel upstream of the interchange area contains some bedrock in the bed, and minor outcrops of bedrock in the banks. Most of the banks are composed primarily of fine material, with occasional large clasts. Much of the length of this segment has trees and shrubs thickly covering the banks.

There are signs of erosion along most of the banks in this segment. The severity varies from slight to severe, but moderate to severe erosion was most common. The most common evidence of erosion was the presence of exposed or dangling roots and nearly vertical active channel streambanks. There were also places where drain pipes and culverts were left hanging unsupported on the channel side of streambanks.

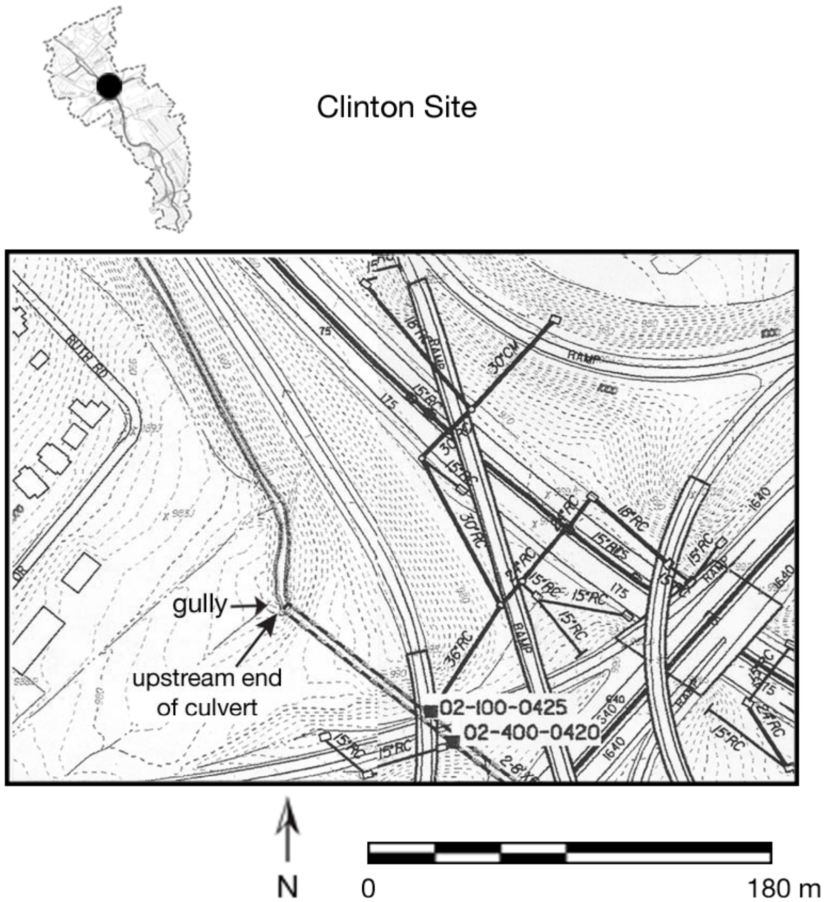

Figure 3.16. Map of the downstream end of the Inskip segment. (Base map from City of Knoxville Stormwater Engineering, Knoxville, TN.)

There were a few places where fine material mantled the more common coarse bed material. Small midchannel bars, exposed only during low flow conditions, were often associated with these sites. The area containing most of the bars and fine sediment was located 50 to 100 m downstream from Inskip Avenue. There are houses close to the stream at this location and upstream of it. Near the north (upstream) side of the Inskip Avenue culvert, large riprap has been placed in the channel near the banks (Figure 3.17). Signs of severe erosion at the location, such as erosion around the end of a concrete-lined drainage ditch and the wing-walls of the culvert, indicate why these were thought necessary.

Erosion of the right bank close to the ball fields has destroyed earlier fences, whose post locations are still visible at the edge of and in the stream channel. There is some erosion of the left bank in the same location, but it is less severe and less extensive than erosion of the right bank. Overall, the stream is becoming wider near the ball fields.

Segment 11: Merchant Drive

The length of this segment is 225 m. It extends from the tributary on the north side of Inskip Park to the upstream end of the culverts under Merchant Drive (Figure 3.18). There is an accumulation of predominantly fine sediment in the stream channel under and downstream (south) of Merchant Drive (Figure 3.19). Perennial flow in Second Creek begins only a few meters upstream of this location, north of Merchant Drive. The creek flows under Merchant Drive through double reinforced concrete box culverts that are 1.2 m in height, 3 m wide, and 25.3 m long. Fine sediment and gravel <0.1 m deep cover an area of about 9 m^2 of the bottom of the western-most of the two culverts under Merchant Drive. The eastern culvert contains more sediment. From visual inspection and estimation, I estimate that about one-third of the floor of the eastern culvert contains sediment about 0.15 m deep, and the other two-thirds have sediment that varies in depth, but averages about 0.4 m. Using those figures, there is 24 m^3 of sediment in the eastern box culvert, which is about one quarter of the total volume of the culvert.

Downstream from the Merchant Drive culverts, the stream channel is wide, shallow, and contains wetland vegetation (also shown in Figure 3.19). The alluvium in the bottom and on the gently sloping sides of the channel is mostly fine-grained. There are minor amounts of gravel in the bottom of the low-flow channel. Much of the alluvium is unconsolidated, and generally more than knee-deep. Sediment that in some places is deeper and more consolidated has collected along the right bank close to the culverts under Merchant Drive. Some of it diverts the creek to the east at low-flow levels, and appears as a bar during moderate high water events. There has been some erosion where the deflected current hits the left bank. The right streambank is cut by two wet weather tributaries. One is outflow from a culvert and ditch from the southwest that enters Second Creek immediately downstream of the road and the other is from a 0.91 m diameter culvert located about 30 m downstream of Merchant Drive (Figure 3.20). Water from the latter has carved a small peninsula in the sediment for about 10 m downstream until the flow from the culvert joins Second Creek.

Figure 3.17. Large rocks placed near the Inskip Avenue Bridge. View is looking upstream. The yellow bar is 1.22 m (4 ft) long. (Photograph by the author.)

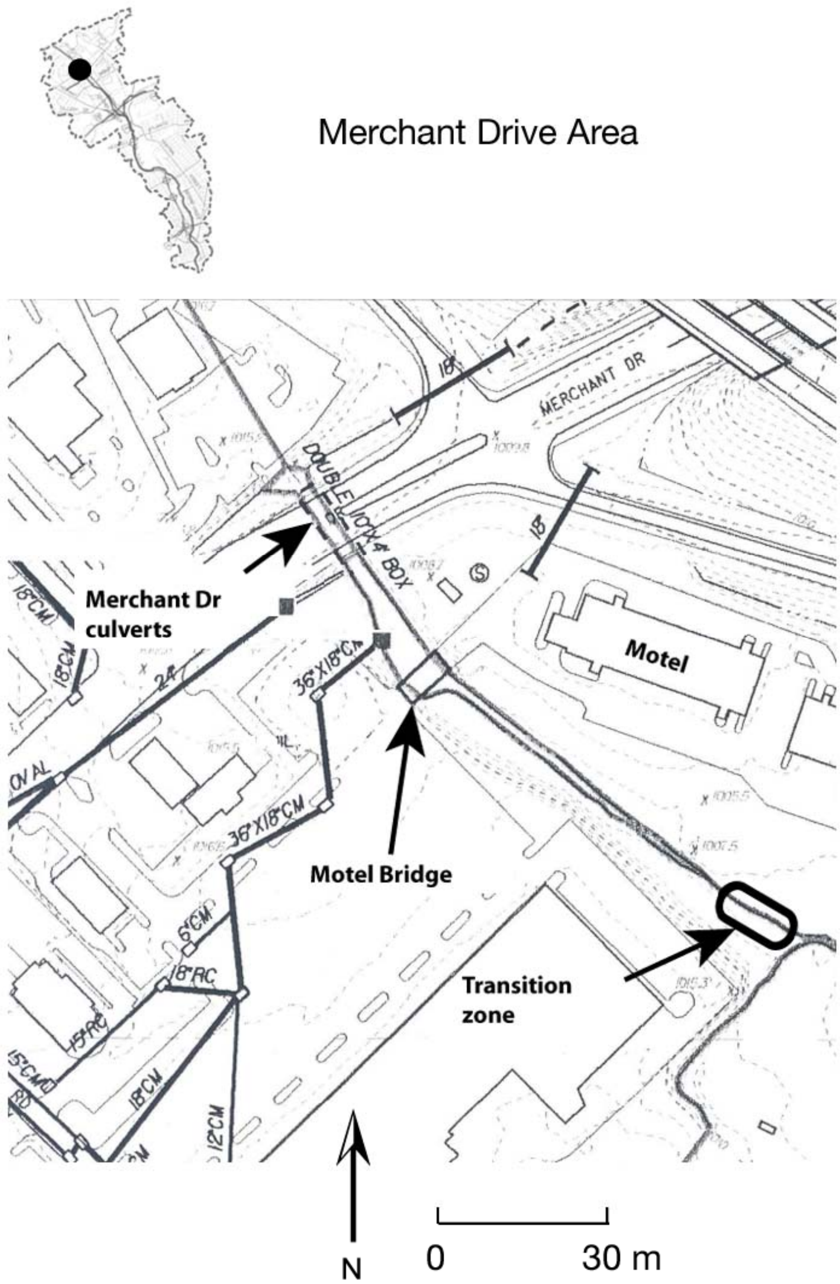

Figure 3.18. Map of the Merchant Drive area. The headwaters of the perennial portion of Second Creek are located just above the arrow pointing to the Merchant Drive culverts. The creek flows from upper left to lower right. A tributary enters the creek from the southwest just downstream of the transition zone. (Base map from City of Knoxville Stormwater Engineering, Knoxville, TN.)

Figure 3.19. The channel close to Merchant Drive. *Top*: The downstream side of the culverts under Merchant Drive. Low flow is diverted toward the viewer by the accumulation of sediment in the center left of the photograph. *Middle*: Looking at the culverts from farther downstream. View is from the left bank. *Bottom left*: Looking upstream towards Merchant Drive. There is a great deal of vegetation on the sediment in the channel. *Bottom right*: Looking downstream along the left bank. One culvert under the Motel Bridge is visible to the right of the tree. These photographs were taken in 2000. The trees were cut down less than a year later. (Photographs by the author.)

Figure 3.20. The area downstream from Merchant Drive. *Top*: Looking upstream towards Merchant Drive during a modest high water event. *Middle*: A "tributary" entering Second Creek from a 0.91 m diameter concrete pipe. *Bottom*: Looking upstream at storm runoff water running into Second Creek from a ditch along the southwest side of Merchant Drive. (Photographs by the author.)

A private drive 43 m downstream from Merchant Drive crosses Second Creek to provide access to a motel on the northeast side of the creek. Eight 1.2 m (4 ft) corrugated metal culverts under the drive allow passage of the creek (Figure 3.21). Although I could see a small amount of deep, fine, soft alluvium in some of these culverts, I did not attempt to assess the amount they contained because access to them was poor and potentially dangerous. I assume the amount was so small as to make little difference to the total sediment accumulated in this part of the channel, and omit them from the calculations. For convenience, I refer to the raised part of the drive that goes over these culverts as "the Motel Bridge."

The width of the stream channel is about 16 m on the upstream side of the Motel Bridge and about 8 m at the downstream side of Merchant Drive. Comparing topographic maps and old photographs with the present landscape shows the land on both sides of Second Creek in this area was extensively re-shaped 20 to 30 years ago in order to provide suitable places for businesses and the interstate highway. If the post-construction channel had a fairly flat bed at the same elevation as the bottom of the culverts, and if the average depth of the sediment now present is 0.5 m (an estimate), then the total volume of sediment stored in this part of the channel is 258 m^3. Although much of the sediment appears stabilized by vegetation, some aggradation may still be occurring, as there were small areas of sediment bare of vegetation located on the downstream sides of both Merchant Drive and the Motel Bridge. I also observed freshly deposited sediment 10 to 20 mm deep between plants in some locations along the left bank after a high water event.

The channel becomes narrower downstream of the Motel Bridge (also shown in Figure 3.21), although it still contains accumulations of fine sediment and wetland vegetation. Ninety meters downstream from the motel bridge, fine sediment is 0.35 m deep in the 5 m wide channel. The fine sediment gradually thins in the downstream direction, having completed the transition to a firm bottom containing coarser particles about 140 m downstream from the motel bridge. This location is a few meters upstream of the confluence with a tributary flowing from the southwest (informally called the Inskip Tributary). For a conservative estimate of sediment storage between the Motel Bridge and the entrance of the Inskip Tributary, I assume an average channel width of 5 m and average depth of sediment equal to 0.25 m for 130 m of channel length. Based on these figures, 163 m^3 of sediment is stored in the channel downstream of the motel bridge. Adding the volume of sediment stored in the Merchant Drive culverts and in the channel upstream of the Motel Bridge to this figure gives a total volume of 445 m^3 of predominantly fine-grained sediment that has accumulated in this 216 m long segment of Second Creek.

Figure 3.21. Second Creek near the Motel Bridge. *Top left*: The upstream side of the Motel Bridge during a modest high water event. Some debris was collecting at the culvert entrances. A stain above the top of the culverts reveals the level of a recent flow. *Top right*: The downstream side of the Motel Bridge, at a time of low flow. *Bottom left*: Looking upstream towards the Motel Bridge. The left bank is in grass, but the right bank contains thick shrubs and trees. Sediment in the channel at this location is almost knee-deep. *Bottom right*: Looking downstream from the Motel Bridge during the same runoff event as shown in the photograph in the upper left. The channel narrows considerably about 5 m downstream from the bridge. (Photographs by the author.)

All Segments

A comparison of the cross-sectional geometry of the channel at different locations along the length of Second Creek is shown in Table 3.3. The locations of the cross-sections are shown in Figure 3.22, and descriptions of the locations and diagrams of each cross-section are given in Appendix B. As can be seen from the data in Table 3.3, there was quite a bit of variation in width to depth ratios (W/D) along the length of the stream. Values ranged from 1.9 near the upstream end of the perennial portion of the creek to 15.3 near the mouth. Although the largest values occurred downstream and the smallest upstream, there was not a strong relationship between distance from the mouth and W/D along the length of the stream.

More than 38% of the length of the perennial portion of Second Creek is lined with concrete, and quite a bit of the remainder of the perennial channel has armored or partially armored banks. Greater percentages of the banks in lower part of the drainage basin are armored than in the upper part. The armor consists of rock walls, riprap, bedrock or other materials. In spite of this, there is evidence of recent erosion of and deposition within the channel. The term "recent," in this context, refers to events that have occurred within the last three or four decades. The locations of anthropogenic channel armoring and the places with the greatest amounts of recent erosion and deposition are shown in Figure 3.23. The banks, where not covered with concrete or other anthropogenic armor, are typically composed of fine-grained regolith. There are exposures of bedrock in the banks in only a few places. Bedrock exposures occur more frequently in the bed of the channel, but most of the streambed contains alluvium composed of a mixture of fine and coarse particles (see Chapter 3 for more details about bed material).

DISCUSSION

First I will discuss the segments or areas of the channel that had the most significant deposition or erosion, and then the stream in general.

Merchant Drive Area

There are several possible causes of the channel aggradation evident in this part of Second Creek. It is likely that some combination of the following factors have created the conditions favorable for the deposition of sediment.

In comparing 1:24000 scale topographic maps from 1953 and 1978, I noticed that the course of Second Creek upstream of Merchant Drive had been altered at some time between those dates. Instead of flowing more or less directly from the northeast to the location of Merchant Drive, it was rerouted to pass under the interstate highway at a location to the northwest of its old course. The new U-turn in the channel resulted in a

Table 3.3. Cross-sectional geometry at different sites in Second Creek. Sites are listed in order from downstream to upstream.

Site	Depth[1] (m)	Width[2] (m)	Area (m^2)	W/D	Date Surveyed
U	1.03	14.8	15.2	14.3	July 2001
UT	0.78	11.7	9.1	15.0	Aug. 1998
Western Ave.	0.73	7.7	5.6	10.5	May 2001
Industrial	1.16	9.3	10.8	8.0	Same
S. Bernard	1.22	5.4	6.7	4.5	Same
N. Bernard	0.86	8.2	7.1	9.5	Same
S. Baxter	0.90	9.0	8.1	10.0	Same
Davanna Down	1.23	11.9	14.7	9.7	Apr. 1997
Davanna Up	0.72	11.0	7.9	15.3	Same
Clinton Dnstm	1.29	11.7	15.1	9.1	July 2000
Clinton Upstm	0.83	10.2	8.5	12.3	Same
Heiskell Dnstm	0.93	9.5	8.8	10.2	Same
Heiskell Upstm	0.76	7.0	5.3	9.2	Mar. 2001
Inskip 200	0.61	7.0	4.3	11.5	Same
Inskip 166	0.55	3.5	1.9	6.4	Same
Inskip 134.4	0.66	5.0	3.3	7.6	Same
Inskip 90.9	0.81	6.0	4.9	7.4	July 2000
Dutch Valley	0.60	4.2	2.5	7.0	July 2001

[1] Average depth. Depth is measured from estimated bankfull water level to the streambed.
[2] Width at estimated bankfull water level.

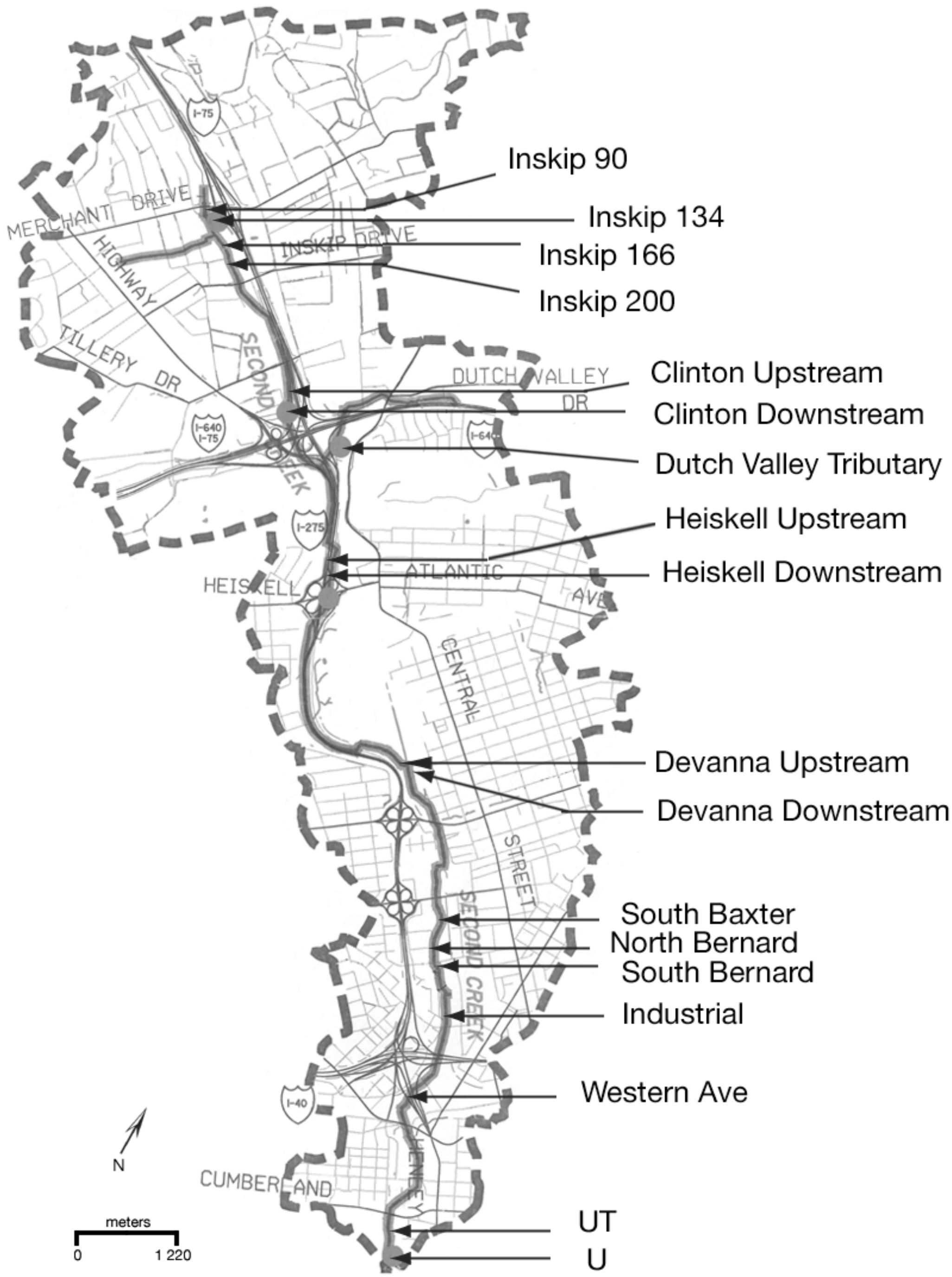

Figure 3.22. Locations of cross-sections of the channel of Second Creek. (Base map from KGIS, Knoxville, TN.)

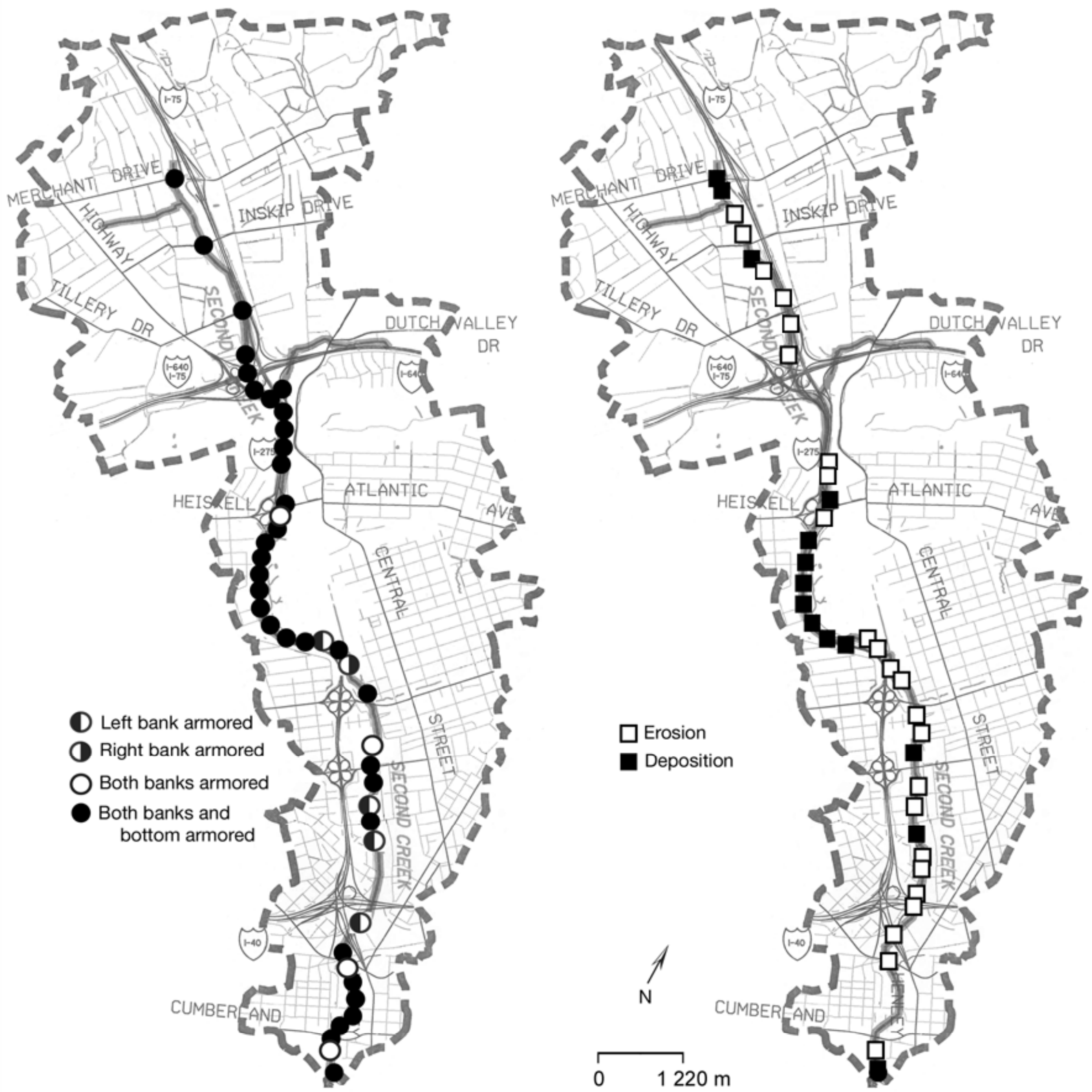

Figure 3.23. Locations of armored channel and areas of greatest recent deposition and erosion. Most channel armoring is anthropogenic in origin, but a small amount is formed by bedrock. Right and left bank are as viewed when looking downstream. (Base maps from KGIS, Knoxville, TN.)

reduction in slope due to the added length of the stream (Figure 3.24). Using data derived from topographic maps, I calculate that the slope of the creek from a point 152 m (500 ft) upstream of Merchant Drive to just downstream of the road was 0.036 prior to construction and 0.005 afterwards. To the extent that channel aggradation was driven by the decrease in slope in this part of the channel, it may be fruitless to remove sediment from this part of the channel with the expectation that it would stay clear in the future.

Another condition that probably caused sediment to be deposited in the channel is the restriction of flow caused by the Motel Bridge. When I visited the site during a less than bankfull runoff event, I noticed that some of the culverts were partially blocked by debris, and water was pooling upstream of the bridge. A water stain about 0.6 m above the top of the culverts indicates that water rises above the top of the culverts. I would expect even more pooling, with the attendant reduction in water velocity and deposition of sediment, when water levels exceed the height of the culverts in response to greater amounts of storm runoff than I witnessed.

A third possible cause of aggradation is the likelihood that a large amount of sediment was delivered to Second Creek during land development. This would be consistent with what Wolman (1967) noted was typical during the construction phase of land use change. A photograph taken looking downstream across Merchant Drive in 1979 (Figure 3.25) reveals an area stripped of all vegetation in the foreground. This area is now a paved parking lot, but it is likely that considerable sediment washed into the adjacent stream before the ground was paved. However, other parts of the channel such as the one shown in the upper photograph in Figure 3.25, where construction-related sediment accumulated in the past, do not currently contain accumulations of deep, soft, fine material. This suggests that reduction of channel slope and/or channel restriction caused by the Motel Bridge culverts are more likely the cause of recent sediment deposition in and downstream of the Merchant Drive culverts.

One expected consequence of channel aggradation is more frequent flooding. In this area, the partially blocked culverts under Merchant Drive pose an additional flood risk. This is a busy road, as can be inferred from the vehicles in the photographs. It is also an important route for emergency vehicles. City of Knoxville engineers would like to remove the excess sediment in the culverts and downstream of them in order to lower the frequency of flooding (Hagerman, 2000), but the area has been declared a wetland by the Department of Environment and Conservation and is thus legally protected from sediment removal.

The amount of active aggradation of the channel in this area seems to be low. If it were rapid, vegetation would not have a chance to become established before being buried in new sediment.

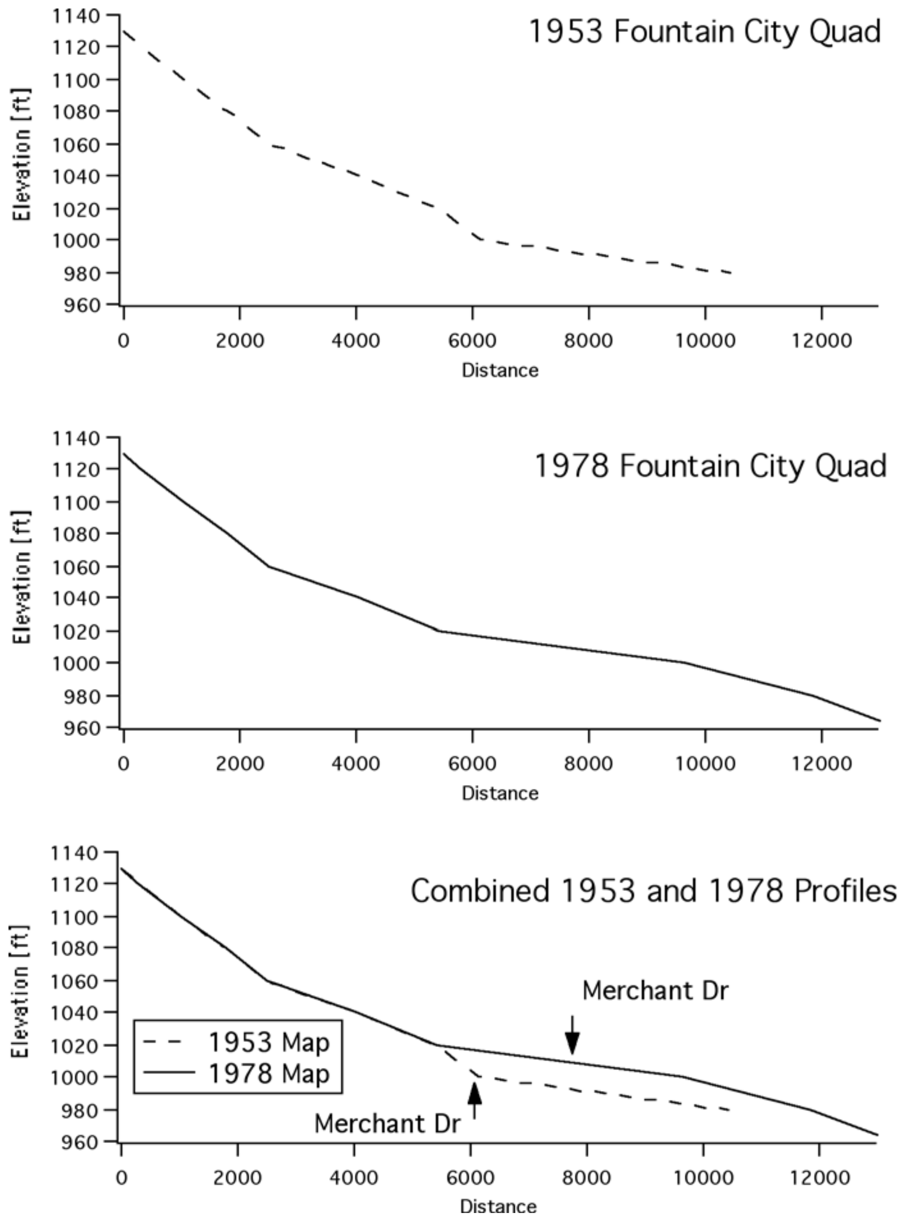

Figure 3.24. Longitudinal stream profiles in the Merchant Drive area. Second Creek was lengthened to flow around the I-75/Merchant Drive interchange, and, as a consequence, the slope of the stream was reduced in that area. Elevation and horizontal distance are presented in miles, as on the original maps (1 m = 3.28 ft; 1 km = 0.624 mi).

Figure 3.25. Bare soil exposed during construction projects. *Top*: Looking south towards the I-75 – I-640 interchange. *Bottom*: Looking south at Merchant Drive. Both photographs were taken in 1979. (Photographs from TVA archives, Knoxville, TN.)

I watched turbid water flowing down storm drains and ditches that drained to this part of Second Creek in 1999. Unless sediment reduction measures have become more effective since that time, sediment from this part of the basin is contributing to the suspended load of Second Creek. Judging from the material I collected in rising stage samplers at Site I, particle sizes are generally fine, and much of the sediment from this area may be carried through Second Creek as washload. If so, it does not have much effect on channel stability.

Heiskell Avenue Area

The culverts and concrete walls in this part of the channel were undoubtedly constructed at the same time as the overpass and interchange at Heiskell Avenue were built. The upper photograph reproduced in Figure 3.26 was taken in January 1979, when construction of culverts under I-275 through Sharp Ridge was occurring not far upstream of the Heiskell site. The photograph clearly shows sediment with vegetation growing on it in the channel on the downstream side of the onramp to northbound I-275. The presence of vegetated alluvium indicates that significant amounts of sediment had previously accumulated, and that it had been there long enough to allow the growth of plants. I suspect much of the sediment came from earlier highway construction adjacent to the creek. Deposition of some of the construction-generated load may have been encouraged near Heiskell Avenue if the new stream culverts and concrete walls were wider than the channel immediately upstream of them.

A photograph of the Heiskell culvert area taken in 2001 (Figure 3.26, lower part) shows more sediment in the channel than was present in 1979. In addition, the thalweg now follows a more sinuous course in this particular part of the stream than it did in 1979.

Tennessee Avenue Area

Photographs of Second Creek adjacent to the Coster Yard area taken in 1979 show a series of tall concrete pillars in a concrete-lined channel (Figure 3.27). This part of the channel was located under I-275. In the early 1980s, Second Creek was moved to the west approximately 45 m, where it was placed in a new concrete-lined channel. The interstate highway was placed on fill material in the creek's old location. I estimate that about 100 m was added to the length of the stream during the relocation. If the drop in elevation from the upstream end to the downstream end of the stream segment remained the same, which seems likely, its slope would have been reduced 7/100 of one percent, from 0.59% to 0.52%. This is not a great change, and accordingly, it should not have triggered a great deal of channel aggradation.

There are other possible causes for the sediment deposition in the channel following its relocation. Slopes adjacent to and close to Second Creek upstream of this segment were bare of vegetation during interstate highway construction (as shown earlier in Figure 3.25.) It seems likely that large amounts of sediment continued to be delivered to Second Creek from these slopes for several years, until a thick vegetative cover was established.

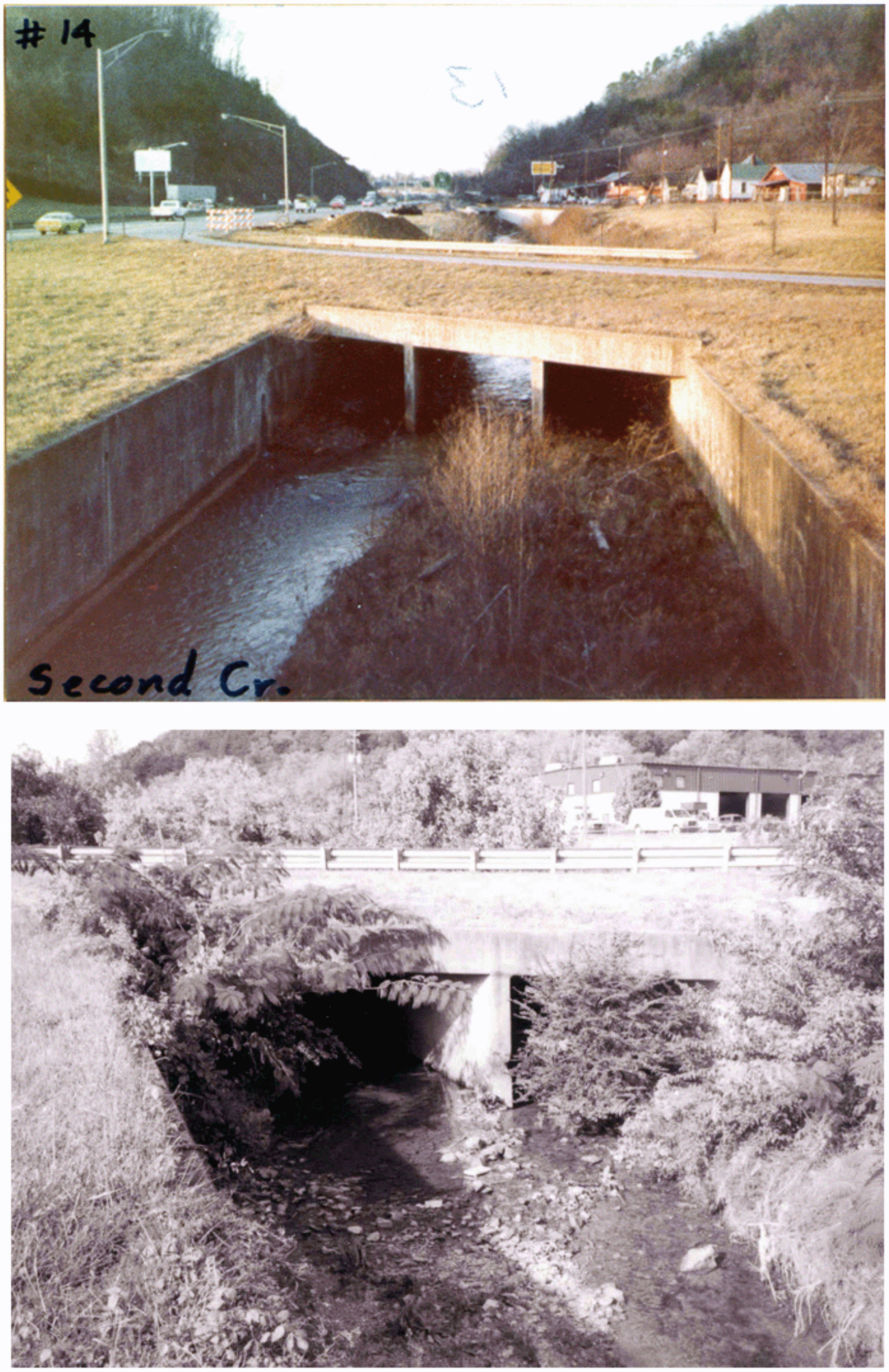

Figure 3.26. Old and modern photographs of the Heiskell culvert area. The triple box culvert shown is located under the on-ramp to I-275 N. Top photograph was taken in 1979, the lower photograph in 2001. (Top photograph from TVA archives, Knoxville, TN. Bottom photograph by the author.)

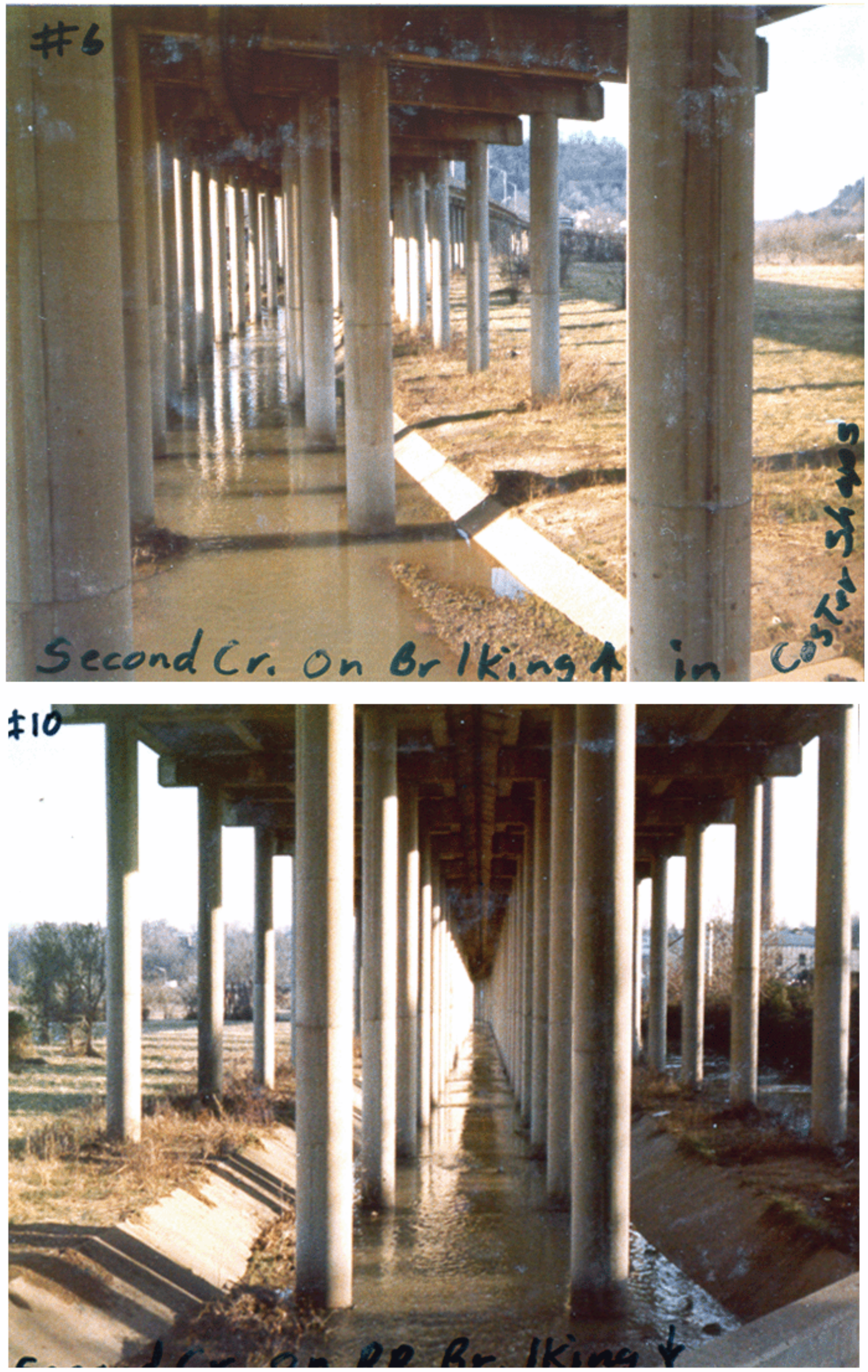

Figure 3.27. Support piers for I-275 in Second Creek in 1979. The view is upstream in the top photograph and downstream in the lower one. (Photographs from TVA archives, Knoxville, TN.)

Some of this sediment could have been deposited in the Tennessee Avenue segment and stabilized by vegetation instead of being transported farther down the stream.

Deposition in certain places in the channel could have been triggered where there were local increases in channel roughness. Two sources of roughness in the smooth concrete channel are rocks from the riprap-covered slope above the left bank and where the branches of riparian trees and shrubs hang down into the channel. Some of the larger rocks in the channel may have rolled into the channel during the time the riprap was placed on the slopes or soon thereafter, and therefore be colluvial in nature. I suspect that many have been thrown or rolled into the channel more recently. There are houses close to this part of Second Creek, and I have seen children playing on the Tennessee Avenue Bridge and the nearby riprap-covered slopes. The stream bottom close to the bridge contains a greater number of large rocks than found in most other parts of this concrete-lined stream segment.

Davanna Street Area

This segment contains abundant evidence of severe erosion, especially in the portion of the channel upstream from the Oldham Avenue Bridge. The cause of much of the erosion may be the loss of a significant amount of floodplain upstream, in the Coster Yard area. Low-lying land in that area was still accessible to floodwater in 1979, as shown in the photograph in Figure 3.27. In the early 1980s, a long, tall ridge was constructed to support I-275, cutting off the floodplain from Second Creek. If this has been a factor in accelerating erosion downstream of the Coster Yard area, the stream channel has had less than 20 years to become adjusted to the new hydrologic conditions.

The Entire Channel

There is a great deal of variation in channel width to depth (W/D) ratios (shown in Table 3.3) in Second Creek. Although some of it was likely caused by difficulty in locating bankfull levels, the scatter in ratio values typifies the variation that exists between different parts of the channel. Stream channels often shown an increase in W/D ratios in a downstream direction (Gordon, et al., 1992). W/D ratios in Second Creek should be relatively low, as it is a small, second order stream. Rosgen (1994) calls W/D ratios <12 in natural streams "low," but notes that the limit of the category can fluctuate by ± 2. Fourteen of the 18 cross-sections in Second Creek have ratios <12, but only 10 of them have W/D ratios <10.

Channel materials and channel dynamics also affect W/D ratios. In natural areas, wider, shallower channels generally occur where sand and gravel are the primary bank materials, and narrower, deeper channels are usually found where banks are composed of bedrock or a mixture of clay and silt. The latter have more cohesion than mixtures of larger clasts, such as sand and gravel (Schumm, 1977). There are no sand or gravel banks along Second Creek, but portions of the channel are lined with concrete, rock, brick, timbers, or bedrock. I did not measure cross-sections in parts of the channel that had walls on both sides and rock or concrete forming the bed, a situation that could be regarded as the urban equivalent of a bedrock channel, but I did measure 3 locations with a wall on one side. The W/D ratios in those places were 14.3, 4.5, and 9.5 (Table 3.3). This suggests that factors other than channel materials are also affecting channel shape.

Channels undergoing aggradation or degradation experience shifts in their width to depth ratios, becoming wider and shallower (higher W/D) as aggradation occurs and narrower and deeper with channel degradation. Channel enlargement, the typical response to urbanization, is often accomplished through bank erosion, producing channels with greater W/D ratios. This, in combination with factors such as turbulence due to structures in the channel and anthropogenic widening, may explain the higher W/D ratios I found at four locations in Second Creek.

Rapid or catastrophic streambed incision may occur as a response to urbanization in some locations (Booth, 1990), but I found little evidence in Second Creek of this sort of change in the channel. This was not surprising, as there are many concrete-floored or metal culverts and periodic outcrops of competent bedrock to act as grade controls along the length of the channel. The longest portion of Second Creek between places with either bedrock or concrete in the bed is about 1.3 km. It is located from a place between the I-40 E onramp and Oak Avenue to the downstream end of the culverts under Baxter Avenue. There were a few places, mainly in the downstream part of the stream, where there was evidence of a small amount of bed incision.

The stream segment farthest upstream (near Merchant Drive) was the only location that had deep, fine, unconsolidated sediment in the bed. Sediment may still be accumulating in that part of the channel. The other places where I found significant amounts of recent (in the last three decades) channel aggradation were in concrete-lined sections of the channel located roughly halfway along the length of the perennial stream. The sediment was well-consolidated (easy to walk on), and much of it supported the growth of shrubs and small trees. Erosion of channel banks seems to be the dominant process in the channel upstream and downstream of these areas of deposition. There was some evidence of erosion of the active channel banks in the areas of sediment accumulation. I suspect that sediment accumulated and stayed in the concrete-lined channel and box culverts because the floors or "bed" of those structures was built wider than the rest of the channel. The sediment has served to reduce the size of the active channel to approximately what it is in nearby areas where the banks are formed of regolith. If this is so, and sediment is cleared from these areas, it would most likely build up again over time.

In the downstream third of the stream, from south of the Coster Yard area to the mouth of the stream, there were very few signs of deposition, but much evidence of erosion in places not protected by rock or concrete. If this trend continues, it will cause problems where railroad tracks, businesses, parking lots, sewer lines, or other pieces of infrastructure lie adjacent to the channel.

CONCLUSIONS

From my examination of the channel of Second Creek, it is apparent that this stream as a whole has not reached a state of quasi-equilibrium. Although short in length, the stream channel is far from homogeneous in condition. Some segments of the stream appear to be relatively stable, some experiencing mild aggradation, and many undergoing rapid channel enlargement, primarily through bank erosion.

Sediment accumulations in parts of the channel lined with concrete at different times from the late 1960s to early 1980s provide evidence of recent (within several decades) aggradation. Most of these deposits, located about halfway between the headwaters and outlet of Second Creek, have become thickly vegetated, indicating rapid aggradation has essentially stopped. Recent aggradation may have occurred in other parts of the channel not lined with concrete, but it could not be identified as recent without a known maximum age provided by a concrete-lined channel or culvert or some other artifact to make dating possible. Active aggradation, shown by the presence of fine alluvium in the channel and by mid-channel or lateral bars, is occurring in a few locations, but is minor in extent.

This is not the case for channel erosion, however. Evidence from many parts of the stream indicates rapid erosion is occurring. Most material has been removed from the channel banks, increasing channel width, rather than depth. There are a few places with evidence of streambed incision, but the rate of incision, while rapid by geomorphic standards, is not catastrophic, as it was in cases reported by Booth (1990), nor is it likely to become so because of the grade control exerted by natural outcrops of bedrock and concrete and metal culverts. Both occur with some frequency along the course of the stream.

Quite a lot of sediment has been stored in the channel of Second Creek since the 1960s, and some of it, especially where located downstream of the Coster Yard area, is likely to contain pollutants. It is possible that unusually large storms and the high stream discharge that would follow could result in the entrainment and rapid spread downstream of sediment that has been stored in or along the stream for decades.

Approximately 38% of the channel of Second Creek is lined with concrete. Thick or thin riprap lines about 60% of the remainder in the downstream of Baxter Avenue, and only about 10% of the upstream part of the creek.

CHAPTER 4

SUSPENDED SEDIMENT

INTRODUCTION

Running water has been identified as the most important geomorphic agent in shaping landscapes (Ritter et al., 1995). Once particles of rock or soil have been moved by water, they are referred to as sediment (Goudie, 1994), and while in motion they constitute the sediment load. The volume and caliber of sediment delivered to a stream are determined by many factors, including both storm and landscape characteristics.

Once in streams, the sediment load becomes one of several factors that affect the shape and size of stream channels, as discussed in Chapter 3. Of more immediate concern to many people than changes in stream channel dimensions are water quality problems. Sediment has been identified as the most widespread pollutant in rivers and streams in the United States (USEPA, 2000) and in Tennessee (Denton et al., 2002). It fills reservoirs and lakes, affects drinking water treatment processes, and plays an important role in the transport of contaminants, especially metals and nutrients, which are readily adsorbed onto clay-sized particles (Dong et al., 1984; Beckwith et al., 1986; Novotny and Olem, 1994). The transportation of contaminants is of concern in Second Creek because, as mentioned in Chapter 2, this creek has been known to contain hazardous levels of metals, nutrients, and pathogens, and to carry high amounts of sediment. Where polluted sediment is deposited, contaminants may become detached from sediment particles and migrate into water or groundwater (Logan, 1995). There is also the possibility of further spread of contaminants if sediment deposited in the channel in earlier times becomes exposed, re-entrained, and carried to downstream locations during periods of high flow.

Fine sediment can be harmful even if toxic chemicals are not present, as sediment deposits degrade or destroy stream habitat for many aquatic organisms (Ellis, 1936; Culp et al., 1986; Weaver and Garman, 1994; Waters, 1995; Wang et al. 2000). The habitat that supports the greatest number of aquatic species includes a mix of larger particle sizes, from boulders down to sand-sized (Gordon et al., 1992). High sediment loads also reduce the recreational uses and aesthetic appeal of streams.

All of the land within a drainage basin is potentially a source of sediment. Mineral particles that have become loosened from parent material through weathering processes become available to be picked up and carried downhill by running water, although when this occurs depends on several different factors. Erosion rates are higher where sparse vegetative cover and steep slopes prevail, where the land surface is smoother rather than rougher, and where the erodibility of surface regolith or rock is high (Elliot and Ward, 1995). Because the location, intensity, and duration of storms and the condition of vegetation and the land surface change with time, the sediment delivered to streams typically has spatially and temporally diverse sources.

Particles may be carried from the site of weathering to a stream during one runoff event, or in an interrupted, downhill stepwise manner during a series of them. The greater the distance from a stream, the greater the chance that eroded particles will not be carried to the stream during one runoff event, but rather will be deposited and stored for some length of time. Thus, the sediment delivery rate is lower for larger drainage basins than for smaller ones (Schumm, 1977; Trimble, 1977). Second Creek drains a small (18.6 km^2) area, therefore sediment delivery rates should be high. In addition, Second Creek flows through an urban area, where ditches and culverts speed storm runoff and whatever sediment it carries to the creek.

The amount of sediment contributed to streams in areas undergoing development is expected to increase dramatically from pre-development levels during construction, but to drop to low levels once the urbanization process is complete, when most land is occupied by pavement, buildings, or lawns (Wolman, 1967; Trimble, 1995). Soil loss from areas made impervious essentially ceases, but new sources of sediment are created. Fine particles are generated by the disintegration of roads, automobile tires, and vehicles; from construction sites, industrial areas, unpaved roads or alleys; and from high-use grassy areas where soil is exposed (Beckwith et al., 1986; Line et al., 1996). These particles tend to accumulate until storm runoff flushes them into streams. Although the amount of sediment from such urban sources is typically low compared to the amount of sediment generated during land development, it is not negligible. When sediment concentrations were measured in samples collected with automatic water samplers from several subbasins in Knoxville, they were found to vary by land use category (TVA, 1984). The greatest amounts of sediment came from strip commercial areas, with less from the central business district and medium density residential areas, and the least from low density residential areas. The drainage basin of Second Creek includes these land uses and others, including industrial areas and transportation corridors. The TVA (1984) report notes that automatic sampler intake lines repeatedly clogged when water levels were below 0.3 ft (0.1 m), so samples were not collected until water levels rose to that height. There was no mention of the type(s) of material causing the clogging of the lines.

Sediment can also come from within the stream channel, if stream banks, beds, or alluvial bars erode during high water events. Channel enlargement typically occurs in streams downstream of urban areas, as discussed in Chapter 3. Accelerated erosion of stream channels receiving runoff from newly urbanized areas continues until the channels become wide and/or deep enough to accommodate post-development hydrologic and sediment-supply regimes (Hammer, 1972; Ebisemiju, 1989; Henshaw and Booth, 2000).

When particles are entrained by flowing water, as typically occurs during storm runoff events when water levels are high, they will be transported as long as water velocity and depth provide sufficient energy. As water levels fall after the main pulse of stormwater moves downstream, successively smaller particles are deposited in the channel and, if the stream flowed out of its banks, in the areas flooded. The smallest particles, those less than about 0.0625 mm, remain in suspension in streams almost indefinitely. These fine particles, the wash load, are so small and settle so slowly that very little washload material is found in the beds of streams (Graf 1984).

Komar (1988) points out that differentiating washload and suspended load in practice may not be possible, and Gordon et al. (1992) note that saltating bedload particles may be trapped in suspended sediment samplers. I use the terms "suspended load" or "suspended sediment" to refer to all material collected in suspended sediment samplers.

Because determining the state of adjustment of Second Creek to urban conditions is a major goal of this study, I examined the suspended sediment load of the stream with the objective of finding answers to the following questions:

1) Are sediment concentrations low (<100 mg/L)? If Second Creek has progressed beyond the stage of accelerated erosion of its channel, and if sediment contributions from land in the basin are low, as expected in long-urbanized areas, overall sediment concentrations should be low.

2) Is more sediment coming from the upper and middle parts of the basin, where there are more strip commercial areas, than from the lower part of the basin?

3) Are sediment concentrations affected by the time intervals between high flow events? If a significant percentage of the suspended sediment load comes from the basin rather than from erosion within the channel, sediment concentrations should vary with length of time between storms. Longer between-storm intervals provide more time for sediment to accumulate in the basin before being flushed into the stream, whereas sediment deposited in the channel during waning flows or eroded from banks or bed by stormwater should not be affected by the length of time between storms.

METHODS

During three low (base) flow and nine small storm events, I used depth integrating samplers to measure the suspended load at a location several hundred meters upstream of the stream outlet (Figure 4.1). The sampling site was located under the second footbridge downstream of Cumberland Avenue. The reasons for selecting this site were that the location is reasonably close (less than 300 m upstream) to the outlet of Second Creek, the footbridge is essentially perpendicular to the length of the channel, and the footbridge is on the same level as an adjacent parking lot. The lack of steps to the footbridge allowed easy access from truck to bridge for the DH-59 depth integrating sediment sampler and Class A bridge boom, the heavier equipment I used when the water was too deep and fast to use a DH-48 depth integrating sampler on a wading rod. I did not select the bridge over Neyland Drive, located only 21 m upstream of the outlet of Second Creek, as a sampling location for several reasons. The traffic over that bridge was normally heavy, there was limited room to maneuver equipment, there was no good parking space adjacent to the bridge, and, most importantly, when water levels are moderate to high in

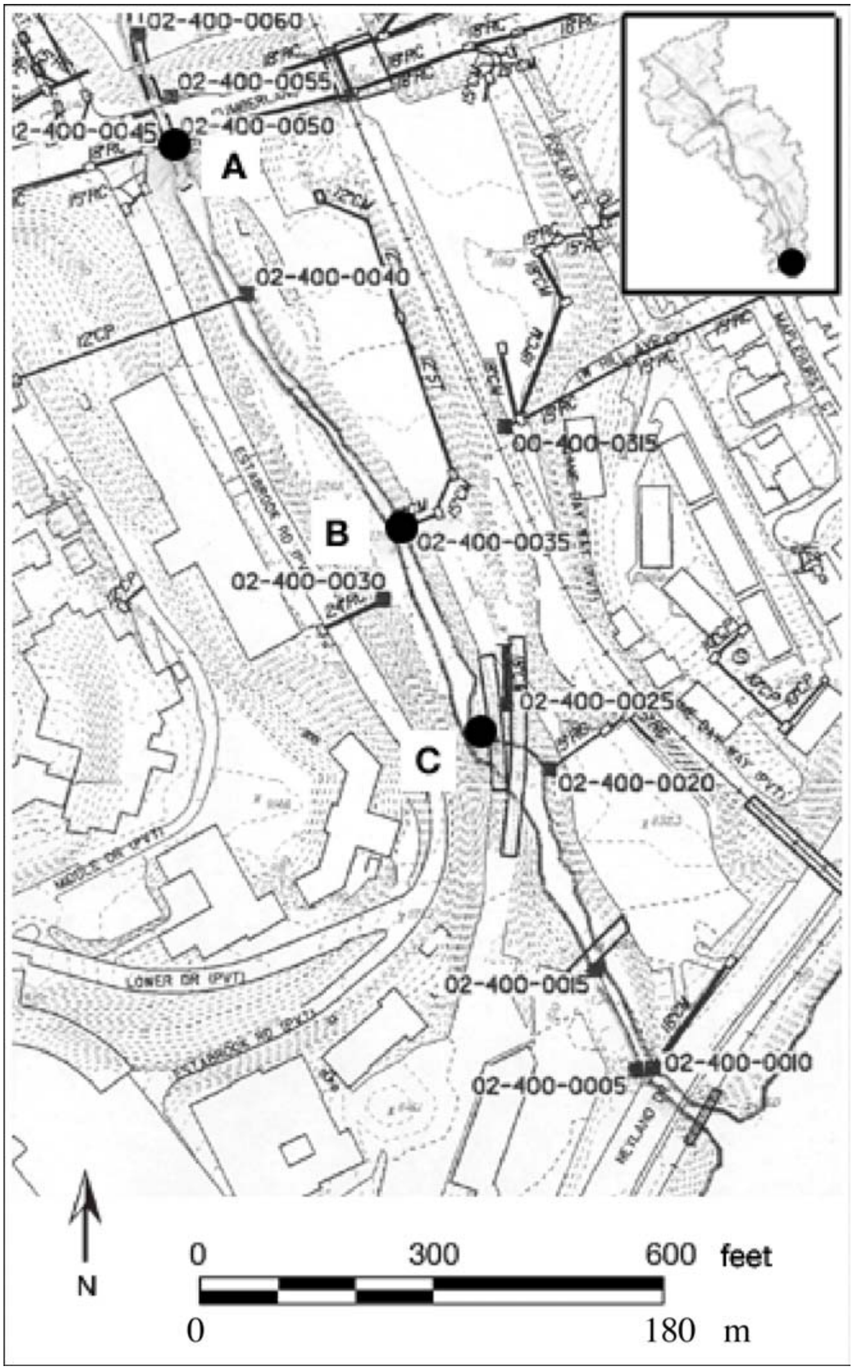

Figure 4.1. Location of sediment sampling sites in lower Second Creek. Site A is the City of Knoxville's sampling location in the box culvert under Cumberland Avenue; "B" marks the location of Sampling Site UT, located at a footbridge; and "C" indicates the location of Sampling Site U, the farthest downstream location of rising stage samplers. (Base map from City of Knoxville Stormwater Engineering, Knoxville, TN.)

Fort Loudoun Lake, the slack water of the reservoir extends up Second Creek past this location.

I measured stream discharge immediately before or after collecting the sediment samples, using a Price AA current meter when water levels were high or a Pygmy meter when they were low. For these measurements I followed U.S. Geological Survey protocol (USGS, 1977), using the six-tenths method because stream depth was either too shallow or changing too rapidly to use the two-point method.

To get a better idea of the spatial variation in sediment concentrations than I could obtain using depth integrating samplers, and to be able to sample water during each high water event, I used rising stage samplers (called "single stage" samplers by the Subcommittee on Sedimentation, 1961). Rising stage samplers consist of a vertically arrayed series of sample bottles. In my samplers, glass jars were spaced every 152 mm (6.0 in) vertically, with the bottom of the lowest jar positioned to sit at low water level at the edge of the stream, on or close to the streambed. The number of jars in the vertical arrays depended on how high I judged the water would rise in all but the most exceptional floods.

Each 250 ml (0.5 pint) jar ("jelly"-size canning jars) had a water intake and air exhaust tube sealed into holes in the lid (Figure 4.2). Both tubes had an interior diameter of 6.4 mm (0.25 in). The height of the tubes allowed approximately 120 to 140 ml of water/sediment mixture to be admitted into each jar. Because of the design of the equipment, each sample was collected as the surface of the rising water reached the top of the intake tube. Thus, only surface water or near-surface water (when there were waves) was collected in each jar, no matter what its vertical position in the array at each sampling site.

In most installations of this type, the jars are held on a post or board placed at the edge of a stream (Subcommittee on Sedimentation, 1961; Finlayson, 1981; Gordon et al., 1992). Fearing destruction or loss of the jars due to large debris such as pallets, tree limbs, and sections of utility poles (objects in the flotation load that I observed in Second Creek during times of high flow), I placed the sample jars within sturdy PVC jar holders and located them out of the direct line of stream current. The sample jar holders were attached with stainless steel hose clamps onto steel fence posts that were driven into the streambed. As a further precaution against losing jars and holder in case a fence post was dislodged, I secured each sample holder to a stake in the ground, a tree, or a bridge support with lightweight but strong steel cable.

Within the holders, each jar sat on a short bolt covered with plastic tubing, and was held in place by a bolt extending clear though the holder. These bolts were positioned just above each jar lid between the water intake and air exhaust tubes. The bolts had nylon lock nuts, so that two wrenches were required to remove jars from the holders. I took this measure to thwart the removal of jars by visitors other than myself to the sampling locations.

Figure 4.2. Rising stage sampler. (Photograph by the author.)

I placed arrays of rising stage samplers at four sites in the stream and at one location in a tributary close to its confluence with Second Creek (Figure 4.3). In describing locations in or adjacent to the stream, I will use the terms "left bank" or "right bank" to refer to the streambanks as they would appear to an observer standing in the stream facing downstream. Listed in order from upstream to downstream, and shown in the photographs in Figure 4.4, the sampling locations were:

Site I (Inskip), on the left bank of the creek 190 m downstream of the downstream edge of Merchant Drive and 14 m upstream of the unnamed tributary along the north side of the Inskip ballpark.

Site C (Clinton), on the left bank of the creek immediately upstream of the entrance to the large concrete box culvert under the I-640/I-75 highway interchange.

Site D (Dutch Valley), on the left bank of the tributary draining Dutch Valley (east of Second Creek and north of Sharp Ridge), about 8 m upstream of a concrete box culvert that joins Second Creek under the I-640/I-75 highway interchange.

Site H (Heiskell), on the second concrete pier from the downstream side of the Heiskell Street overpass over I-275.

Site U (University), on a wooden bridge trestle near the left bank of the creek. The trestle is one of the supports of the first vehicle bridge located downstream of Cumberland Avenue. The site is on the farther upstream of two closely spaced, almost parallel bridges. Its location is approximately 190 m upstream from the mouth of Second Creek. The stream flows parallel to the bridges at the sampling site, then makes a sharp bend to the left about 9 m downstream and flows under both bridges.

These sites were selected for ease of access; for duplication, when practical, of former water quality testing sites; for locations that would yield data on the relative contributions of sediment from different parts of the drainage basin; and for places where some protection for the samplers was available. I installed the rising stage samplers during the first eight days of October 1998. During a year of sampling, I visited all five sampling sites after the water receded, following almost all high water events. At each site I collected the jars that contained water and replaced them with clean, dry sample jars. Samples that could not be processed immediately were stored in a large cooler kept at 5^{o} C.

In the laboratory, I used a Millipore vacuum filtering system and pre-wetted, dried, and pre-weighed fiberglass filters to separate suspended solids from water. I followed EPA-approved lab procedures as described by Hach (1992) for total nonfilterable residue (Suspended Solids), Method 8158, except that I used entire samples of about 110 to 145 ml for the analysis. I soon discovered that this technique was not adequate for samples containing large amounts of sediment, as the filters became clogged before the entire

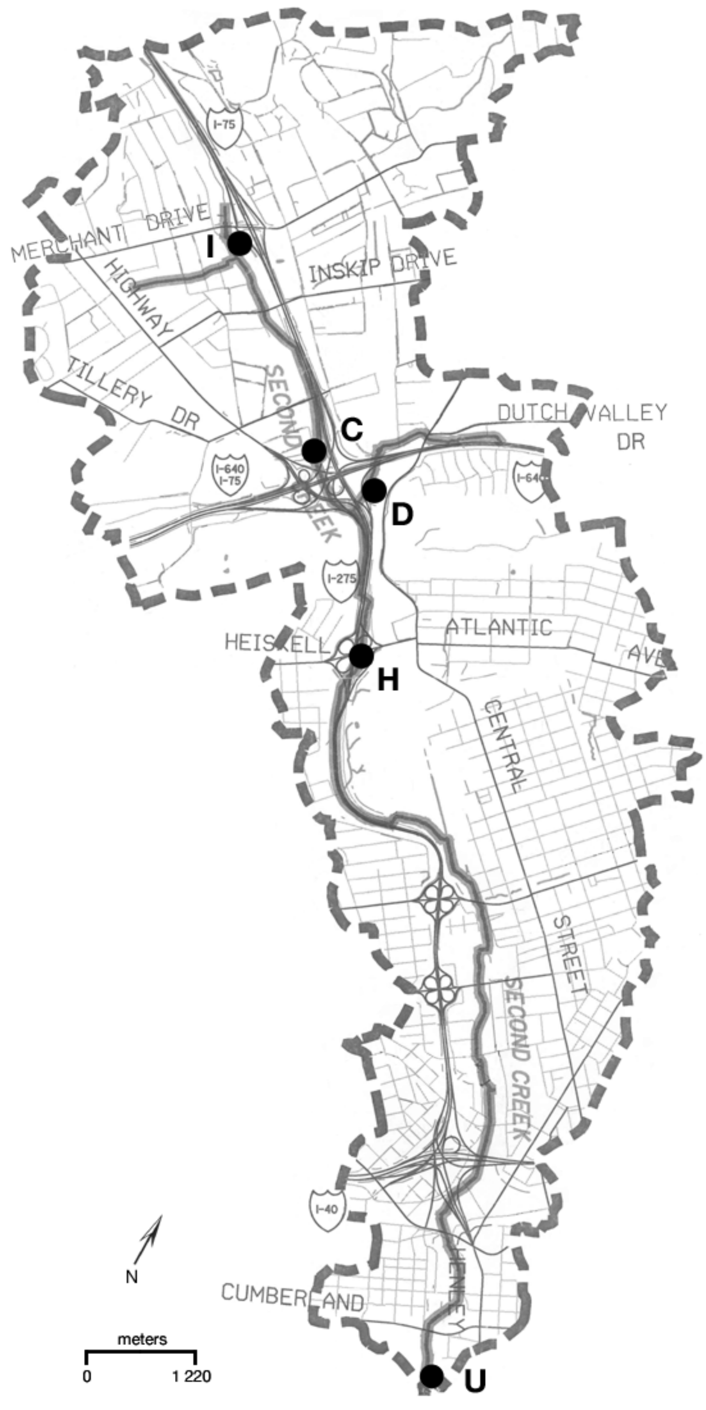

Figure 4.3. Locations of rising stage sediment samplers. The letters stand for nearby streets or landmarks: I = Inskip, C = Clinton, D = Dutch Valley, H = Heiskell, U = University. (Base map from KGIS, Knoxville, TN.)

Figure 4.4. Photographs of rising stage sediment samplers in place. *Top*: The Inskip site sampler, looking upstream. *Center left*: The sampler is in the right side of this photograph of the Dutch Valley Tributary, looking upstream. *Middle*: The Heiskell location, looking upstream. The shadow of the farthest downstream support can be seen at the base of the sampler. *Center right*: Sampling site U, looking upstream. *Bottom*: Site C, looking downstream. (Photographs by the author.)

sample could be drawn through them. In cases where sediment was more than one or two millimeters deep in the collection jar after settling, I modified the lab procedure. In these cases, after moving the sample jars into the processing lab, I let them sit undisturbed until the sediment settled to the bottom and the water above appeared clear. Then I decanted most of the water, measured its volume, and filtered it, following the procedure mentioned above. Next I agitated the sediment/water mixture left in the bottom of the jar and poured it into a graduated cylinder. The volume of all rinse water required to complete the transfer of sediment to the graduated cylinder was recorded and subtracted from total sample volume. Following the volumetric measurement of the sediment/water mixture, I transferred the samples to small pre-weighed crucibles, again poured off and filtered excess water, and oven-dried, cooled, and weighed them using an analytical balance, as described in the Hach method, except that I extended the drying time to two hours. Fine particles remained trapped in the filters after drying, so it was not possible to analyze the sediment samples for particle size distribution following the lab procedure described above.

RESULTS

During low (base) flow, stream discharge was between 0.10 and 0.21 m^3/sec (3.6 and 7.5 cfs) under the footbridge at Site UT. The concentration of suspended sediment during those conditions was less than 8 mg/L, based on samples I collected with a DH-48 depth integrating sampler. These results are consistent with the usual visual clarity of the water during low flow. On two different visits to the creek downstream of Cumberland Avenue, the water was low but was not clear in appearance. In both cases, the water had a light blue, somewhat opaque appearance, rather than the normal tan-brown color of turbidity caused by suspended sediment.

Between August 13, 1997 and June 14, 1998, I sampled suspended sediment with depth integrating samplers at Site UT during nine different high water events. Water level was rising as I collected samples and measured stream velocity in three of the events, and was falling as I gathered data during the other six events. Sediment concentrations ranged from 10.0 to 443 mg/L. A comparison of water discharge and sediment concentration is shown in Figure 4.5, and complete results from the depth integrating sampling are shown in Appendix D.

I collected 375 samples with rising stage samplers from 46 high water events. The period of sampling began in early October 1998 and ended in mid-October1999. During this time, water levels did not go above the highest sampling jar at any site. Table 4.1 shows the number of samples collected at each vertical position at each sampling station. Site U, the farthest downstream of the sampling locations, experienced more frequent rises in water levels than any of the other sites; thus, there are more samples available from this location in spite of the fact that the equipment at Site U was installed eight days and two high water events later than equipment at the other four sites. Suspended sediment concentrations for all samples collected with the rising stage samplers are listed in chronological order in Appendix E.

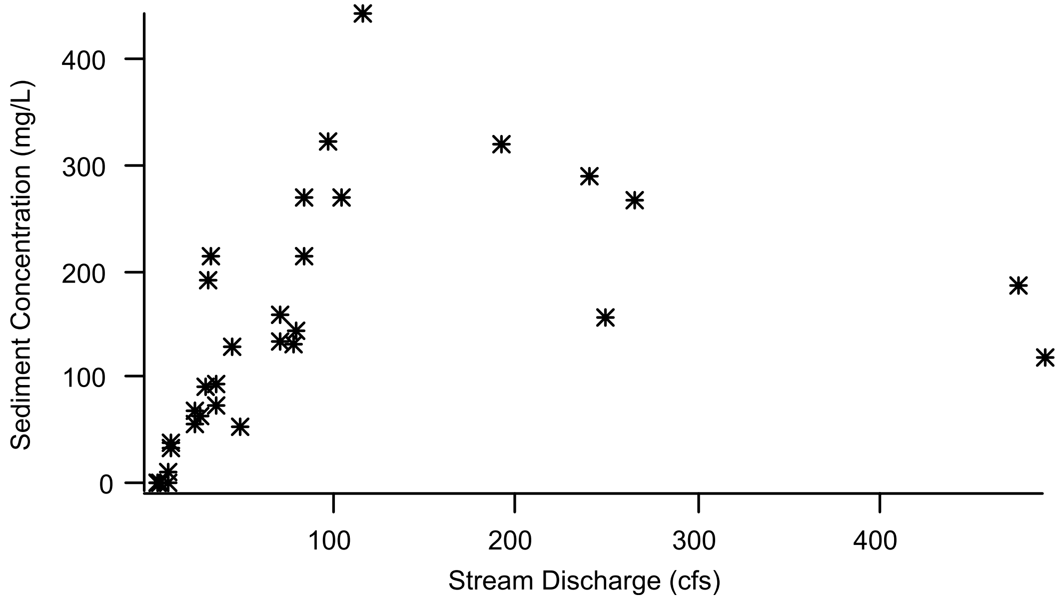

Figure 4.5. Suspended sediment concentrations at Site UT. These samples were collected with depth integrating samplers at several different times.

Table 4.1. Number of samples collected at each site[1].

Vertical Distance of Intake Above Bed	Site I	Site C	Site D[2]	Site H	Site U
Level 7 (1067 mm)	0	0	0	1	2
Level 6 (914 mm)	2	1	0	0	5
Level 5 (762 mm)	5	2	0	1	8
Level 4 (610 mm)	12	4	2	2	13
Level 3 (457 mm)	17	9	4	3	20
Level 2 (305 mm)	22	17	12	9	36
Level 1 (152 mm)	38	34	25	26	43

[1]Sites are listed from upstream (Site I) to downstream (Site U)
[2]Site D was located in a tributary, close to its junction with Second Creek.

Although there was more than an order of magnitude difference in sediment concentrations at each of the five sites during the year of sampling, as shown in Figure 4.6, sediment concentrations were generally high. At Site U, near the outlet of the creek, 57 samples (45.5%) of the 128 collected and processed had sediment concentrations between 1,000 and 10,000 mg/L, and slightly more than one-third of the samples had extremely high concentrations, greater than 10,000 mg/L.

The lowest jar at Site U often had sand and gravel packed around it after high water events. After one event (on June 13, 1999), a new piece of very coarse gravel with a b-axis of 45 mm was lodged against the base of the sampling stand. During the entire year of sampling, the largest gravel left on the lid of the lowest jar at Site U, which sat 98 mm above the bed, had a b-axis of 15 mm. The largest piece deposited on the lid of the second jar up, 250 mm above the bed, measured 7 mm along the b-axis. None of the other jars at Site U had particles larger than sand-size on their lids after being submerged. The lowest jar at Site H had several particles of coarse sand or very fine gravel (1 – 3 mm) on the lid after one high water event. On two occasions sand and gravel were deposited around the lower part of the bottom jar. The jars at Site I, the farthest upstream of the sampling locations, usually had 1 – 3 mm of fine sediment ("mud") on their lids after high water events, and the jars in the tributary (Site D) usually had a thin or non-continuous layer of mud on them. The other jar tops were usually clear of sediment following high water events.

Sediment concentrations were usually higher when more storm water (as represented by greater depth) flowed down the stream. This is illustrated by a comparison of samples in jars from adjacent vertical positions. Jars at the lowest level at all sites contained higher sediment concentrations than jars at the next level up 169 times out of 201, or 84% of the time. This upwardly decreasing trend continued in samples taken at greater distances from the bottom of the stream.

In general, sediment concentration increased with distance downstream. This is shown by increasing median values in the downstream direction (Table 4.2).

A comparison of sediment concentration and the time between high water events is shown in Figure 4.7. As is evident from the scatter of points, there was no significant correlation between these factors.

DISCUSSION

It was difficult to use depth integrating samplers to gather sediment data during high water events. Challenges I encountered included (1) being able to get to the sampling site with the equipment before the water began to rise, (2) having time to sample at multiple locations across the stream before the level of the water changed, (3) finding time to stay at the stream and sample throughout the duration of high water events, (4)

Table 4.2. Median suspended sediment per runoff event from rising stage samplers.

Site	Median Sediment Concentration (mg/L)
I (upstream)	399
C	2,355
H	3,336
U (downstream)	4,590
D (tributary)	409

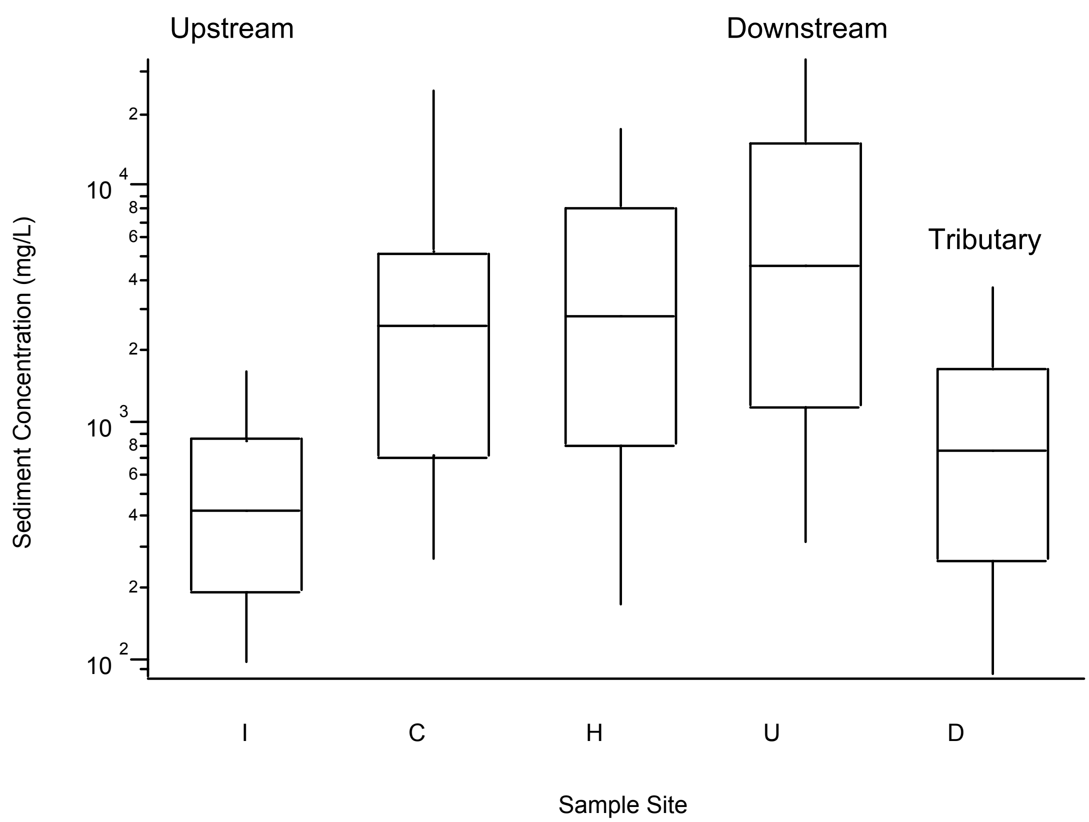

Figure 4.6. Suspended sediment concentrations from all sites. These samples were collected with rising stage samplers.

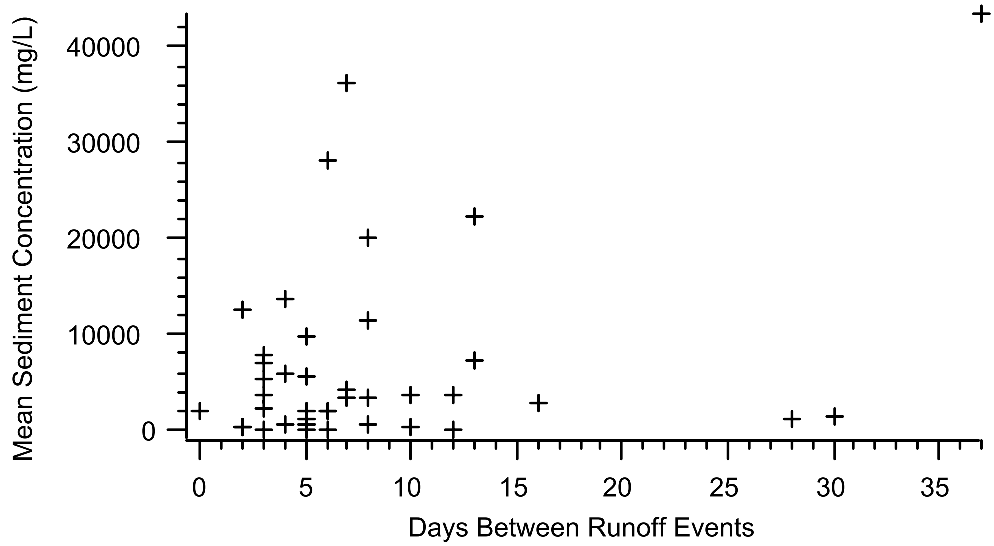

Figure 4.7. Sediment concentrations versus time between storms.

preventing equipment damage and/or loss due to large debris, (5) being limited in sampling locations during high water events by the locations of suitable bridges, and (6) the possible danger and the inconvenience of working during rainstorms.

An examination of the rising stage data (in Appendix E) reveals a general pattern of decreasing sediment concentrations with increasing height above the streambed. However, there are exceptions to this pattern. Several different phenomena affected some of the results, and probably caused at least some of these seemingly anomalous sediment concentrations. At Site I, a nearby sewer line backed up and flowed out of a manhole close to my sampling equipment under certain conditions, such as when heavy rain fell on soil that was already saturated. Part of the sewer overflow ran into Second Creek immediately upstream of the sampling equipment. Although I never tested the effluent, evidence left on the grassy field around the manhole and between the manhole and the creek gave testament to a considerable load of solids carried by and deposited from the flow. This solids-rich flow suddenly entering Second Creek may help explain some of the "out of place" values for the following samples at Site I, although dry organic material does not weigh as much as dry mineral matter.

Sediment concentrations were probably also affected in jars where the intake tubes became partially plugged with debris or gravel, presumably while the jar was filling. Such jars contained the same amount of water as the others, but had lower sediment concentrations than expected. The jars that had partially plugged intake tubes after high water events are listed below.

Site I: the lowest jar on October 5, and the third jar up on December 9.

Site C: the lower two jars were partially plugged on June 25.

Site U: the lowest and second jars on December 9, and the lowest jar on February 13 and October 4.

I found debris wrapped around the lower parts of my sampling arrays at Site C on May 19 and June 25, and at Site U on January 16. Although it did not seal off the intake and exhaust tubes, it prevented the direct flow of water from reaching sample jars low in the array. It is likely that sediment concentrations in these jars were lower than they would have been without the debris piled up against them.

I did not expect sediment concentrations to increase in the downstream direction. If the primary sources of sediment were from land in the drainage basin, as I assumed during the sediment-sampling phase of this study, then the lower part of the basin contributed higher sediment concentrations than did the upper part. Bank erosion, however, appears to be occurring in many places along Second Creek, as discussed in Chapter 3. The increase in suspended sediment concentrations in the downstream direction may be explained by the addition of eroded sediment from various places along the length of the channel. Placing suspended sediment samplers or monitors at the upstream and downstream ends of channel segments that appear to be rapidly eroding, especially those with few drain line outfalls, would provide data needed to assess the relative importance of in-channel sediment sources. There is also a possibility that some suspended sediment is piped from outside the drainage basin through crevices or channels in carbonate rocks. Studies using chemical, magnetic, or isotopic sediment "fingerprinting" or tracing would be necessary to determine the origin of sediment carried by Second Creek.

City of Knoxville stormwater engineers began monitoring stream discharge and water quality in Second Creek in 2000. They installed an ISCO automated pumping sampler that draws water from the bottom of the creek as it flows through the concrete box culvert under Cumberland Avenue. Water is not sampled during baseflow conditions. The sampler is programmed to begin a rinse and purge routine when water in the culvert rises to a certain level. Following the purge routine, it collects a sample, and continues to collect samples at 15 minute intervals during the high water event. Four samples are placed in a one-liter container. Individual containers are manually combined after the high water event to form a composite sample in such a way that the contribution from each container is proportional to the volume of stream discharge during the hour the samples were taken. Thus, the composite sample is used to represent water quality for an entire stormflow event. Composite samples are analyzed for total suspended solids (TSS) and many other water quality parameters.

Results of the City of Knoxville water quality tests are reported as event mean concentrations (EMCs), which are defined as "…the total pollutant mass discharge divided by the total runoff volume for a given storm event" (City of Knoxville, 2000 – 2001). EMCs from their monitoring of Second Creek in 2000 and 2001 are listed in Table 4.3. They calculated the suspended load for a year as 1,094,600 kg (1,200 tons).

The EMCs listed above represent low to medium sediment concentrations, using the definitions set forth by in the National Urban Runoff Program (TVA, 1984). Their definitions were:

High > 1,000 mg/L
Moderate from 100 to 1,000 mg/L
Low < 100 mg/L

In my study, sediment concentrations in water collected in the rising stage samplers were often much greater than in water collected in either the automated pumping or the depth-integrating samplers. This is particularly true of the results from Site U, the rising stage site close to the locations of the other types of sampling.

The disparity in results between samples collected with the rising stage and automated pumping equipment may be explained, at least in part, by extremely rapid increases in sediment concentrations as stormwater enters the creek. This situation was found in an

Table 4.3. Sediment event mean concentrations for Second Creek at Cumberland Avenue.[1]

Date	Total Suspended Solids (mg/L) EMC
10 Aug 00	142
8 Nov 00	104
17 Jan 01	278
13 Feb 01	178
24 Feb 01	135
12 Mar 01	88
29 Mar 01	90
6 May 01	102
21 May 01	94
20 Jun 01	188
25 Jun 01	166

[1] Data from City of Knoxville, 2000 – 2001.

urban area in Massachusetts by Solo-Gabriele and Perkins (1997), and described as "bursts" of sediment on the rising limb of the hydrograph. They ascribed the rapid increase in sediment levels they measured to the flushing of highly mobile sediment from storm sewers, from areas close to the river that drain directly into it, and from sediment deposited in the channel during earlier waning flows. It is well known that sediment concentrations exhibit hysteresis with regard to stream discharge, in that they are almost always greater during the rising limb of a storm hydrograph than on the falling limb. The size of the drainage basin affects shape of the hysteresis loop or curve by affecting the timing of peak sediment versus peak stream discharge. Smaller basins have shorter lag times between these peaks (Heidel, 1956; Reid et al., 1997), and may often experience the peak sediment concentration before the peak water discharge (Williams, 1989; Reid et al., 1997). Second Creek not only drains a small area, but is also primarily urban in character and has a typical urban, flashy hydrograph. It seems likely that the water rises so rapidly in Second Creek that the automated sampler misses early bursts of suspended sediment that pass downstream while the machinery is running its rinse and purge cycle. I also missed sampling the earliest-arriving part of the "flood wave" during the times I used depth integrating samplers. The closest I came to sampling the first rise in storm runoff water was when I collected a sample four minutes after I watched the initial surge of stormwater come down the creek. The water rose very rapidly in that event. Rising stage samplers, especially those closest to low water levels, catch samples as soon as the water rises high enough to fill the lowest jar.

Another factor that may have contributed to the difference in results may be in the design of my rising stage samplers. The intake tubes on the sample jars were vertical. There is a possibility that sediment continued to rain down into the collecting jar after it had stopped admitting water but was still submerged. I have no formal test results to disprove this, but I left sample jars in the holder at Site U for a year after the end of the sediment-data gathering period. When I finally collected the jars, the level of the water in them was similar to levels after one submergence, and they did not appear to contain more sediment than they did after one high water event during the sampling period. If a significant amount of sediment had entered the jars after the initial filling during one high water event, I would have expected the jars to be full or nearly full of sediment after multiple immersions during a year. Therefore, I do not think this factor had much affect on the results.

The placement of the rising stage samplers may have also affected the results, in that most sample jars were out of the direct current. The array at Site U was on the downstream side of a trestle post (as shown in Figure 4.4), where water eddied or swirled around it. I asked the opinion of an engineer as to whether this was likely to cause greater or smaller amounts of sediment to be captured, and he thought that the amount would be smaller than would have been collected from sampling in the main downstream current (Tschantz, 1999).

The sizes of particles collected could be causing some of the different results between rising stage samplers and the automated sampler. The intake tube of the automated sampler has a larger diameter (9.5 mm) than the intakes of the rising stage samplers (6.4 mm), but the size of the particles that the automated sampler can collect is also regulated by the amount of suction the machine produces and the length of vertical tubing between the intake and the sample bottle. Only one large particle collected by one type of equipment but not the other could make a great deal of difference in the sediment concentration of a sample.

The nature of the stream channel around and upstream of the sampling intakes may have been another factor affecting sediment concentrations. The automated sampler is located close to the downstream end of a concrete box culvert that is approximately 631 m long. This culvert is usually clear of sediment. Upstream of the box culvert, the stream channel is lined with concrete that also contained no or little sediment whenever I checked it during the late 1990s. In contrast, the rising stage samplers at Site U were surrounded by sand, gravel, and cobbles, and were downstream of approximately 275 m of non-hardened channel. Thus, the rising stage samplers could have been measuring sediment that was eroded from the nearby channel or from scouring close to the base of the sampler, in addition to sediment delivered from farther upstream.

If there is an early, rapid spike in sediment concentration that is missed by most sampling equipment or techniques, it might be causing a significant underestimation of the sediment load of Second Creek. To estimate the effect of an early high sediment peak, I calculated yearly sediment loads using several different assumptions about the duration of the high sediment concentrations. My calculations were based on a hydrograph from August 10, 2000 that was generated by the City of Knoxville using data from their instruments under Cumberland Avenue (Figure 4.8). Judging the shape of the hydrograph to be typical of most for high water events in Second Creek, I retained the shape of the curve while adjusting peak values to correspond to the highest water levels at Site U during each event during the year of sampling. I estimated peak discharges for each of the 46 high water events by noting the maximum height the water reached in each event, and by comparing the height with a stage versus discharge rating curve I developed from Site UT, 95 m upstream. I calculated the sediment load for the year of rising stage sampling in the following three ways:

1) Median rising stage sediment concentration values represented the sediment load for all stream discharge during the rising limb of the hydrograph

2) Median rising stage sediment concentration values represented the sediment load for only the first half of the rising limb

3) Median rising stage sediment concentration values represented the sediment load for only the first five minutes of the high water event.

In all scenarios, the median rising stage sediment concentration was derived by including all the times a certain number of jars filled during the year. For instance, for an event that

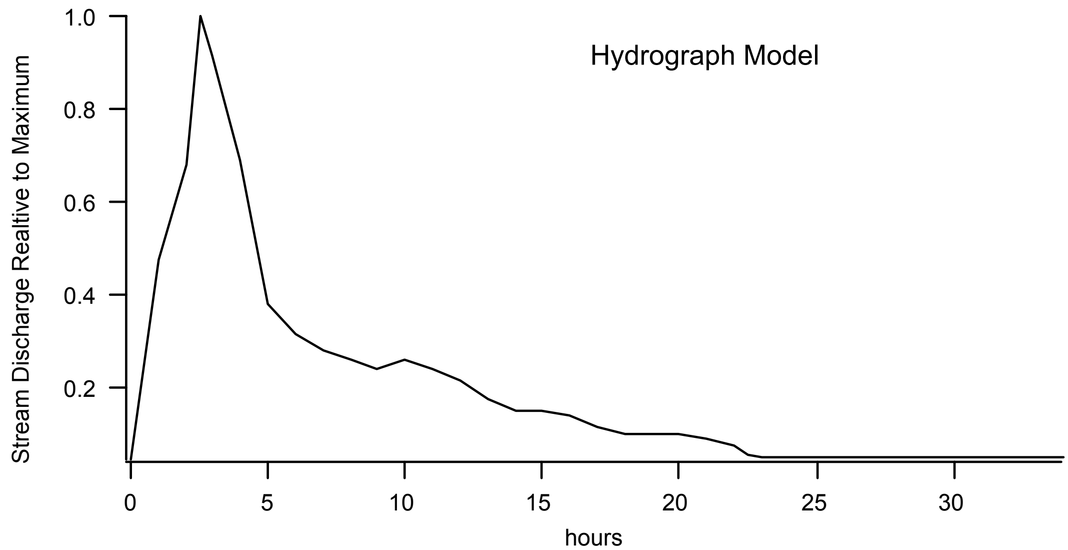

Figure 4.8 Normalized hydrograph model used in sediment load calculations. (Data taken from City of Knoxville Stormwater Engineering, Knoxville, TN.)

filled 3 jars at Site U, I calculated the median value of all the jars that filled during all 3-jar events at Site U. Sediment concentration values for the falling limb came from my measurements with depth integrating samplers during the falling limb of the hydrograph. I noted stream discharge at the halfway point in time along the falling limb of the representative hydrograph, and selected the sediment concentration associated with that amount of discharge to represent sediment concentrations during the entire falling limb.

The three sediment loads I estimated (to the nearest hundred kg) for October 1998 to October 1999 are shown in Table 4.4, in comparison with City of Knoxville (1993) estimates of yearly suspended sediment load. In my opinion, the third Grable estimate or a result slightly higher (if very high sediment levels exist for more than 5 minutes following the initial rise of water) best represents the actual situation in Second Creek, where there seems to be an extremely high amount of sediment in the initial rise of stormwater, followed by a rapid decline in suspended sediment concentrations.

The City of Knoxville (2000 – 2001) more recently estimated the yearly TSS load for Second Creek to be 1,949,800 kg, based on suspended sediment data collected with an automated sampler and the use of a watershed model. This figure is reasonably close to the yearly sediment load I estimated, and may indicate that the initial high sediment "wave" at the leading edge of a stormwater runoff event may be too brief to have a major effect on the yearly sediment load. All the estimated sediment loads discussed above include sediment transported during high water events and omit sediment transported during periods of low flow.

Precipitation during the year of rising stage sampling was 147.8 mm (5.82 in) above normal, although many months had below normal or almost normal precipitation (Table 4.5). Much of the surplus occurred during the month of July. These precipitation data were collected at the official weather station for Knoxville, located at McGhee Tyson Airport, about 21 km south southeast of the center of the Second Creek drainage basin. Some precipitation is widespread, and totals for that type of precipitation should be similar at the airport and in the basin of Second Creek, but precipitation often varies in

Table 4.4. Estimates of yearly suspended sediment load (kg/yr).

Year Estimated	Estimate By	Low	Medium	High
1993	City [1]	934,000	3,512,500	7,080,900
1998 – 99	Grable[2]	1,257,200	5,585,700	17,879,400

[1] City of Knoxville (1993) estimates based on a TVA (1984) sampling and a watershed model.
[2] Estimates based on rising stage and depth integrating sediment samples collected by the author and using a standardized hydrograph.

Table 4.5. Precipitation and rising stage sediment sampling[1].

Month	Total (in)	Total (mm)	Departure From normal (in)	Departure From normal (mm)	Days ≥0.5 in (12.7 mm)	Days ≥1.0 in (25.4 mm)	Days With Samples At Site U	No. of Samples At Site U
October '98	1.42	36.1	–1.42	–36.1	1	0	0	0
November	2.51	63.8	–1.24	–31.5	2	0	3	6
December	5.95	151.1	1.41	35.8	4	3	4	15
January '99	6.62	168.1	2.45	62.2	6	3	4	14
February	3.50	88.9	-0.56	–14.2	3	0	6	11
March	4.73	120.1	–0.36	–9.1	4	1	5	8
April	3.40	86.4	–0.32	–8.1	3	0	4	7
May	4.92	125.0	0.79	20.1	4	1	4	14
June	5.58	141.7	1.61	40.9	3	2	3	17
July	12.66	321.6	7.99	202.9	7	5	6	21
August	0.85	21.6	–2.28	–57.9	0	0	2	10
September	0.82	20.8	–2.25	–57.2	0	0	1	1
October	2.84	72.1	0.00	0	3	1	2	5

[1] Precipitation data for McGhee Tyson Airport, Knoxville, from National Climatic Data Center, 2003.

intensity and duration over short distances. The latter is especially true for thunderstorms, a common type of precipitation in the summer in Knoxville. If the amount of precipitation in the vicinity of Second Creek was close to the amount recorded at the airport, my yearly sediment load estimates may be somewhat higher than would occur during years of normal or below normal precipitation.

CONCLUSIONS

Sediment levels in Second Creek are generally high (> 1,000 mg/L) to extremely high (> 10,000 mg/L) during the initial part of high water events, as measured by rising stage samplers. Samples collected with automated pumping equipment and depth integrating samplers have moderate (100 to1,000 mg/L) and a few low (< 100 mg/L) concentrations. The timing and techniques of the latter types of sampling cause the omission of samples from the initial rise of stormwater, when sediment concentrations are most likely the highest, but provide samples from the remainder of the high water event. Overall, sediment concentrations in Second Creek are not low, even though almost all land in the drainage basin was developed over 40 years ago.

Sediment concentrations, as measured by rising stage samplers, do not indicate that more sediment comes from the upper part of the drainage basin than the lower part. Instead, suspended sediment in the rising stages of stormwater runoff events generally increases from upstream to downstream. More study will be necessary to quantify the relative contributions of sediment from different parts of the drainage basin and from erosion of the stream channel.

There was no correlation between rising stage sediment concentrations and length of time between storm runoff events. One possible explanation for this result is that the amount of sediment flushed from land surfaces, ditches, and culverts in the basin may be minor in comparison with the amount of sediment entrained from within the channel of Second Creek.

Planners and others concerned with water quality should be aware that controlling the amount of sediment entering urban streams will have little effect on reducing total suspended sediment loads if much channel erosion is occurring. A more effective method of reducing suspended sediment would be to implement better storm runoff control. Ideally, bankfull discharge should not occur more than 1.5 to 2 times per year, the average recurrence interval for streams in natural areas (Dunne and Leopold, 1978).

CHAPTER 5

BED MATERIALS AND BEDLOAD

INTRODUCTION

Coarse particles in streams alter the flow of water and thus affect channel morphology. The roughness of stream channels increases when large particles are present, and channel roughness is one of the factors that affect water velocity, as shown by the Manning equation:

$$v = 1.49 \frac{R^{2/3} S^{1/2}}{n}$$

where v = velocity, R = hydraulic radius, S = slope, and n = a roughness coefficient. (This version of the equation requires the use of English units.) Byrd, Furbish, and Warburton (2000) found the velocity profiles of streams to be disrupted by coarse particles with greater diameters than 1/10 of the depth of water.

When stormwater flows into streams, progressively larger particles can be moved as stream velocity and depth increase. This creates a sorting effect, as larger particles move only while stream discharge is high, whereas smaller particles move for longer times and thus greater distances during the same high water event. In general, the greater the discharge, the less frequent the event, so smaller particles have more opportunities to move than large ones. For example, Chin (1998) calculated that boulders 1 m or more in diameter could be expected to move every 100 to 200 years in mountain streams in coastal California, while smaller particles (< 200 mm) were in motion at least every 5 years.

Material that moves along the bed of a stream by rolling, sliding, or saltation (bouncing) is called bedload. The size of a particle strongly affects its mode of transport. Knighton (1984) notes that gravel-sized particles typically roll, and sand-sized particles generally travel by saltation.

The amount of bedload in streams has been estimated to range from 0 to 50% of the total sediment load (Morisawa, 1968; Reid and Frostick, 1994). Bedload is not often included in sediment yield calculations because measuring bedload is difficult, dangerous, and expensive. Conditions are extreme when most bedload particles are moving. Water velocities and turbulence are high, turbidity is likewise high, water depths are greater than during normal flows, and floating debris of considerable mass is frequently carried along with the current during high water events. In addition, many studies have found the amount of bed material in motion to vary from side to side across streams, and at one station through time, for a variety of reasons (Gomez et al., 1989). Because of the difficulties involved with measuring bedload, it is often ignored, and the term "sediment load" typically refers only to suspended load.

Coarse material may be delivered to stream channels by mass wasting processes such as debris flows or landslides on slopes adjacent to streams (Ritter et al., 1995; Grant and Swanson, 1995; Benda and Dunne, 1997). These events occur sporadically, most often during or after heavy rains, at locations dependent on factors such as the angle of slope and bedrock; amount, type, and health of vegetation; degree of weathering and depth to bedrock; and others. A wide range of particle sizes may be delivered to streams via mass movement. Mass movement is not as likely to occur in urban areas as in natural areas, because of measures such as terracing, drainage systems, and retaining walls that are used in areas with steep slopes to prevent it.

Erosion of poorly consolidated stream banks or bed may liberate coarse particles, or, in bedrock-lined channels, particles may be quarried, plucked, or knocked loose from the submerged part of the channel by impact from clasts (the process of corrasion) during high water events (Tinkler and Wohl, 1998). Bedload, like suspended load, eventually accumulates in reservoirs, lakes, oceans, or other places where stream velocity drops to low levels.

Although there is often a shift towards finer sizes in the sediment delivered to streams after urbanization (Booth and Jackson, 1997), coarse particles may also be added to streams in urban areas. They may come from exposures of bedrock in the channel, as occurs in natural areas, but they are also commonly added to urban stream channels to armor streambanks (as riprap or rock or brick walls). Rocks may roll or fall into the channel at the time of emplacement, or may roll, slide, or fall into the channel later, due to weathering and erosion of the surrounding materials. Items other than rocks or bricks are sometimes intentionally dumped into streams. Examples are refuse, noted by Ebisemiju (1989), and slag (Hess and Johnson, 2001). Many studies (e.g., Wolman, 1967; Leopold, 1973; Graf, 1975; Trimble, 1995) have focused upon changes in channel morphology and sediment delivery to streams due to urbanization of their drainage basins. However, there are, to my knowledge, no previous studies of the effects of anthropogenic debris on particle size distributions in streams. Ebisemiju (1989) touches on the subject with a mention of the common practice of dumping refuse into urban streams in Ado-Ekiti, Nigeria. Although he notes that the introduced refuse causes a reduction of water velocity, ponding, sediment deposition, and increased flooding, he does not include information about the quantities or sizes of particles introduced into those streams. In a recent study, Pizzuto et al. (2000) compared particle sizes and other parameters in paired urban and rural streams in Pennsylvania, but they did not mention the presence of non-natural particles in any of the streams they examined.

This part of my study of Second Creek focuses on the loose material in the streambed. The sizes of the particles are important, as they affect streamflow and thus channel shape and stability. Anthropogenic particles affect channel stability just as much as naturally generated particles, but they have been largely ignored in fluvial studies of urban areas.

Very few studies include measurements or estimates of bedload, especially for urban streams. To help bridge these gaps in knowledge, and to better understand the sediment dynamics of Second Creek, I examine the creek to find answers to the following questions:

1) What sizes are the particles in the bed of the stream?
2) What proportion of them are anthropogenic?
3) Are the anthropogenic particles numerous and/or large enough to alter statistical measures, such as the median particle diameter (D_{50}), that are used in bedload transport and other fluvial formulae?
4) How much bedload is this small urban stream transporting?

METHODS

Particle Size and Origin

I selected eight different locations along Second Creek for particle size measurements (Figure 5.1). The sampling sites are named after nearby streets or highways. Their names, in order from upstream to downstream, are: Inskip Drive, Clinton Highway, Heiskell Avenue, Tennessee Avenue, Woodland Avenue, Bernard Avenue, Interstate 40, and Cumberland Avenue.

The criteria I used for selection of particle size sampling sites included:

1) relatively straight stream segments (not on curves or bends),
2) spacing of sites at roughly equal intervals of 1 to 1.2 km along the stream,
3) general homogeneity of particle sizes in the length of stream to be measured,
4) weak riffle/pool or run channel bed morphology,
5) relatively easy accessibility,
6) close to a prominent landmark for documenting purposes, and
7) water depths less than 0.4 m at low water

I used the Wolman (1954) pebble count method to characterize particle sizes of the surficial material at each site. At each site, I measured more than 100 particles (actual counts ranged from 102 to 135.) To avoid bias in sampling, stream traverse locations were determined using random numbers for distance upstream rather than using a fixed interval. Sampling points across the stream were spaced at regular intervals. Most particles selected were picked up from the streambed and measured with a metal tape. A few were too large to pick up, so they were measured in place. Because of polluted water in the stream, the person reaching into the stream wore waterproof gloves. It was very difficult to pick up particles less than 4 mm in diameter while wearing gloves, so that size was the smallest measured. The b-axis length of the particles was recorded in phi-scale classes (Krumbein, 1936) in separate categories for natural and anthropogenic particles.

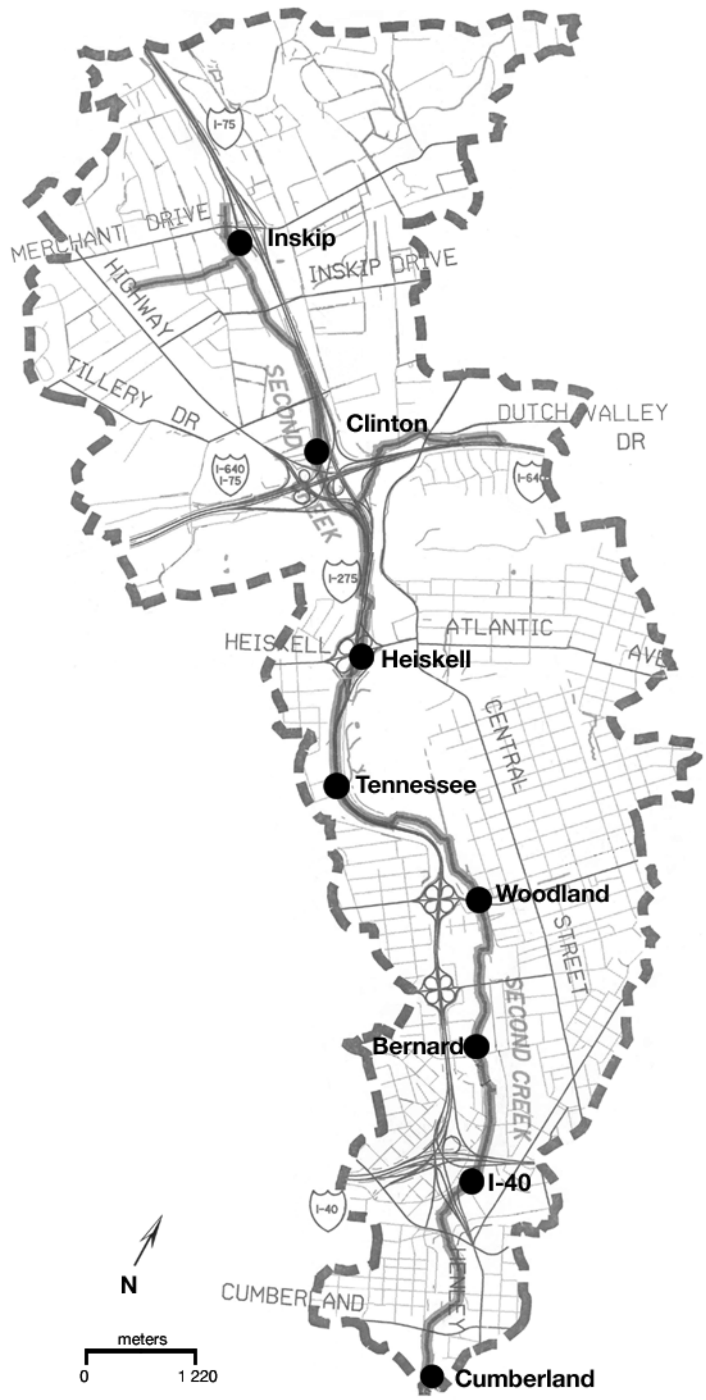

Figure 5.1. Particle size sampling sites. (Base map from KGIS, Knoxville, TN.)

In phi notation, $\phi = -\log_2(d)$ where d is the particle diameter in mm. I followed the convention mentioned by Leopold (1970), and represented particles by the smallest diameter in their size category. For example, a particle with a diameter of 7 mm was listed in the $\phi = -2$ (4 to 8 mm) category. This is analogous to the results of sieving, where a 7 mm particle would be held on a 4 mm sieve. Fine particles were all recorded in one size category, "less than 4 mm."

For anthropogenic particles, the type of material (e.g., brick) and the size were recorded. It was very difficult to discern the origin of most particles smaller than 4 mm, so I categorized them as natural rather than anthropogenic. In addition, if there was any question as to whether rocks were derived from riprap or from bedrock, or if gravel could have been liberated from concrete, I recorded them as natural.

Estimate of Bedload

In the winter and spring of 1998, during times when the water in Fort Loudoun Lake was low, a considerable amount of sediment was visible in the reservoir at the mouth of Second Creek (Figure 5.2). In June 1998, surveyors measured elevations in and around the downstream end of Second Creek, including the shoreward part of this ridge of sediment. Their purpose was to supply information needed for construction of an extension to the southwestern end of the existing pier located in Lake Loudoun. The pier is positioned roughly parallel to the shore, and it extends along the banks of the reservoir on both sides of the outlet of Second Creek. I used bathymetric data from the survey (ETE, 1998) to calculate the volume of the sediment deposited at the mouth of the Second Creek (Figure 5.3). The surveyors did not extend their measurements away from the shore of the reservoir far enough to document the outward end of the deposit, so I estimated its position as 30 m out, measured on a perpendicular from the southwestern end of the pier. The estimate of the length of the deposit was based on my observations during low water periods in the reservoir, when the sediment was exposed (as in Figure 5.2) or when it was so close beneath the surface that birds walked on it. As I did not ascertain the depth of sediment in the mouth of the creek, I defined the landward end of the sediment ridge as a point in the center of the ridge (as shown in the map), 1.2 m towards the shore from the landward side of the pier. The volume of sediment was calculated by fitting a curve to the general shape of the ridge, computing the area under the curve, and multiplying by the estimated length of the ridge.

RESULTS

Particle Size and Origin

Two to 21% of all particles sampled from the surface of the streambed at eight different sites along Second Creek were anthropogenic objects (Table 5.1). Overall, they averaged

Figure 5.2. Sediment exposed at low water near the outlet of Second Creek. These combined pictures were taken in early 1997. The view is downstream in this upper part of Lake Loudoun reservoir on the Tennessee River. (Photographs by the author.)

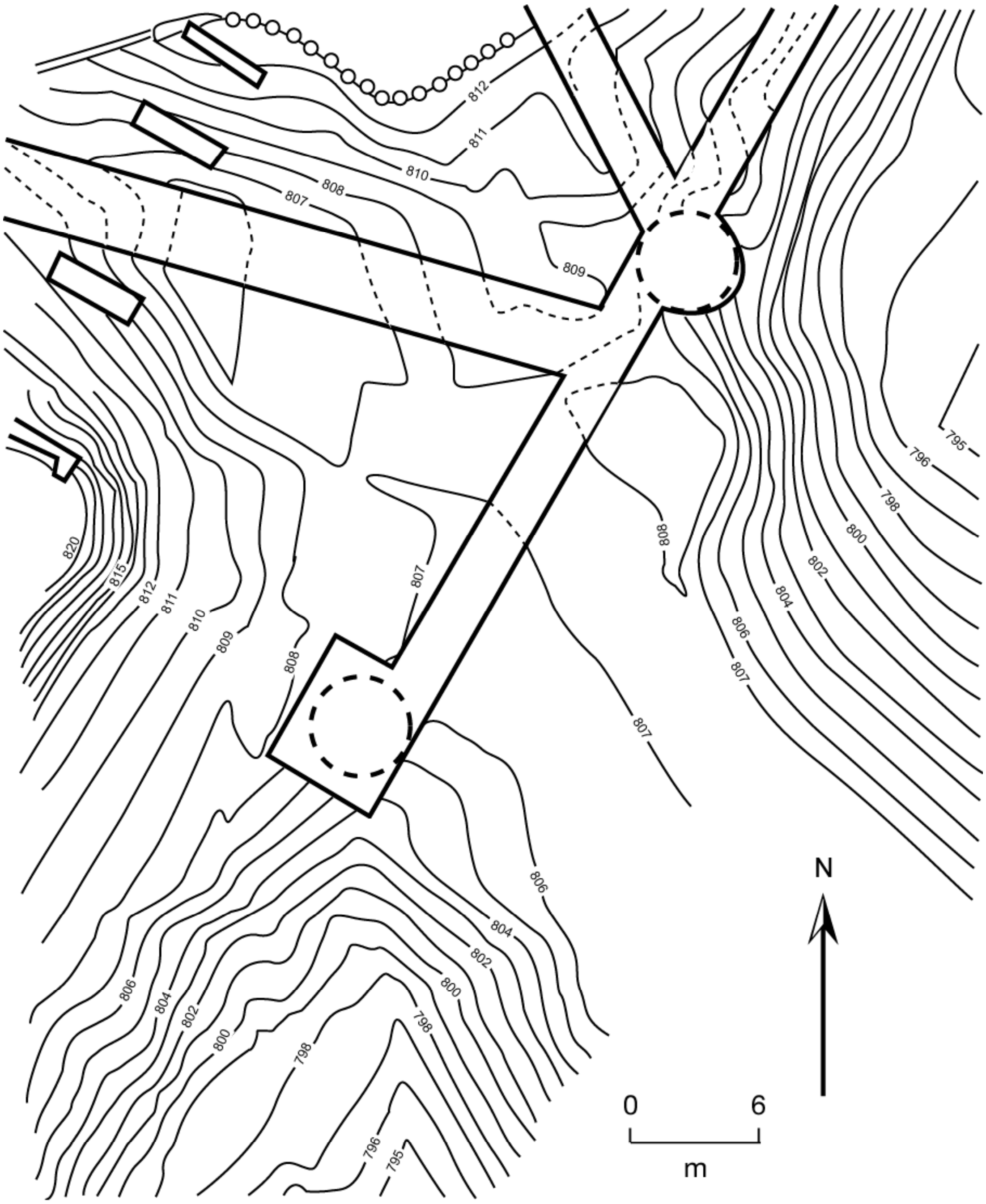

Figure 5.3. Bathymetric map of the bottom of Lake Loudoun at the outlet of Second Creek. Second Creek comes out from the upper left, under the walkway out to the pier. The positions of the circular concrete pier supports are shown by heavy dashed lines. Current in the reservoir flows from upper right to lower left. Depths shown in feet above mean sea level. (Map by ETE Consulting Engineering, Inc., 1998)

Table 5.1. Anthropogenic objects in Second Creek.[1]

	Upstream						Downstream		
MATERIAL	Inskip	Clinton	Heiskell	Tenn.	Wood.	Bernard	I-40	Cumb.	TOTAL
Riprap	10	1	0	14	1	2	0	3	31
Shaped Rock	0	0	0	0	0	0	1	9	10
Concrete	2	1	1	3	4	0	4	4	19
Cinder Block	0	0	0	0	1	0	1	0	2
Brick	0	0	0	0	6	0	4	1	11
Asphalt	1	1	0	0	5	1	5	0	13
Glass	0	0	0	0	3	4	3	1	11
Cinders[2]	0	0	0	0	0	1	2	2	5
Metal	0	0	0	0	1	2	1	0	4
Other	3	1	1	1	2	2	2	1	13
TOTAL	16	4	2	18	23	12	23	21	119
D_{50}	200	128	70	64	60	40	28	100	
% All Particles	15	4	2	16	21	8	17	19	13

[1] Sampling sites are named after nearby streets or highways which pass over the stream. Their full names, in order from upstream to downstream, are: Inskip Drive, Clinton Highway, Heiskell Avenue, Tennessee Avenue, Woodland Avenue, Bernard Avenue, Interstate 40, and Cumberland Avenue.

[2] "Cinders" are black, lightweight, volcanic-looking particles that are probably from old railroad locomotives.

13% of all particles sampled. Rocks derived from riprap and pieces of concrete were the most common type of anthropogenic particles. There was great variety in the type and size of the other particles. Materials categorized as "other" in Table 5.1 include waterlogged pieces of wood, broken pieces of clay drainage pipes, and a partly rusted bucket full of cemented-together metal parts. Objects I have observed in the bottom of the stream channel but did not encounter during particle sampling include the following:

1) various car parts
2) a shopping cart
3) most of a toilet bowl
4) a tile-layer's trowel
5) a metal folding chair
6) portions of metal, clay, or concrete pipes of various sizes
7) pieces of plastic of different types and sizes
8) a large metal vehicle loading ramp.

Henceforth I will refer to anthropogenic particles in or close to the stream channel as coarse riparian urban debris (CRUD). In many parts of Second Creek, CRUD is plentiful and often large in comparison with the sizes of naturally occurring particles.

The size distributions of natural particles and CRUD at each sampling site are displayed in Figure 5.4. There was quite a bit of variation in the sizes of natural particles at different sites, with no trend of fining in the downstream (or upstream) direction. Most sites had few particles in the $\phi = -2$ category (4 to 8 mm), and only Inskip, the site farthest upstream, had more than 10 particles in the $\phi = -8$ category (256 to 512 mm). The amount of CRUD at the sampling sites also varied quite a bit. The size of most pieces of CRUD was in the $\phi = -5$ (32 to 64 mm) category or larger. There were no apparent trends in change in size or amount of CRUD in the upstream or downstream direction.

Comparison of the median particle diameter (D_{50}) of natural particles with the D_{50} of natural particles plus CRUD at each site (Figure 5.5) reveals essentially no difference at three sites (Clinton, Heiskell, and Bernard), slight increases in median diameter at two locations (Tennessee and I-40), and large increases at three sites (Inskip, Woodland, and Cumberland). Where median particle diameters were unchanged when CRUD was added into the count, the number of pieces of CRUD was very low (less than 10% of particles sampled in each case.) Even though CRUD median diameters were considerably larger than those of the sampled natural particles, there were too few of them to have a noticeable effect on overall median diameters. At the two sites where slight increases in median diameters occurred when CRUD was included with the natural particles, non-natural particles were more numerous (16 and 17% of total particles), and their median diameters were somewhat larger than those of natural particles. The most marked change in median diameters upon addition of CRUD occurred where those objects were not only abundant but also very large. These criteria were met at the Inskip site, the site farthest

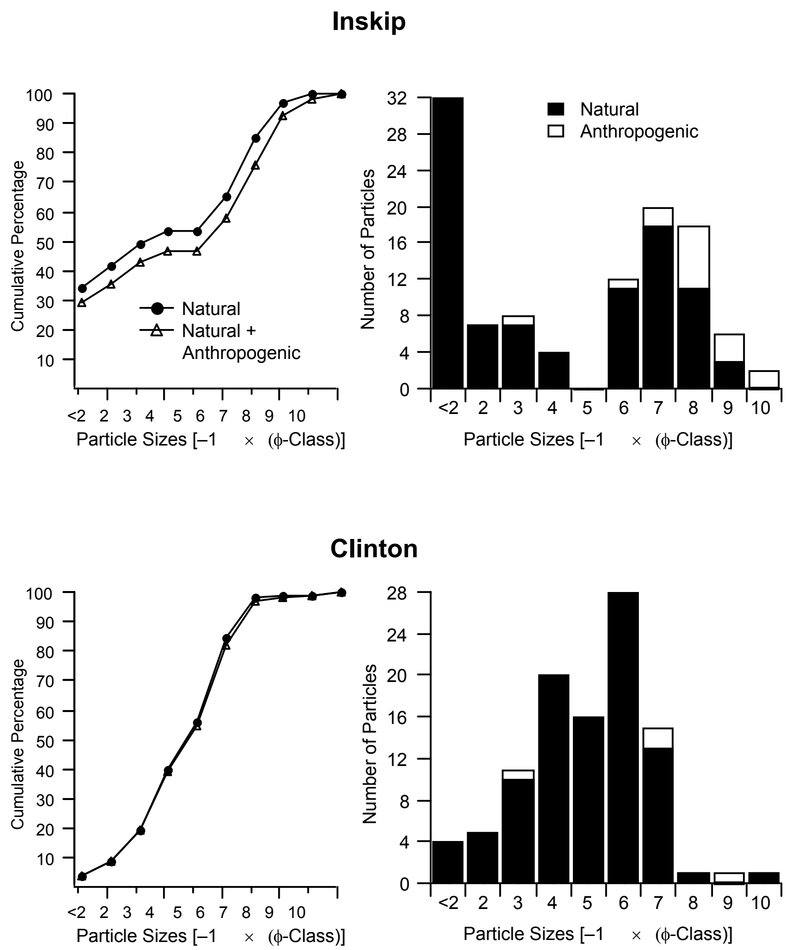

Figure 5.4. Natural and anthropogenic particle size distributions in Second Creek. Results from sites are shown in order from upstream (Inskip) to downstream.

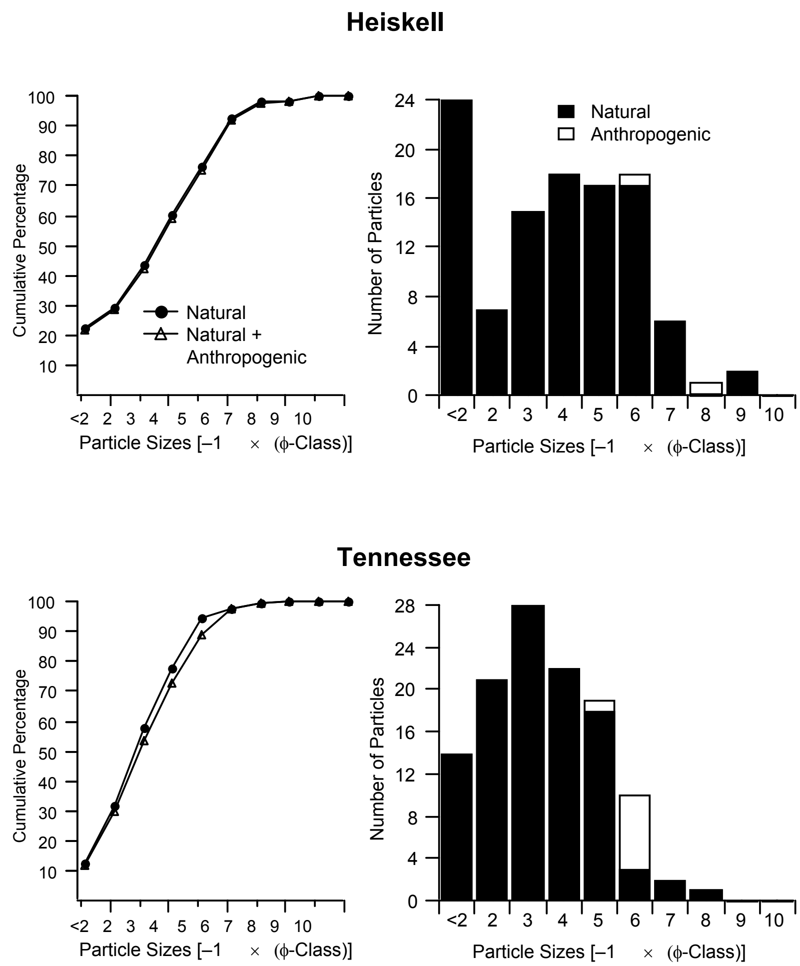

Figure 5.4. Continued

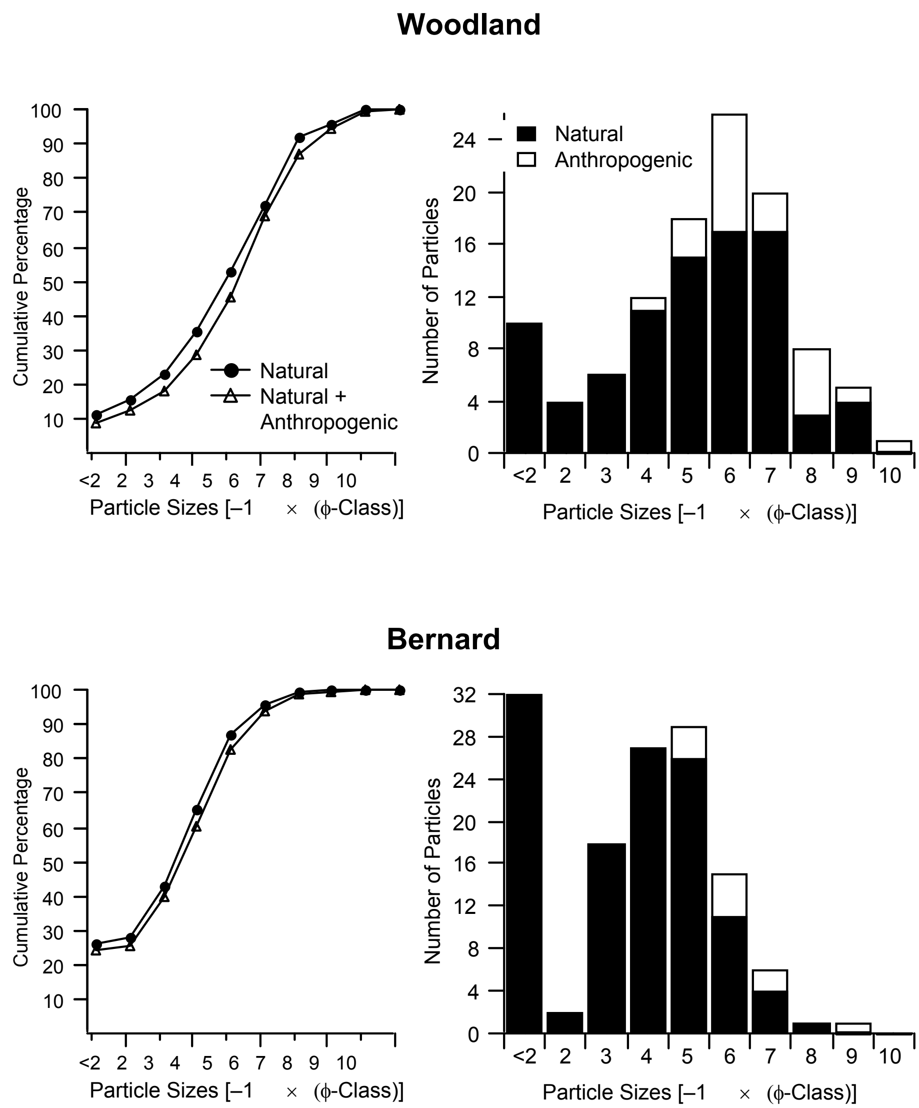

Figure 5.4. Continued

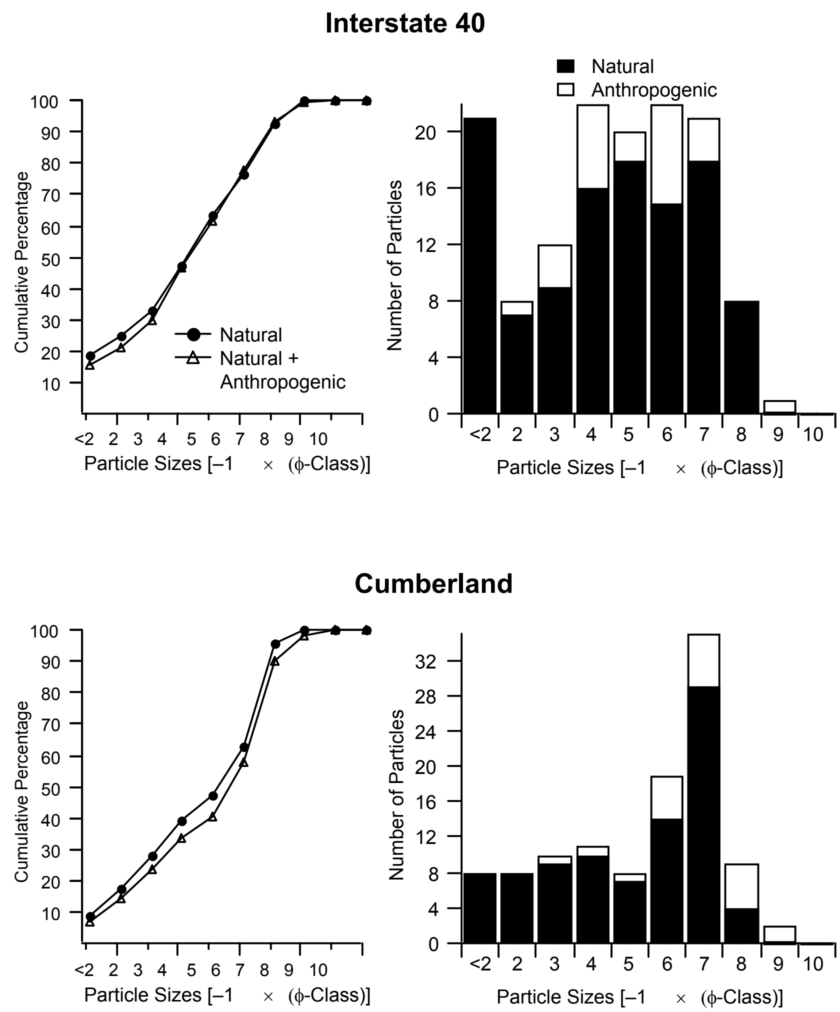

Figure 5.4. Continued

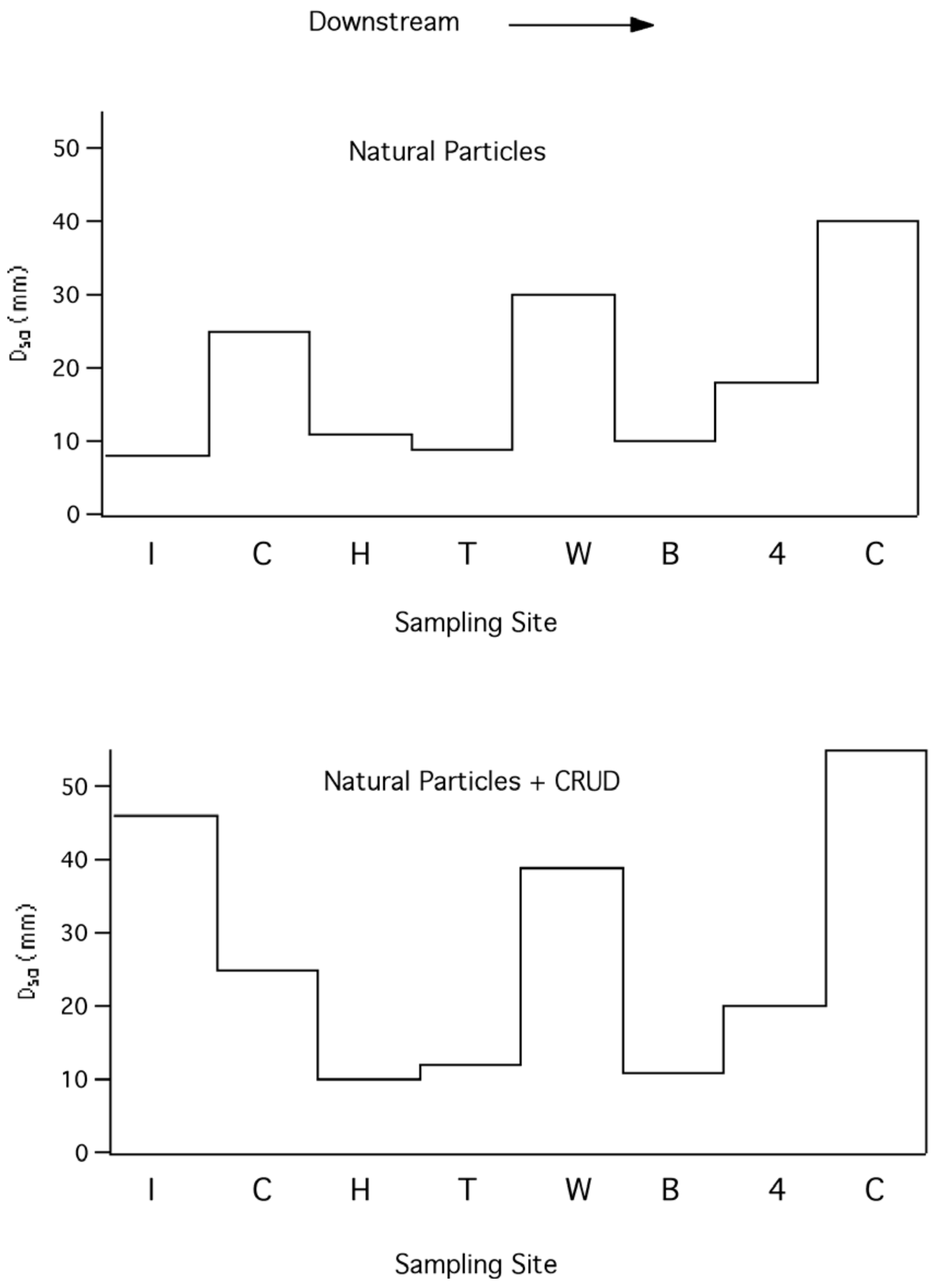

Figure 5.5. Change in median particle diameters due to the addition of anthropogenic particles.

upstream, where 15% of total sampled particles were CRUD, and their median diameter was 200 mm. The addition of these particles to the naturally occurring ones raised the median diameter from 8 to 46 mm, a jump of two ϕ-scale classes. Almost all the large pieces of CRUD at the Inskip site were displaced riprap. Near the other end of Second Creek (at the Cumberland site), rock from collapsing rock walls, displaced riprap, and pieces of concrete on the streambed caused the median diameter to increase from 40 mm to 55 mm when CRUD was included in the particle count.

Estimate of Bedload

The volume of the ridge of sediment beyond the outlet of Second Creek ("the delta") is approximately 3,650 m^3. The delta is almost certainly not more than 50 years older than the date of the survey (1998), as the outlet of the creek was moved to its present location between 1948 and 1952, based on maps of those dates. Assuming all the material in the delta was carried as bedload by Second Creek, and that all of it was deposited and remains in the delta, the average annual volume of sediment delivered to the lake was approximately 73 m^3. Using 1,601.7 kg per m^3 (100 lbs per ft^3), a common figure for converting volume of sediment in lakes or reservoirs to weight (Dunne and Leopold, 1978), Second Creek carried an average of 117,020 kg (129 tons) per year of bedload over the past half-century.

DISCUSSION

Particles in the Stream

Except for a few places where there is recent evidence of minor slumping or sliding of the stream banks, I did not see much evidence of naturally caused mass movement that would have delivered particles to Second Creek. This stream, however, is in an urban area where anthropogenic activities are common. Some "mass movement" has occurred recently as the result of the actions of bulldozers or dump trucks. I watched one instance of this, when a dump truck unloaded riprap on the banks of the stream at a newly rebuilt railroad bridge near Oklahoma Avenue. Some of the rocks rolled into the stream. Riprap of various sizes has been placed at many other locations at different times, and it is most likely that some of it entered the stream during emplacement. Some finer material, often with occasional larger clasts, has almost certainly fallen or rolled into the stream during fill and grading activities adjacent to the stream.

It seems likely that there was considerable coarse load in Second Creek in the past, when the stream was in a more pristine condition, because of the steeply dipping strata that occurs in many places along the course of the stream (see Figure 2.7). Some of those potential source areas are now covered with concrete, rock walls, or riprap (see Chapter 3 for more information on the amounts and locations). Only a few places along the modern stream contain large (greater than sand-sized) natural particles in the banks. Although some potential sources for coarse particles have been cut off from the stream, others have occurred. Anthropogenic clasts, such as bricks, cut or shaped rock, broken concrete, or pieces of asphalt are now common.

When I sampled particles at the locations shown in Figure 5.1, I listed all the small (< 4 mm) ones as being of natural origin. If some were anthropogenic, could an unknown quantity of fine CRUD affect the relative importance of CRUD in determining median particle diameters at several locations? If many of the fine particles were the weathered, broken, disassociated, and abraded remnants of CRUD, it seems likely that there would also have been many CRUD-derived particles of intermediate sizes, such as in the 4 to 8 mm category. I found very few particles in that category, and only slightly more in the 8 to 16 mm category. Also, if a great deal of fine CRUD was accumulating in the channel, there would have been lengths of the channel bed dominated by fine, deep material. There were only a few places in the streambed where there was little or no coarse material, and all but one of those areas were limited in areal extent and depth. The Merchant Drive area was the exception (see Chapter 3 for details). Therefore, I think it unlikely that the D_{50} results would be substantially different had I been able to discern the origin of the fine particles.

There probably would have been greater differences in median particle diameters shown in Figure 5.5 if I had been able to tell if rocks not close to the base of a slope covered with riprap were from natural bedrock outcrops or were transported from areas with riprap. I suspected many were pieces of riprap that had been moved, but was not sure. In such cases, wanting to be conservative, I included them in the "natural" category. When I was present during the addition of riprap to the banks of the creek, as described earlier, I asked the workers where they picked up the rock. They said it came from one of the quarries along the shore of the Tennessee River, just upstream of Knoxville. When I checked the geologic map, I noticed the same formations (Lenoir Limestone and Holston Formation) in that area as in some outcrops in Second Creek. Rocks are heavy and expensive to transport, so it is probable that most if not all the riprap on the banks and slopes of Second Creek was derived from local areas. It is easy to see why the riprap was often indistinguishable from naturally occurring rocks.

Some of the anthropogenic particles in the channel are short-lived, as people periodically "clean up" Second Creek (recently once a year or more often). Forms of CRUD such as bottles, cans, car parts, and other pieces of obviously anthropogenic debris are removed during these times. Other coarse anthropogenic particles, including bricks, cinder blocks, pieces of concrete, and rocks from riprap, were not removed during the five years I visited the stream. Because of this, and because most change in median particle diameter due to CRUD was from pieces of concrete and riprap, the changes in median particle diameter probably occur at a much slower rate than the times between stream clean-ups.

Second Creek, like most urban streams, is flashy, and I have seen evidence that seems to indicate that large particles are sometimes moved by water. The imbricated pieces of concrete shown in Figure 5.6 suggest that large particles have been moved by Second Creek. The location of this phenomenon was about 100 m downstream from the culverts

Figure 5.6. Imbricated slabs of concrete in the channel. The positions of these pieces of concrete, located in between Coster Yard and Oldham Avenue, suggest that Second Creek can occasionally move large particles. Flow is from left to right. (Photograph by the author.)

under multiple railroad tracks south of Coster Yard. There was one other set of large imbricated slabs of concrete in the same vicinity. There was no noticeable change in position of boulders near Site C or near Sites UT or U from 1997 to 1999.

Bedload Estimation

Several factors may have affected the volume of the deposit at the outlet of Second Creek. The order in which they are discussed below is not related to their likely importance in affecting the volume of sediment.

Some of the sediment in the delta could have come from construction of the pier at the mouth of Second Creek. If excavations for the concrete pier supports went down 3 m, and all the excavated material stayed at the site, about 56 m^3 from each pier support would have been added to the deposit. Two pier supports are adjacent to the delta, and one more is 29 m upstream from the middle support. The estimated volume of material from the holes for three supports amounts to about 5% of the total volume of the delta. There is also the possibility that the current in the reservoir moved sediment from locations upstream of Second Creek, and left some of it where flow was disrupted by the pile of sediment already deposited at the mouth of Second Creek.

Sediment delivery to the outlet has undoubtedly occurred in pulses. Not only is sediment transport affected by the amount of storm-related stream discharge, but also by the supply of sediment available for transport by the stream. Construction within the stream channel has occurred at various times (see Chapter 2 for details), and large but unknown quantities of loose material would have been available for transport by Second Creek at and subsequent to those times. Figure 5.7 shows an accumulation of sediment in the stream during construction of culverts beside I-75. The streambed in the same location is now mostly covered with gravel and cobbles, an indication that much or all of the sediment shown in the photograph was re-entrained and carried downstream sometime after the major influx of construction-related sediment ended. Because the sediment probably moved down the channel in pulses or waves, the estimated average sediment yield of 117,020 kg (130 tons) per year is just that, an average. Like all averages, it gives no information about the amount of fluctuation in the data.

There is current in Fort Loudoun Lake at the outlet of Second Creek because it is located in the uppermost part of the reservoir, where the flow of the Tennessee River is still noticeable. It seems likely that the current would have entrained the finer material delivered by Second Creek and carried it downstream, toward Fort Loudoun dam. During times of high flow in the river, the current has probably eroded sediment from the delta at the mouth of Second Creek. Two years after the delta was surveyed, it was no longer visible at low water levels. As the area at the mouth of Second Creek has never been dredged (Koroa, 2003), the most likely explanation for the missing sediment is scour by the Tennessee River during high water events. If the delta was removed when the river was high, the same thing most likely has occurred several times during the 50 years that the mouth of Second Creek has been at its present location. This means the

Figure 5.7. Sediment in the channel during construction in 1979. This location is upstream of the I-75/I-640 interchange and Sharp Ridge. The Tillery Road overpass is visible in the background. Photographs courtesy of TVA.

delta measured in 1998 was probably much younger than 50 years, and thus the yearly bedload rate was probably much greater than my calculations indicate.

Compared to annual sediment yields for drainage basins of similar size, but not containing urban land use (Dunne and Leopold, 1978), the bedload estimate (using 50 years for the time of accumulation) for Second Creek is quite low. The data from other locations were mostly calculated from total reservoir accumulations, not from just one part of the reservoir as in this case. Total reservoir accumulations include most sediment delivered as suspended load in addition to bedload. Sediment carried as suspended load in Second Creek is likely to have been transported farther downstream in Lake Loudoun than the delta at the mouth of Second Creek, and, as previously discussed, most of the sediment delivered by the creek may be periodically entrained and carried farther downstream in the reservoir.

CONCLUSIONS

Surficial material in the bed of Second Creek is mostly a mixture of fines (including sand), gravel, and cobbles. There are at least a few boulders at all locations sampled in this study. There is no downstream trend of increasingly fine particles, but Second Creek is a short stream. In addition, the underlying geologic structure has resulted in outcrops of competent bedrock in several locations along the length of the channel, so there are potential new supplies of coarse bed material at intervals along the stream. There are undoubtedly fewer potential sources of bedload exposed in the streambed than there were before the construction of box culverts and concrete-lined sections of the channel.

Many large particles have been added to the stream channel by human actions, either intentionally or inadvertently. Two to 21% of the coarse particles sampled Second Creek were anthropogenic. It seems that some attempts to constrain the stream are having unintended consequences. At several locations in the stream, riprap, shaped rocks, bricks, or pieces of concrete from walls have ended up in the channel where they increase the median particle diameter. They are adding roughness to the channel, reducing water velocity, and increasing the potential for flooding and for deposition of sediment in the channel.

Approximately 3,650 m^3 of sediment has accumulated in a ridge beyond the mouth of Second Creek during the last 50 years or less. If it was all transported by Second Creek, and if it was carried at a relatively steady rate for 50 years, the annual load was 117,020 kg (130 tons) per year of sediment. This estimate is probably much lower than the actual bedload transport rate, as periodic removal of sediment by the Tennessee River seems to occur during high water events.

CHAPTER 6

CONCLUSIONS

Second Creek drains a relatively small area (18.6 km^2) that was almost entirely urbanized at least 40 years ago. In spite of being developed, land use changes have continued, and have resulted in continuing increases in impervious surface area in the basin. Such changes could be expected to alter the hydrology of the creek, but the amount of alteration remains unknown because hydrologic data were not systematically gathered from Second Creek until recently. As long as the hydrologic regime of the stream is changing, the channel is not likely to become statically adjusted to urban conditions. This study reveals that both erosion and deposition have occurred in Second Creek in recent decades and continue to occur. The detailed observations of the channel, bed materials, suspended sediment loads, and storm flow of Second Creek obtained in this study contribute new data on the behavior of an urban stream, and support a dynamic view of the nature of stream channel adjustment to urbanization.

The thorough inspection of Second Creek conducted as part of this study shows much variation in channel size, materials, associated vegetation, and therefore in the appearance of the channel at different places along its length. The variation is due both to the geology underlying the stream as it flows across the strike of sedimentary strata, and to anthropogenic modifications. Approximately 38% of the channel is now covered with concrete, and a variable percentage of the remainder is protected by riprap or other armor. The concrete and riprap are not contiguous but instead occur in different places along the stream. Where riprap is sparse and in unprotected locations, the banks are visibly eroded along much of Second Creek. There are places, however, where recent aggradation has occurred, and other places where the channel has been relatively stable in recent decades. Whereas streams are generally treated and modeled as integrated systems, natural and anthropogenically-produced differences along this small stream have created a series of distinct segments. Even in areas with less geologic variation than Second Creek, anthropogenic impacts of different types, timing, and locations may create more variation in urban channel dynamics than can be accommodated by present stream models.

As part of my examination of Second Creek, I monitored suspended load from October 1998 to October 1999, using rising stage samplers at five locations. Sediment levels measured by these rising stage samplers in Second Creek were generally high (> 1,000 mg/L) to extremely high (> 10,000 mg/L) during the initial part of high water events. The difference between my measurements and those from an automated sampler of the City of Knoxville suggests that the highest concentrations occur early in the rising limb of storm flows, and are not caught by the City's samplers. The relatively high suspended sediment load of Second Creek is evidence for ongoing change in the channel. Materials eroded from the channel appear to add to the load of sediment delivered to the stream from the rest of the drainage basin. Sediment concentrations that increase in the downstream direction, and the lack of correlation between sediment concentrations and length of time between runoff-producing storms suggest that sediment from the land surface may be minor in comparison to the amount of sediment derived from within the channel. People concerned with water quality in Second Creek and other urban streams should recognize the likelihood of the channel as a source of sediment. In this particular stream, some of the sediment eroding from the channel may be polluted material that had been deposited in the channel in earlier decades, before proper disposal and monitoring of hazardous materials was practiced. Given the evidence of bank erosion, the high level of sediment in storm flows and the potential presence of hazardous substances introduced by the remobilization of fine sediments, further testing for pollutants, such as metals, is recommended in sediments deposited downstream from eroding parts of the channel. Future research should also include precise and repeated surveying of streambanks to document the amount and rate of material loss from the eroding portions of the channel of Second Creek.

The amount of bedload transported by Second Creek may be small compared to the suspended load. Using the volume of an accumulation of sediment in Lake Loudoun reservoir at the mouth of the creek, I estimated bedload to be 117,000 kg/yr. However, the amount of bedload transported by Second Creek is probably greater than my calculations show because the deposit is very likely to be younger than 50 years (the time used in the calculations). The deposit measured in 1998 was greatly diminished or removed in 2000 by scour during high water events. This has likely occurred every few years, during periods of high discharge in the Tennessee River. Periodic bathymetric surveys near the mouth of Second Creek would enable more reliable calculation of bedload yield for this urban stream.

Some sources of coarse (potential bedload) particles to the stream were lost as box culverts and concrete-lined channels covered bedrock outcrops. New sources were created, however. Measurements of coarse particles show that material added to the channel through direct or indirect human actions is sufficient in some parts of Second Creek to alter median particle diameters and stream flow characteristics. If the anthropogenic contribution results in a greater total supply of bedload than that under pre-urban conditions, sediment aggradation and channel widening are to be expected. The locations and numbers of anthropogenic particles within the channel change more frequently than those of natural particles, due to frequent dumping of material and stream clean-up efforts. I expect that these alterations trigger responses in channel shape and size, and may delay channel adjustment to urban conditions. Researchers studying urban streams should not ignore such particles as they have to date. The results of this study suggest that the added roughness and mass of these particles would have a notable effect on bedload and flow dynamics.

Present-day deposition of sediment in the channel of Second Creek appears minor. Accumulations of sediment in culverts and concrete-lined channels less than 30 to 40 years old indicate higher deposition rates in the recent past, but most sub-aerial alluvial deposits in the channel are now well-vegetated. Because of the extensive recent erosion, I conclude that the channel of Second Creek has not attained a state of relative stability, or quasi-equilibrium, and that it is still adjusting to conditions in the urban environment.

Applying Wolman's (1967) model of stream response to urbanization, much of Second Creek would now be in the "post-development, channel enlargement stage." At least parts of the stream were set back to the "land development/sediment influx stage" in the late 1970s and early 1980s, due to interstate highway and World's Fair construction. Those locations are now (20 to 30 years later) primarily sites of channel erosion. This study demonstrates that the concept of urbanization as a discrete event is not fully applicable even to small drainage basins, such as that of Second Creek. The length of time an urban basin is monitored also makes a difference. The longer we examine an urban basin, the more change in land use we are likely to find. The slow and even seemingly retrograde channel responses to urbanization in the small basin of Second Creek demonstrate that urbanization and channel response to urbanization are more complex in actuality than as represented in the Wolman model.

Stream channels may have a chance to stabilize, in spite of changing conditions in their drainage basins, if stormwater runoff is controlled. It is well known that most geomorphic work is accomplished by streams flowing at or close to bankfull discharge. If the number of bankfull events in urban areas could be limited to about 1.5 per year, as found in most natural channels, accelerated bank erosion rates should be reduced.

A different management approach would be to allow accelerated erosion to occur, as long as it did not threaten bridges, roads, buildings, or other infrastructure. Without controls, the amount of runoff would increase with an increase in impervious surface until almost all the land in the urban basin became impervious. Eventually, the channel would become wide enough to accommodate the discharge and sediment supplied to it, and accelerated bank erosion would end. Managers should be aware that high sediment loads in the stream are likely to persist throughout the accelerated erosion phase, no matter how effective sediment controls are at reducing sediment delivered to the stream.

As a result of this study, baseline data are now available for Second Creek. The data presented in this dissertation include suspended sediment concentrations, discharge measurements, bedload particle sizes, and cross-sectional surveys. My analysis of the channel, based on these data, demonstrates the need for a more dynamic view of urbanization. It also adds to our understanding of the time scale of adjustment to urbanization and highlights the need to incorporate anthropogenic particles into studies and models of stream dynamics.

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APPENDICES

APPENDIX A

PATTERNS OF RAINFALL INTENSITY IN STORMS IN KNOXVILLE

PATTERNS OF RAINFALL INTENSITY IN STORMS IN KNOXVILLE

To discern patterns in rainfall intensity during storms in Knoxville, I analyzed precipitation data collected by University of Tennessee Agricultural Engineers (Wright, 2001) from a gauge located north of Merchant Drive in the upper part of the drainage basin of Second Creek (Figure A.1). Minute-by-minute rainfall data were recorded from a tipping-bucket type rainfall gauge at that location for a little more than one year, from October 25, 1997 through November 10, 1998. From these data, I selected storms with at least 12.7 mm (0.5 in) of precipitation, and used Huff's (1967) definition of a storm, as "...a rain period separated from preceding and succeeding rainfall by 6 hours or more." For each storm, I calculated the amount of precipitation occurring in each quartile of storm duration and examined the results for seasonal patterns.

During the 54 weeks covered by minute-by-minute precipitation data, the Agricultural Engineering gauge recorded 33 storms with precipitation of 12.7 mm (0.5 in) or more. Storm types, as defined by Huff, and total storm precipitation are shown in Table A.1. Most storms were Type 3, and the next most common was Type 2. One of the largest storms was a Type 1, with more than 50% of the total precipitation during the first quarter of the storm. Huff Type 1 storms should, in theory, produce less runoff from pervious surfaces than Type 4 storms.

Because soils in the Knoxville area are saturated or nearly so for most of the winter and early spring seasons, the timing of intense precipitation makes less difference during those parts of the year. When storm types are arranged by the season of their occurrence (Table A.2), most storms in the spring (March, April, and May) were Type 3. In the summer, all types occurred with almost equal frequency. Slightly more fall storms were Type 3 than the other types. In contrast, all winter storms were either Type 2 or 3. If these results are typical of long-term rainfall patterns, I conclude that the effect of the timing of intense rainfall on runoff generation in the increasingly impervious basin has generally, but not always, been minor.

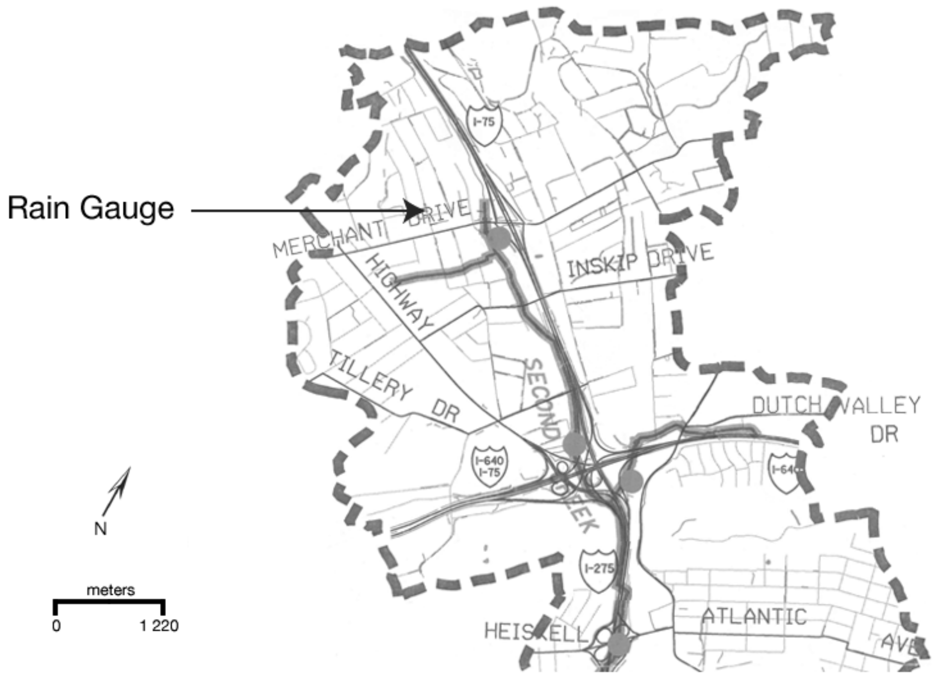

Figure A.1 Location of rain gauge. Base map from KGIS Knoxville, TN.

Table A.1. Storm type versus total storm precipitation, Data from October 1997 to November 1998 for the Church Site.[1]

Total Precipitation	12.7-25.3 mm (0.5-0.99 in)	25.4-50.7 (1-1.99)	50.8-76.1 (2-2.99)	76.2-101.6 (3-4)	Total
Storm Type[2] 1	2	0	0	1	3
Storm Type 2	6	4	0	0	10
Storm Type 3	9	7	1	1	18
Storm Type 4	2	0	0	0	2

[1] Data from Wright (2001)
[2] Types defined by Huff (1967)

Table A.2. Seasonality of storm types for the Church rain gauge location.

Season	Spring	Summer	Fall	Winte r
Type 1	0	3	0	0
Type 2	3	2	2	3
Type 3	8	3	4	3
Type 4	0	1	1	0
Total	11	9	7	6

APPENDIX B

CHANNEL CROSS-SECTIONS

CHANNEL CROSS-SECTIONS

Table B.1. Locations of cross-sections.

Cross-section Name	Location
U	188 m upstream of the outlet of Second Creek; beside the second trestle on the upstream side of the upstream of two adjacent vehicle bridges
UT	Under the second footbridge downstream from Cumberland Avenue
Western Ave.	85 m upstream from railroad tracks crossing Second Creek
Industrial	258 m south of the railroad bridge downstream from Bernard Avenue
S. Bernard	70 m downstream from the center of the railroad bridge south of Bernard Avenue
N. Bernard	60 m upstream from the center of Bernard Avenue
S. Baxter	160 m downstream of the center of the Baxter Avenue Bridge
Davanna Down	55 m upstream of the center of Oldham Avenue Bridge
Davanna Up	134 m upstream of the center of Oldham Avenue Bridge
Clinton Dnstm.	26.6 m upstream from the upstream end of the I-275/I-640 box culverts
Clinton Upstm.	130 m upstream of the same culvert as above
Heiskell Dnstm	189 m upstream from the center of the Heiskell Avenue Bridge
Heiskell Upstm	275 m upstream from the center of the Heiskell Avenue Bridge
Inskip 200	200 m downstream of the downstream side of the Motel Bridge
Inskip 166	166 m downstream of the downstream side of the Motel Bridge
Inskip 134.4	134.4 m downstream of the downstream side of the Motel Bridge
Inskip 90.9	90.9 m downstream of the downstream side of the Motel Bridge
Dutch Valley	8 m upstream of the upstream end of the box culvert under I-275

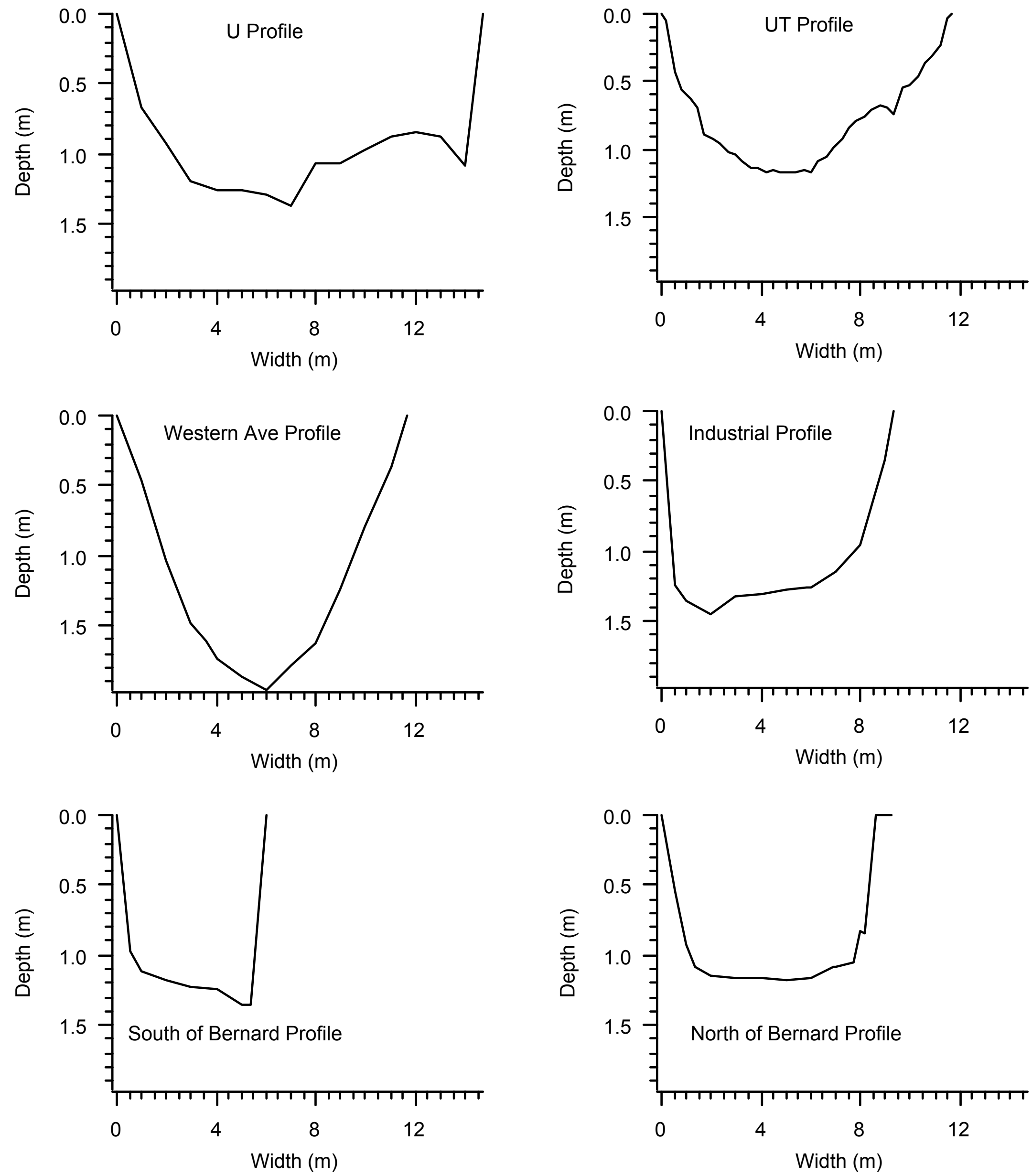

Figure B.1 Cross-sections along Second Creek. West side is zero width.

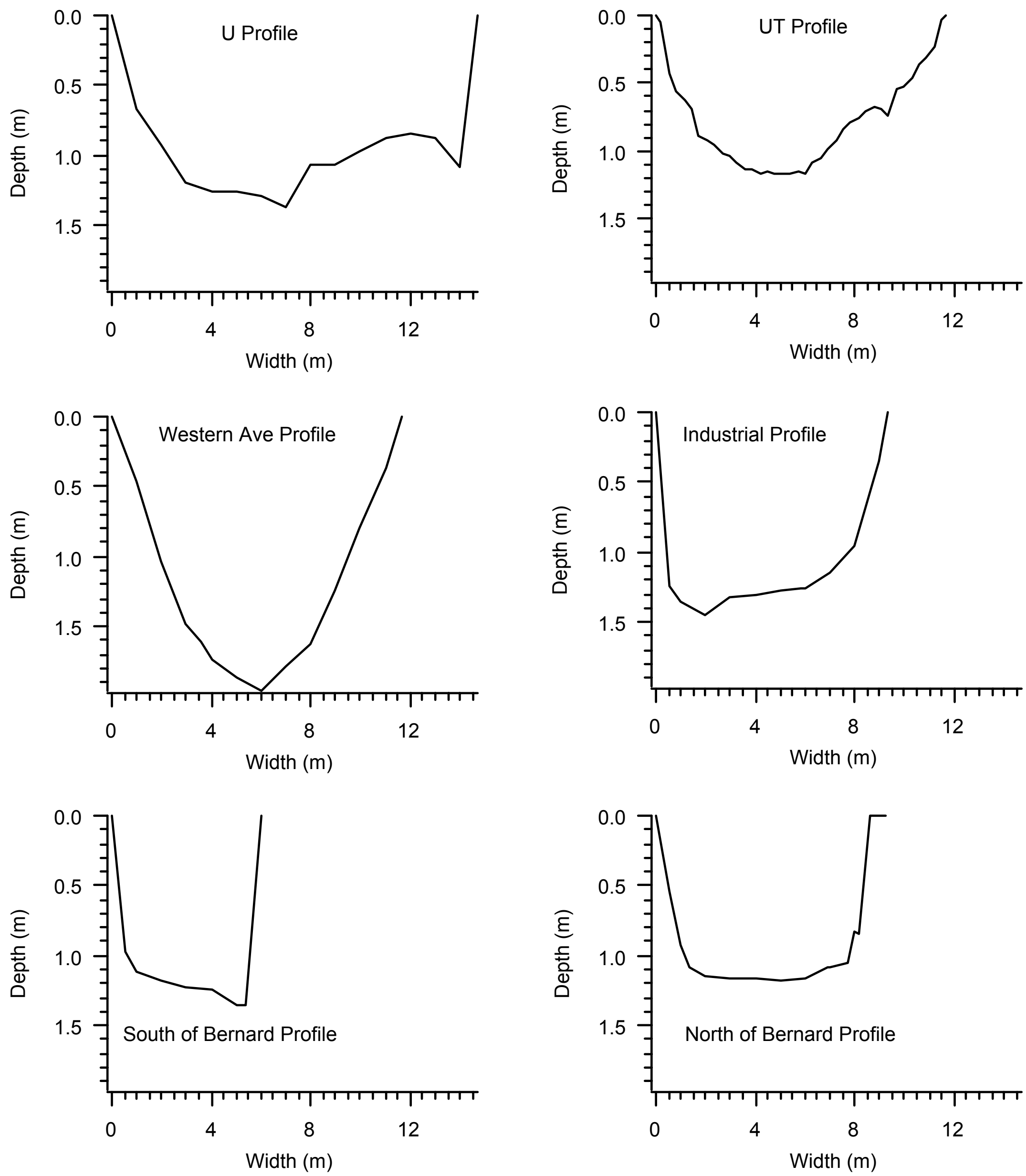

Figure B.1. Continued.

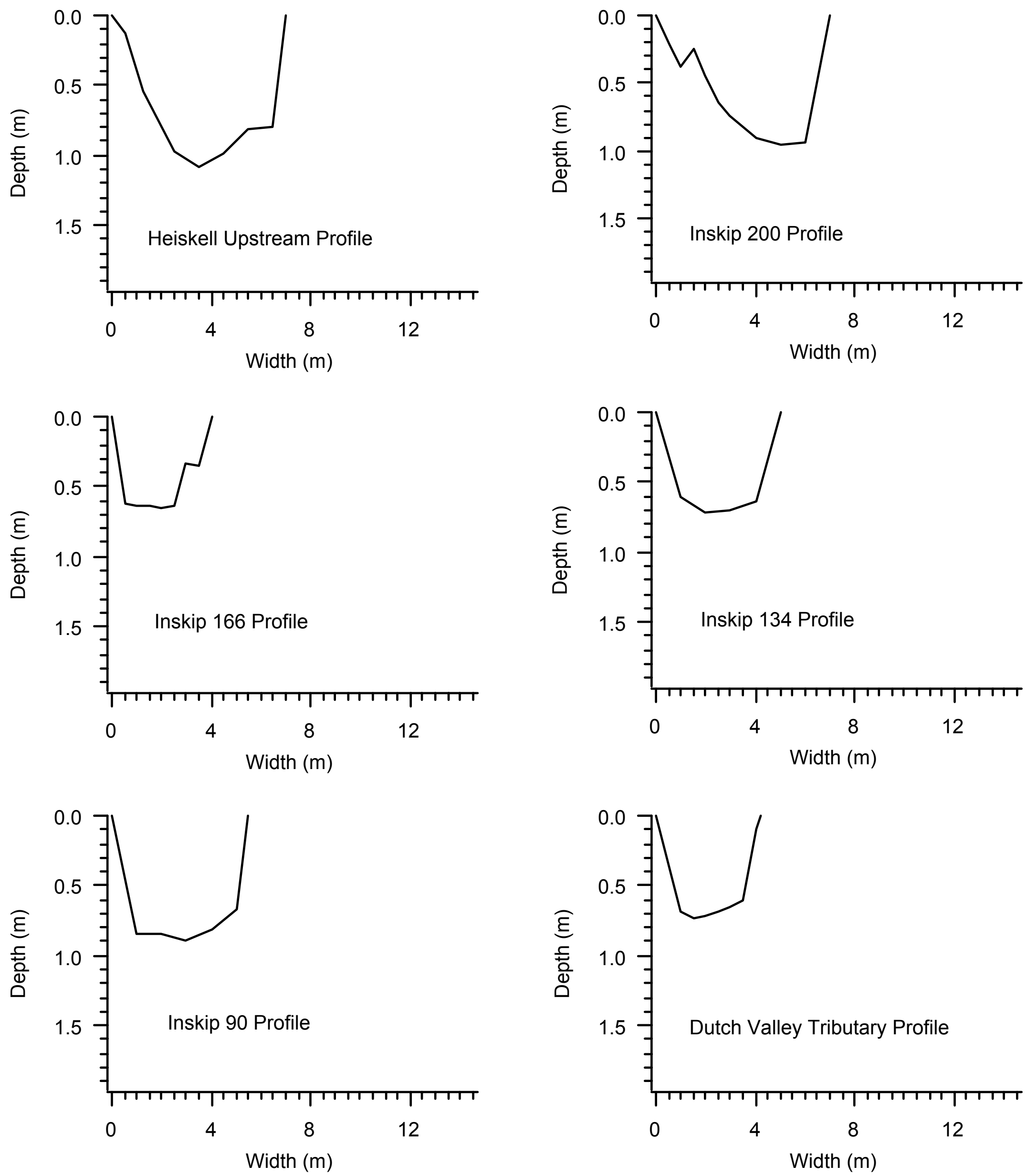

Figure B.1. Continued.

APPENDIX C

SEDIMENT IN HEISKELL CULVERTS

SEDIMENT IN HEISKELL CULVERTS

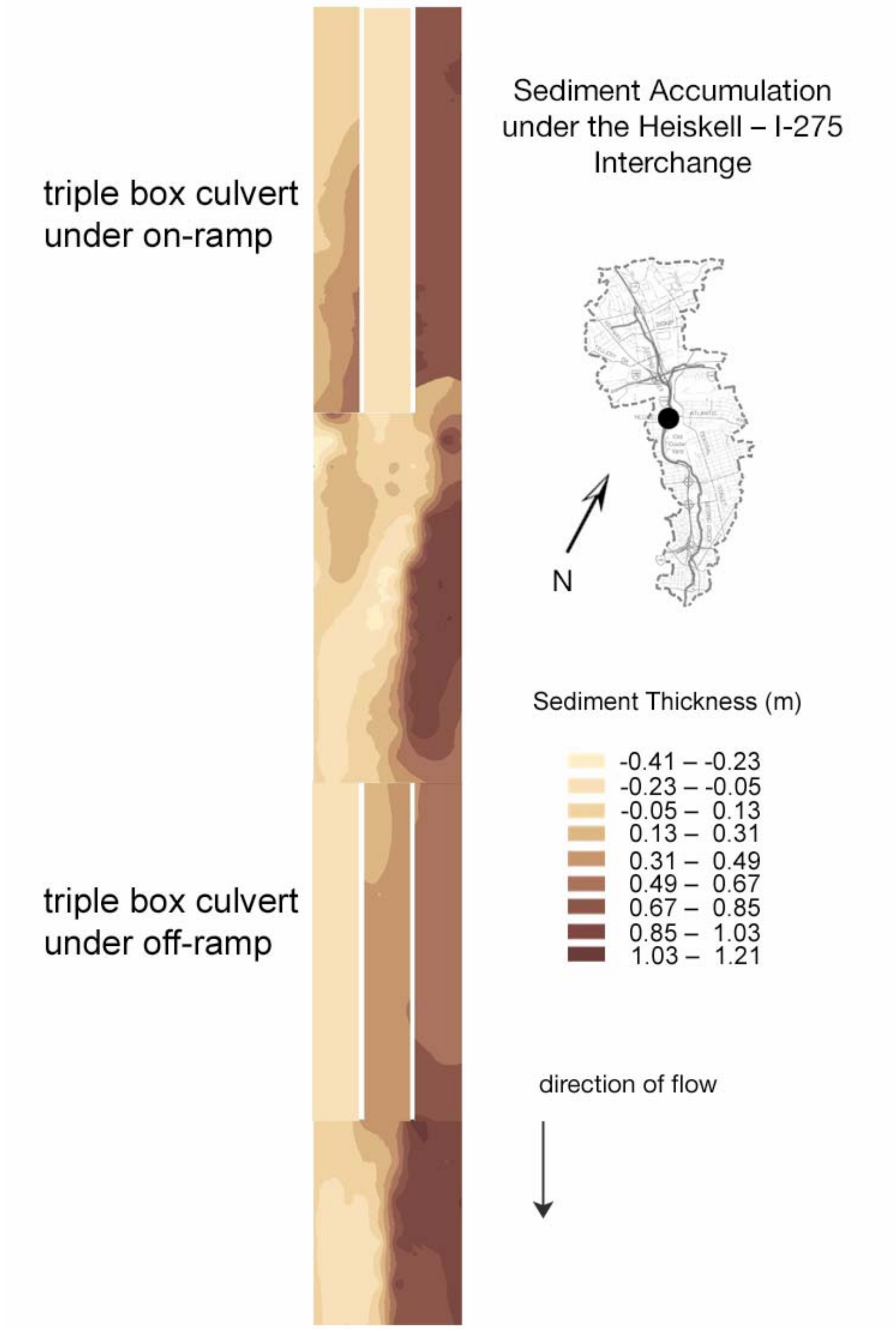

Figure C.1 Combination of Heiskell sediment maps. The Channel shown here is 10 m wide and 81 m long.

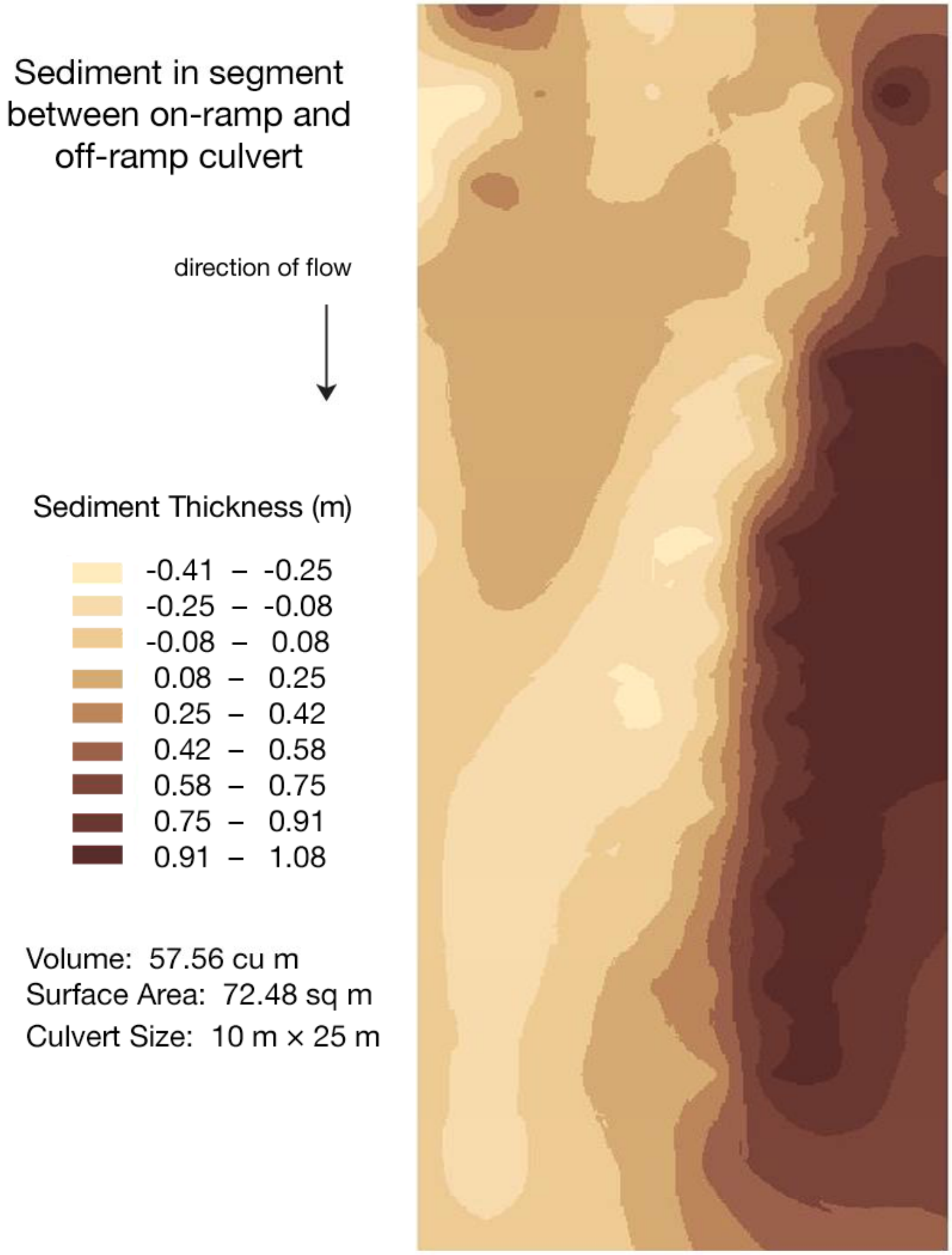

Figure C.1. Continued.

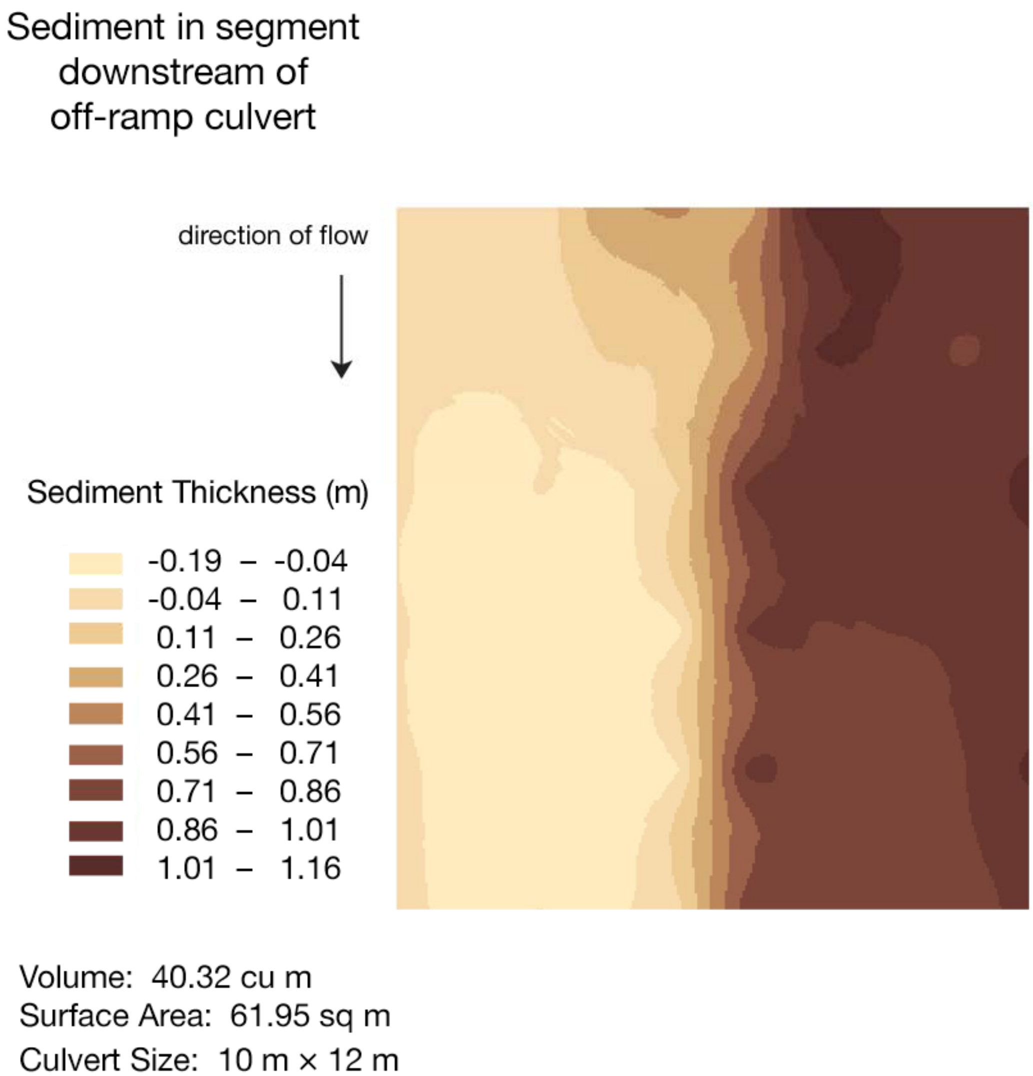

Figure C.1. Continued.

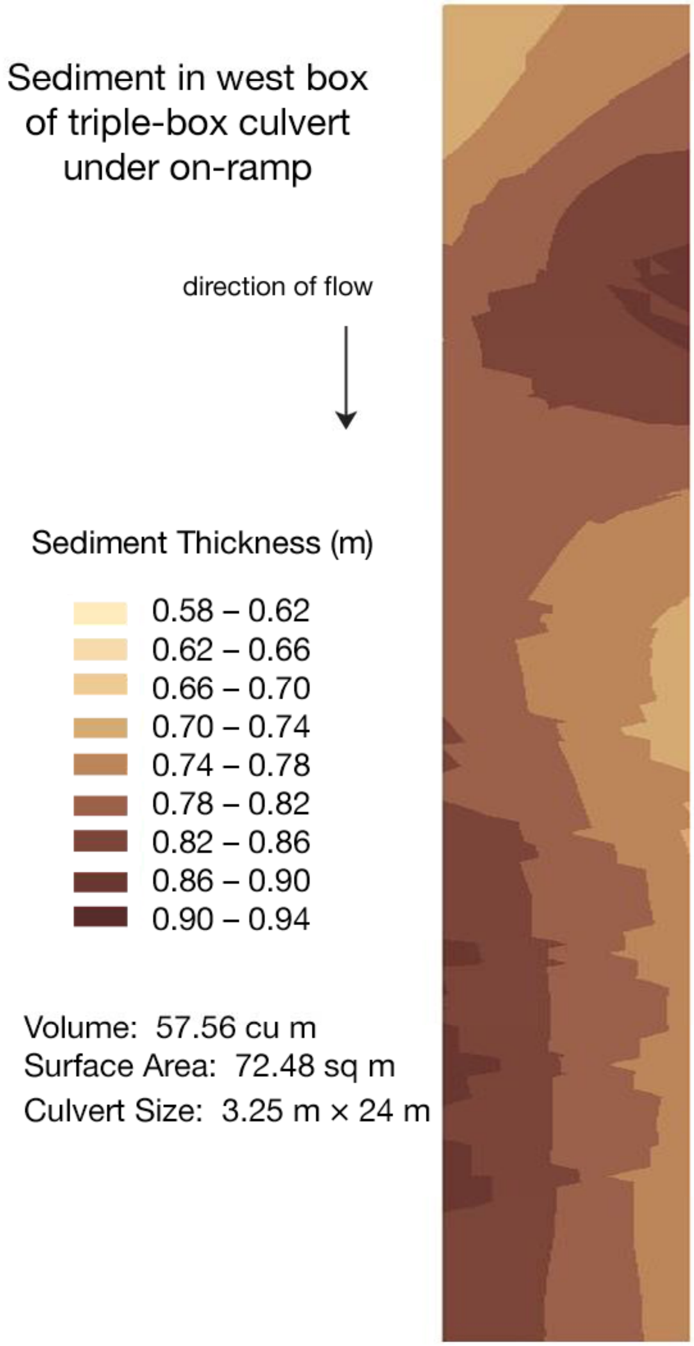

Figure C.1. Continued.

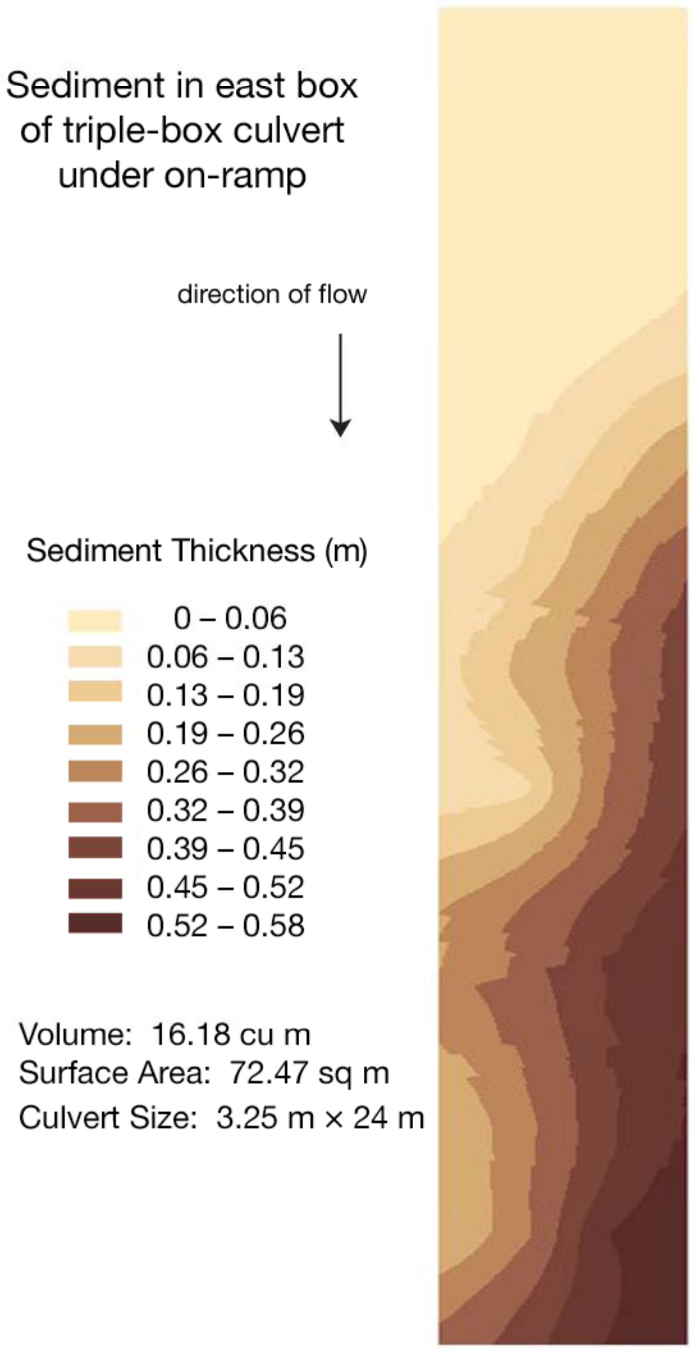

Figure C.1. Continued.

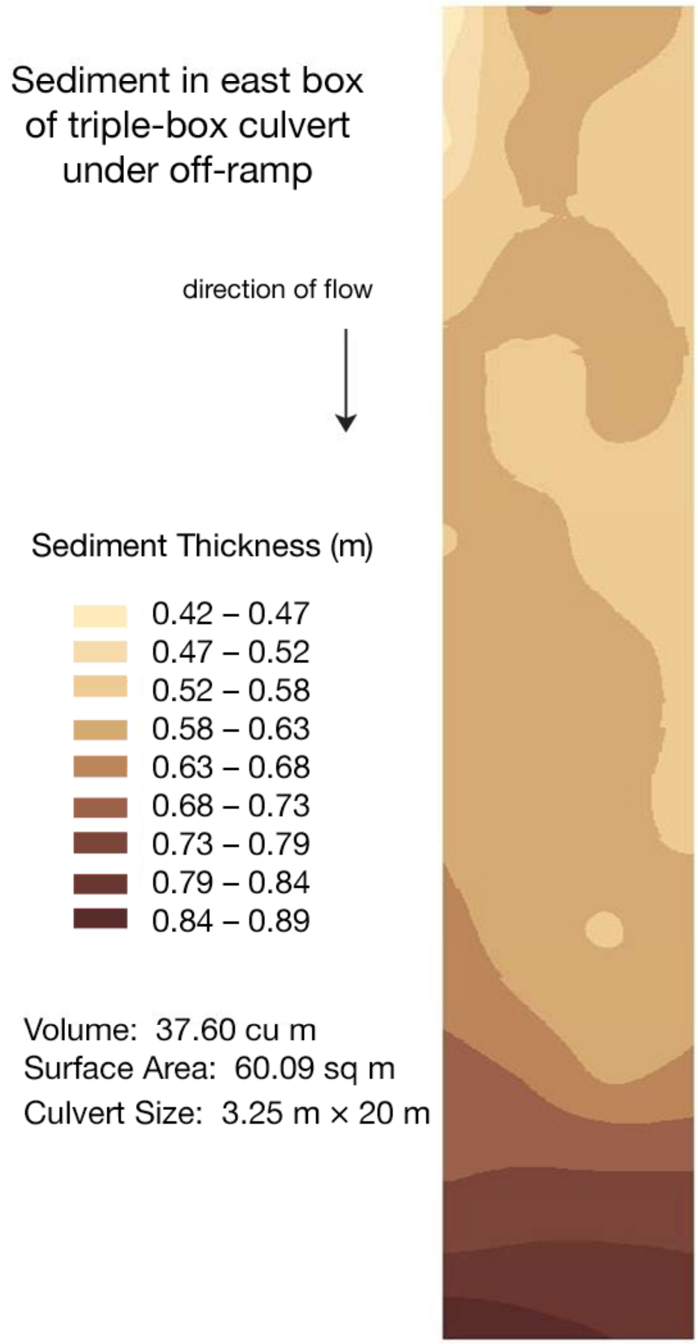

Figure C.1. Continued.

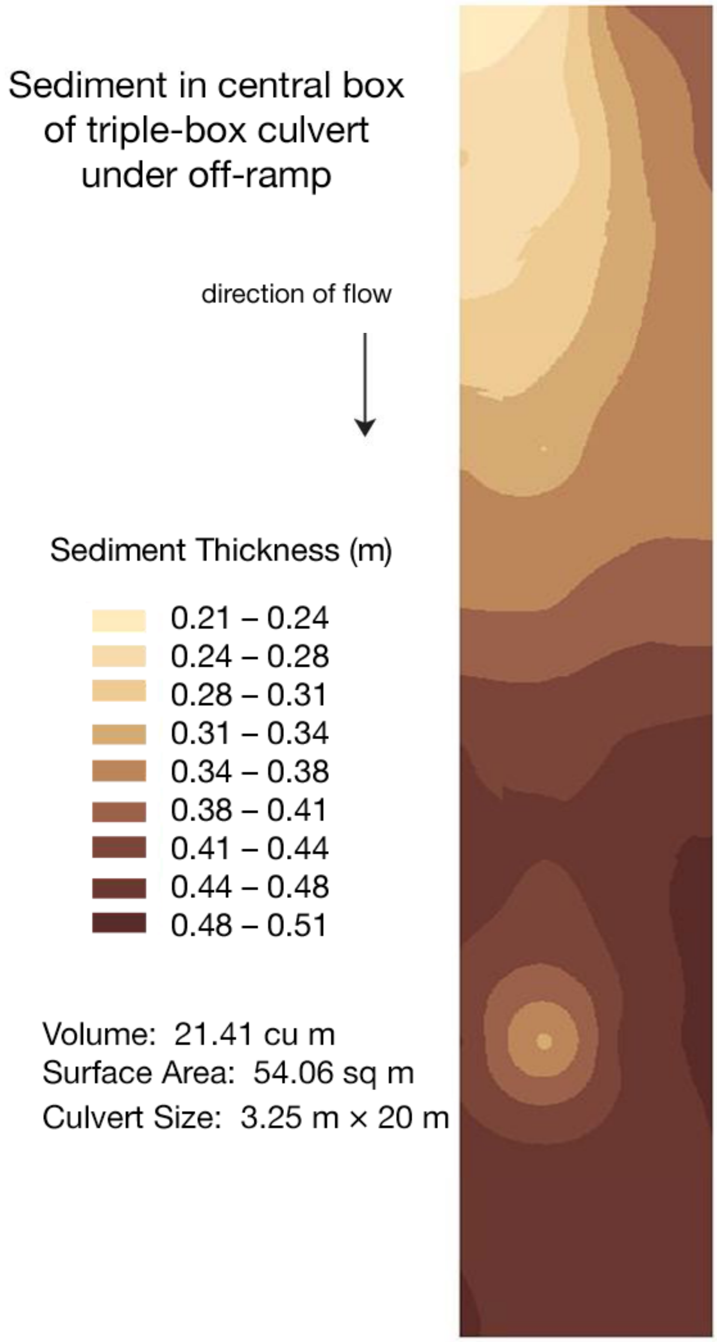

Figure C.1. Continued.

APPENDIX D

SEDIMENT CONCENTRATION AND STREAM DISCHARGE

Table D.1. Depth integrated sediment concentrations

Date	Time	Gauge Height (ft)	Discharge (ft^3/sec)	Discharge (m^3/sec)	Sediment (mg/L)
13 Aug. 97	15:30	19.67	32	0.91	192
	16:22	19.80	17	0.48	69
	16:40	19.85	13.5	0.38	35
	16:58	19.98	12	0.34	37
	17:10	20.00	11.5	0.33	32
	18:04	20.02	7.6	0.22	10.0
15 Aug. 97	17:42	19.00	116	3.29	443
	17:52	19.05	106	3.00	270
	18:10	19.15	82	2.32	269
	18:22	19.15	80	2.27	213
	18:35	19.25	65	1.84	159
	18:50	19.30	61	1.73	135
	19:05	19.50	46	1.30	128
	20:09	19.60	38	1.08	73
	20:38	19.70	26	0.74	63
24 Oct. 97	11:14	19.75	20	0.57	57
	12:29	19.71	24	0.68	92
26 Oct. 97	19:20	19.15	76	2.15	143
	19:22	19.17	70	1.98	133
8 Mar. 98	20:00	19.63	34	0.96	214
	20:20	19.04	98	2.78	322
	20:45	18.67	145	4.12	319
18 Mar. 98	17:05	17.58	521	14.75	No sample
	17:15	17.70	460	13.03	290
19 Apr. 98	11:20	16.80	850	24.07	118
	12:27	17.25	645	18.27	No sample
9 Jun. 98	15:12	17.54	515	14.58	267
	15:55	18.08	342	9.69	187
	16:19	18.63	210	5.95	156
14 Jun. 98	14:46	19.58	41	1.16	No sample
	14:50	19.46	49	1.39	No sample
	15:04	19.31	64	1.81	76
	16:54	19.13	85	2.41	142

APPENDIX E

SUSPENDED SEDIMENT CONCENTRATIONS FROM RISING STAGE SAMPLERS

Table E.1 Suspended sediment concentrations[1] (mg/L)

Date Collected	distance from bottom (mm)	Site I (up-stream)	Site C	Site D (tributary)	Site H	Site U (down-stream)
	304	185				
Oct. 5	152	236 p	2,365		460	lost data
	456	84				
	304	220	2,277			
Oct. 8	152	373	3,402	314	5,061	lost data
	456	109				315
	304	157	535			3,266
Nov. 10	152	189	1,407	1,154	1,694	2,346
Nov.16	152					55.3
	304					305
Nov. 26	152	125				134
	1064					920
	912					5,717
	760	178				23,286
	608	550	137			33,304
	456	574 p	3,765	920	2,340	34,099
	304	958 so	3,503	1,971	10,713	36,722 p
Dec. 9	152	920	7,931	2,815	23,437	1,202 p
	760	110				2,117
	456	237	214			5,854
	304	547	6,608	166	816	11,927
Dec. 14	152	910	18,401	513	3,971	19,748
	304					443
Dec. 22	152	381	332			805
	304					2,384
Dec. 27	152	182	1,689	94	159	1,821
	304					3,448
Jan. 8	152	374	2,663	117	250	3,723

Table E.1. Continued

Date Collected	distance from bottom (mm)	Site I (up-stream)	Site C	Site D (tributary)	Site H	Site U (down-stream)
	760	273				4,472
	456	555				10,300
	304	846	5,625	2,642	667	18,044
Jan. 9	152	1,003	35,095	756	4,806	37,460
	456					683
	304	91				5,286
Jan. 16	152	253	2,570	164	804	3,948 d
	912					7,264
	760	459				12,530
	456	4,831 so	3,968	863		17,811
	304	1,558	3,035	1,550	7,934	31,675
Jan. 24	152	5,259	29,140	7,115	17,086	31,657
	304					106
Feb. 5	152	51	512	73		168
Feb. 8	125	88				101
Feb. 13	152					156 p
	304					
Feb. 18	152	72	523			1,186
Feb. 20	152	47				262
						573
	456					7,477
	304	212	417			15,423
Feb. 28	152	329	3,054	257	2,075	22,298
	456	398				6,002
	304	764	3,916	351		14,563
Mar. 4,5	152	1,950	14,831	466	4,068	20,371

Table E.1. Continued

Date Collected	distance from bottom (mm)	Site I (up-stream)	Site C	Site D (tributary)	Site H	Site U (down-stream)
	304					1,766
Mar. 10	152					2,168
	304	94				
Mar.13	152	145	1,044	59		lost data
	304					1,414
Mar. 14	152	226	1,084	84	40	lost data
	304					1,264
Mar. 27	152	137	693	50	59	6,150
Apr. 2	152	112	210			517
	456	298				
	304	346	745			891
Apr. 10	152	296	4,701	258	634	5,793
	304					402
Apr. 16	152	42	181			3,867
	304					4,586
Apr. 29	152	190	575	119		9,719
	912	601				971
	760	1,630	373			16,984
	608	722	3,178		3,493	25,951
	456	2,051	5,856	2,315	9,483	68,564
	304	2,266	24,107	4,438	15,476	58,270
May 6	152	5,713	47,655	5,552	19,693	46,235
	456					950
	304					6,875
May 11	152					8,943
	456	635				1,019
	304	lost data		993	840	2,082
May 14	152	lost data	3,314	1,585	3,765	4,047

Table E.1. Continued

Date Collected	distance from bottom (mm)	Site I (up-stream)	Site C	Site D (tributary)	Site H	Site U (down-stream)
	304	123				224
May 19	152	293	3,161 d		258	1,095
	1064				737	578
	912	586	1,460		2,329	14,404
	760	1,385	2,180		4,299	31,565
	608	1,566	4,784	802	5,277	35,022
	456	1,795	13,791 d	2,392	8,333	56,242
	304	1,443	35,004 pd	1,424	10,472	67,814
June 25	152	1,265	40,932 pd	3,717	30,558	98,668
	760	370				1,568
	456	419				3,319
	304	1003	2,084	304		5,954
June 28	152	693	24,709	304	1,541	10,755
	760					1,685
	608					7,246
	760	290				10,183
	456	411 so	199			21,525
	304	388	886	200	334	7,896
June 30	152	376	4,741	1716	2,842	27,098
	912					1,499
	760					4,593
	304					5,515
July 3	152	12	83			12,067
	304					416
July 7	152					782
	912					292
	760	151				5,150
	608	307	629			17,713
	456	562	2,129			36,087
	304	1,353	6,475	276	2,764	39,678
July 13	152	3,494	28,210	763	8,123	69,745

Table E.1. Continued

Date Collected	distance from bottom (mm)	Site I (up-stream)	Site C	Site D (tributary)	Site H	Site U (down-stream)
	456					2,205
	304					2,360
July 20	152	178	257			8,394
July 22,23		58				214
	760	562				118
	608	530				3,789
	456	988so	1,346			6,437
	304	813	2,577	lost data		10,899
July 25	152	620	2,413	196	3,336	18,105
	760					2,857
	608					10,534
	456					lost data
	304	668				22,527
Aug. 24	152	857	22,406			20,419
	760					1,047
	608	468				3,966
	456	552 so	368			6,154
	304	464	2,344			5,673
Aug. 27	152	453	12,042	324	2,620	18,183
Sep. 24	152					1,136
	304					5,254
Oct. 4	152					2,061 p
	456	718				615
	304	4,755	1,215			4,302
Oct. 20	152	823	4,469	296	24,675	3,845

[1] p = intake plugged
d = debris caught on equipment
so = possible effect of sewer outflow

VITA

Judith Laing Grable was born in New York. After spending part of her childhood in Pennsylvania, she migrated with her family to Southern California.

Judith graduated from the University of California, Riverside with a B.S. in Geology in 1970. She worked the following summer for the University of Nebraska as a paleontology field technician.

After a period of years in which she pursued other interests, she returned to school, earning an M.S. in Resource Planning in 1995 from Southwest Missouri State University. The title of her thesis was: Water Quality and Urbanization: A Multitemporal Study of the Pierson Creek Drainage Basin, Greene County, Missouri.

In December 2003, Judith fulfilled the requirements for the Ph.D. degree in Geography at the University of Tennessee, Knoxville. She is currently an Assistant Professor in the Department of Physics, Astronomy, and Geosciences at Valdosta State University, Valdosta, Georgia.