

EROSION OF BANKS ALONG PIEDMONT URBAN STREAMS

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DISCLAIMER STATEMENT

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ABSTRACT

Urbanized and non-urbanized tributary streams of the Piedmont are usually cut into post-European reddish sands and pre-European-settlement gray cohesive soils. These streams are eroding by scour and bank failure. Currently, berms (or inner-channel terraces) are a common product of bank failure; otherwise inner-channel deposition is rare and consists of point bars formed as meanders begin to develop. The cohesive sediments are more scour resistant than the sandy sediments. Bank failure is of the slab type, and is a normal part of the erosion process. Traditional design approaches have failed to create stable channels, primarily because (1) we do not understand erosive processes in cohesive sediment, and (2) urban environments require abnormally narrow channels. Erosion in channels less than about twelve feet deep can be reduced significantly by consideration of natural fluvial processes, artificial berm development, and judicious use of rip-rap. Torvane strength, color, composition and particle size distribution readily characterize bank materials and their erodibility.

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RECOMMENDATIONS

Suggestions Regarding Channelization Procedures

Channelization in the Piedmont of the United States, and similar areas, should avoid cutting into mechanically deposited fills or creating such fills in the lower banks. Slope instability and scour can be greatly hindered, without structural protection or with only minor, selectively placed protection, by constructing a berm (or inner-channel terrace) about one-third the bank height for channels deeper than six feet. Channels less than six-feet deep can be protected cheaply by selectively placed rip-rap, retention of trees, and minimal grading following general procedures of Nunnally and Keller (1979) (ie. the use of basic fluvial process considerations such as meandering, velocity reflections, etc.). When streams are so large that design-flood channels have banks greater than twelve to fifteen feet, then continuous rip-rap of the lower third of the banks will constitute a minimal channelization requirement.

Site evaluation for channelization, considering current state of the art design procedures, can be accomplished inexpensively once a design discharge is chosen. The stream segment should be walked with a large scale map or air photo in hand and notes written regarding the presence of vegetation, gulleys, utilities, slumps, bedrock, fill, sediments, obstructions to flow, etc. Profile data from compass, hand-level and rod surveys will usually prove more than adequate, except in cases where there is no available source of information regarding longitudinal stream slope. Considering our current state of knowledge of cohesive soil erosion, most lab testing is unjustified when stream banks are less than six feet high, and for higher banks is often only justified for retaining-wall design. "Texture by feel" determination of grain size and consistency in the field will usually be adequate. Torvane strength at the site is also useful for estimating erodability. With data from these simple methods at hand, channelization can proceed.

Suggestions for Future Research

Four subject areas for future research have become obvious during the course of this study. Many of the interdependent variables controlling erosion are subsidiary to the concept of roughness. A new design approach is suggested wherein we model stream behavior in terms of roughness elements. The Manning equation represents such an approach in a general sense. A first research step would be to observe the relation of roughness at various scales to secondary-current velocity measurements and other dependent variables.

A second research effort is needed for understanding processes of cohesive particle detachment. Laboratory observation and experiment constitutes an initial step.

The third area for future research is a benefit-cost study of various channelization procedures and structural features, with respect to maintenance over a time period of one or more decades.

Lastly, research regarding the details of erosion processes in the field settings of this report is warranted. A study of sequential air photos, several sets over decades if possible, will aid in identifying any long term trends and rates. Also needed is a study of "active" processes, such as time lapse photography, or photogrammetry. Candidate locations are Memorial Hospital section of Little Sugar Creek, Charlotte and the Research Park section of Doby Creek, Charlotte. These sites are suggested because the processes of slab failure and scour had been observed there for several years (up to last visits in July, 1982), and because it is thought that these sites will be active for at least several more years.

INTRODUCTION

The purpose of this study is to survey the areal distribution of streambank failures and eroded reaches in an urban setting and to identify those variables associated with each mode of bank failure and channel shape.

Identification and mapping of stream bank sediments and failure modes were a major part of the research. Variables for measurement included channel width-depth ratio, three-dimensional distribution of cohesive and non-cohesive soils, bank curvature, roots, large voids, sediment size, plasticity and strength. The study provides base-line data regarding the spatial distribution of bank failures and associated sediments.

Characteristics of Natural Streams

Natural streams have a flood plain which, in the most ideal case, consists of lateral migration deposits overlain by flood deposits. The two layer case develops from stream meandering and flooding. The lower layer is composed of non-cohesive channel deposits and the upper layer consists of cohesive, fine-grained flood deposits. This simple picture may be radically altered by urbanization, agricultural incursion, deforestation, glaciation, etc.

The bed of a stream generally is composed of alternating pools and riffles spaced at five to seven times the width of the stream. Pools occur on the outside of bends in meandering streams, opposite from deposits of non-cohesive sediments on the inside of bends. Riffles (rapids) are in straight reaches between bends. In long, straight channels the thalweg (line connecting points of lowest elevation in succeeding cross-sections) tends to meander within the channel bottom and display alternate pools and riffles. These features form during high discharges, such as bankfull flow, attained about once or twice per year, but sometimes several times per year in urbanized streams.

Urbanization often leads to instability. Urbanization, due to ground breaking and the construction of impervious surfaces, normally results in drastic increases in water and sediment discharge. Following urbanization, streams may take 15, 30 or more years to reestablish a stable channel geometry. Often flood plains aggrade while channels deepen during construction periods. Next, channels widen by erosion following construction. Ultimately there is an increased cross-sectional area.

Concept of Stream Channel Stability

A stable channel is one that suffers from neither erosion nor deposition (Lane, 1955). Channel alignment, cross-sectional area and shape remain constant. Channels that fluctuate between minor amounts of erosion and deposition may be considered stable when the fluctuations are complementary and follow short cycles (Nunnally and Keller, 1979).

Factors that influence channel stability have been summarized by many writers and include:

1. slope
2. hydraulic radius, or depth
3. velocity (average, range, distribution)
4. sediment (size, shape, dispersion)
5. channel shape
6. roughness of channel
7. water temperature
8. bank and subgrade material (particle size, shape, cohesive properties, seepage forces, vegetation, voids)
9. secondary currents due to channel geometry or objects in the path of flow
10. channel alignment
11. aging (development of berms; growth of vegetation; smoothing of banks by silt deposition)
12. climate (besides some of the variables already listed, direct effects such as growth of frost and form of precipitation)

Several investigators have compared the variables that control channel stability. For example, Mackin (1948), after studying terraces where streams had graded the landscape to a smooth profile, stated: "A graded stream is one in which over a period of years, slope is delicately adjusted to provide with the available discharge and with the prevailing channel characteristics just the velocity required for transportation of the load supplied from the drainage basin. The graded stream is a system in equilibrium; its diagnostic characteristic is that any change in any of the controlling factors will tend to absorb the change." Lane (1955) discussed sediment discharge as it affected slope and stressed the importance of bedload. Fahnestock accepted the ideas of Lane and Mackin and emphasized the importance of channel shape (1968, personal communication) and the erodability of banks (1963). However, Leopold, Wolman and Miller point out (1964, p. 274): "Where there are a large number of interrelated factors it should be expected that there will generally be an indeterminacy in the manner of their mutual adjustment". General equations for the design of stable alluvial channels will not be completely successful until many more measurements are made of the mutual adjustment of variables.

Stable Channel Design*

Methods of stable channel design include: 1) permissible velocities, 2) the regime concept, 3) analysis of tractive force, and 4) restoration. The first three are commonly used; the fourth, restoration, has been recently proposed and used.

Permissible velocity is the maximum mean velocity before scour occurs. As a design procedure it is simple, easy and inexpensive due to the minimal data necessary for calculation. However, this design procedure does not do a good job in treating aggradation or scour from secondary currents.

* This section is largely summarized from Nunnally and Keller, 1979.

The regime concept was developed by study of straight canal reaches in India and Pakistan. A stream "in regime" is stable and equations relating its geometry to other variables could be used to design channels in similar settings. This design concept works well for simple conditions of steady uniform flow in straight reaches, especially in climatological and fluvial settings similar to the original study areas. However, most stream systems do not meet these conditions.

According to the design concept based on tractive force, the fluid shear stress needed to entrain the particular grain sizes of the stream periphery is not exceeded by design. The input information is simple and easy to obtain. But designed streams are excessively shallow and wide, and secondary currents are not well accounted.

Restoration employs natural channel characteristics as a basis for design. The channel is sized according to discharge - land-use relationships; it is shaped according to Bureau of Reclamation procedures with wide cross-sections at bends and low slopes on the insides of bends; it is not realigned or alignment mimics natural meanders; structural bank stability is minimized by salvaging trees, judicious use of rip-rap, and immediate seeding of grass. Restoration is preferable for urban environments due to the narrow stream widths achieved (Table 1) and the low costs as compared to other design methods.

Table 1.

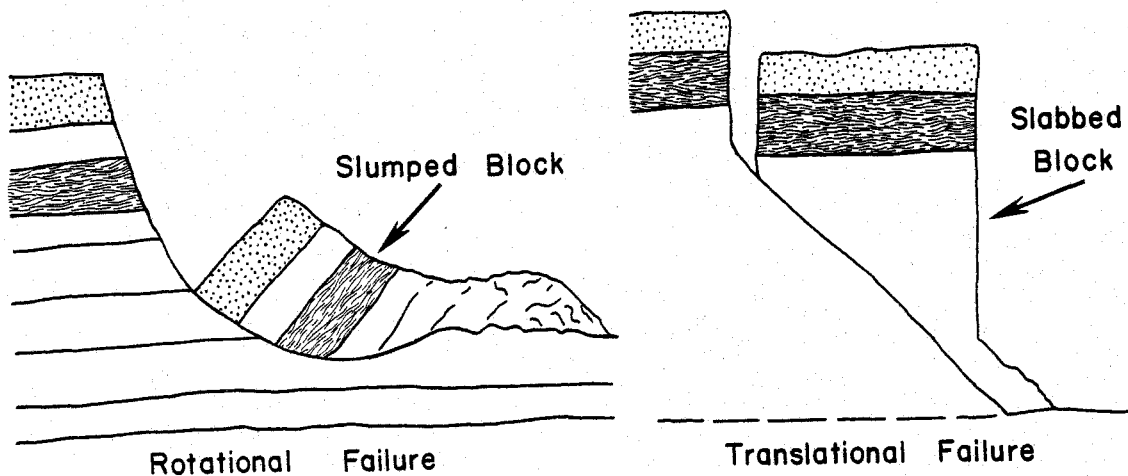
Widths and Depths From Several Design Procedures.
(data from Nunnally and Keller, 1979)

For Briar Creek, Charlotte, N.C.	depth (ft)	width (ft)
permissible velocity	.62	1208
regime concept	5.73	77.2
critical tractive force	.42	2315
restoration	9.5	19.0

Mechanical Failure of Stream Banks

"Mechanical failure" of banks means that bank material collapses into the stream as a coherent mass. Mechanical failures are usually envisioned as slabs (translational movements, Fig. 1) or slumps (rotational movements, Fig. 1).

Fig. 1 Mechanical Failure Modes. (from Slavin, 1977)



Many investigators of bank failure have concerned themselves with lower Mississippi River channelization and bank stability. Hvorslev (1956) found that bank collapse on the lower Mississippi was due to undercutting of cohesive soil in the upper bank. Krinitzsky (1965) suggested that spring floods deepened scour pools adjacent to point bar deposits buried in the alluvium. Such oversteepening led to failure in the relatively cohesionless point bar sands. These studies were expanded by using aerial photo interpretation to map those alluvial deposits of the Mississippi that were relatively cohesionless (point bar sand) versus those that were cohesive (channel fills, such as fine-grained sediments deposited in oxbow lakes) (Turnbull, Krinitzsky, and Weaver, 1966). These investigators found that the most-numerous and largest bank-failures occurred in the sediments underlain by point-bar deposits rather than the channel-fill deposits. These conclusions have been supported by Slavin's (1977) study of Brown's River, Vermont, an underfit stream flowing in its own alluvium. Slavin was able to show that the erosion rate in the point bar deposits was 7.5 feet per year, but only two feet per year in the channel fill (air photo study of thirty-five period).

Most bank failures along the lower Mississippi are "slump" type failures. Slavin (1977) found that failures along Brown's River were of the "slab" type. Thorne (1978) also identified slab failures in his dissertation study area in Wales. Thorne recognized only one slump; it occurred in a ten-foot, vertical, cohesive bank. Both Thorne and Slavin used engineering theory to account for the mechanics of slab failures.

Fine-grained, root-permeated soils develop overhanging beams as the non-cohesive soil underneath is entrained in flow. Slavin (1977)

witnessed this process: stream scour led to subaqueous slumping of cohesionless, lower-bank sand and gravel, then slab failure took place...often leaving the fine-grained, flood-deposited upper bank as an overhanging beam. Thorne also witnessed that scour and slab failure left overhanging beams. Thorne and Lewin (1979) developed stability equations to account for the beam failures.

Previous researchers have quantified several variables thought to be related to mechanical stability of stream banks. Waldron (1977) ran shear tests on 12-inch diameter soil columns permeated with the roots of alfalfa, barley and pine, and fallow soil columns, and he showed that alfalfa roots increase resistance up to five times that of fallow soil. Partheniades (1971, 1972) emphasized that erodibility was not related to macro shear strength in fine-grained soils. Gross (1973) studied the relationship between physical and mineral properties and bank stability. He found uniform clay mineralogy in the bank sediments; and he found that variable bulk density had no effect on stability. He also concluded that clay coatings on sand grains increased stability. Thorne (1978) noted that fine sediments occurred as one to ten millimeter aggregates or peds, and he considered inter-ped strength.

Fukouka and Yamamura (1971) found that shear strength in an artificial river embankment decreased rapidly with increasing water content. Slavin (1977) found a similar relationship for Brown's River. Furthermore, he found that shear strength decreased with depth below ground surface in the river's bank, and water content increased with depth. Because it is well known that shear strength usually increases with depth, he then concluded that the water content was a great influence on bank failure. Slavin also associated decrease in shear strength with lower unit weight of the cohesionless (point bar) deposits. Although he measured parameters such as water content, composition, relative density and overburden pressure, he pointed out the need to also measure degree of saturation, vegetation and animal effects, position along meander, and recent discharge events.

Edminster, Atkinson and McIntyre (1949) concluded in their study of the Winooski River, Vermont, that major bank failures correlated in time with floods and so they ascribed the failures to the floods. Desai (1972, 1973, 1977) studied drawdown and seepage along the lower Mississippi River. He was able to show that the lowering of stage following floods significantly reduced the theoretical "factor of safety" in slope design. His model correlated very well with piezometer measurements. Desai studied silty-sand point-bar deposits under spring conditions. Slavin (1977, p. 53), however, found that high river stages did not correlate with times of failure during summer storms; the correlation only held for spring floods. He therefore concluded that flooding by itself was insufficient cause for failure of slabs along Brown's River. Thorne (1979) placed piezometers in boreholes in two stream banks in Wales. Pore-pressure response to stage variations in the cohesionless soil (gravel) was slight and contemporaneous with stage fluctuations. These gravel banks immediately drained following stream-level reduction. Thorne concluded (1978, p. 433): "On this basis it seems that the generation of significant excess pore water pressures in alluvial banks which are composed of coarse sediments is unlikely."

Thorne and Lewin (1979) concluded that the failure of composite banks (cohesive soil over cohesionless soil) is not the direct result of fluid stresses but is an indirect result of fluvial erosive processes. Thorne developed a model, based on fluid shear stress analysis, for the erosion of cohesive soil crumbs. He measured secondary currents near the upper-bank cohesive soils during high discharge and found them weak. Considering his model and measured velocities he predicted no erosion. Measurements of no erosion verified his prediction.

Stream bank retreat occurs by scour of lower-bank cohesionless components leading to mechanical failure of the upper bank. Removal of the weathering and erosion products from the base of the bank is necessary to continue erosion (Carson and Kirby, 1971). Of the various products of erosion and weathering that accumulate at the bank base (root mats; soil peds or blocks loosened by weathering, including frost activity; and slide or slump blocks), Slavin (1977) noted that vegetated, cohesive-soil blocks remain intact for months or years along the Brown's River. Such blocks protect the lower bank from scour.

History of Piedmont Flood Plains

Trimble (1974) studied the human impact on the southeastern United State Piedmont. Streams flowed clear when European explorers, missionaries, and early settlers entered the region. With the deforestation that accompanied settlement, erosion and sedimentation became a problem. From approximately 1860 to 1920 erosive cultivation of uplands led to great sedimentation in lowlands. Third-order stream valleys in the Piedmont commonly have five or ten feet of vertical accretion deposits (flood sand, silt and clay). Generally, conservation practices following 1920 resulted in a cessation of upland erosion and lowland sedimentation and caused some stream entrenchment in lowlands.

Urban areas in North Carolina began stream channelization projects in the 1920's and 30's so as to decrease flooding, and to lower the water table thus decreasing the potential for insect-borne disease. Most of the streams in Charlotte have been channelized one or more times. Streams in Raleigh, Winston-Salem and Durham were channelized to a lesser extent.

Genetic Types of Deposits

Happ, Rittenhouse and Dobson (1940) recognized several genetic types of deposits in the Tobitubby and Hurricane valleys of the South Carolina Piedmont:

1. Vertical accretion deposits - suspended load deposited across the flood plain during flood recession or in slackwater. Successive floods build a vertical sequence of sand, silt and clay layers and lenses. The coarser sediment is dominant nearer the channel.
2. Flood-plain splays - sandy sediment spread outward from a low point in the stream bank in a thin, fan-shaped deposit.

3. Lateral accretion deposits - sand deposited during the lateral shifting of meanders (also referred to as point bar deposit).

4. Channel fill and channel lag deposits - cohesionless sediments that filled channels during aggradation. Coarse-grained concentrates, lag gravels, occupy channel bottoms and represent particle sizes too large for the stream to carry.

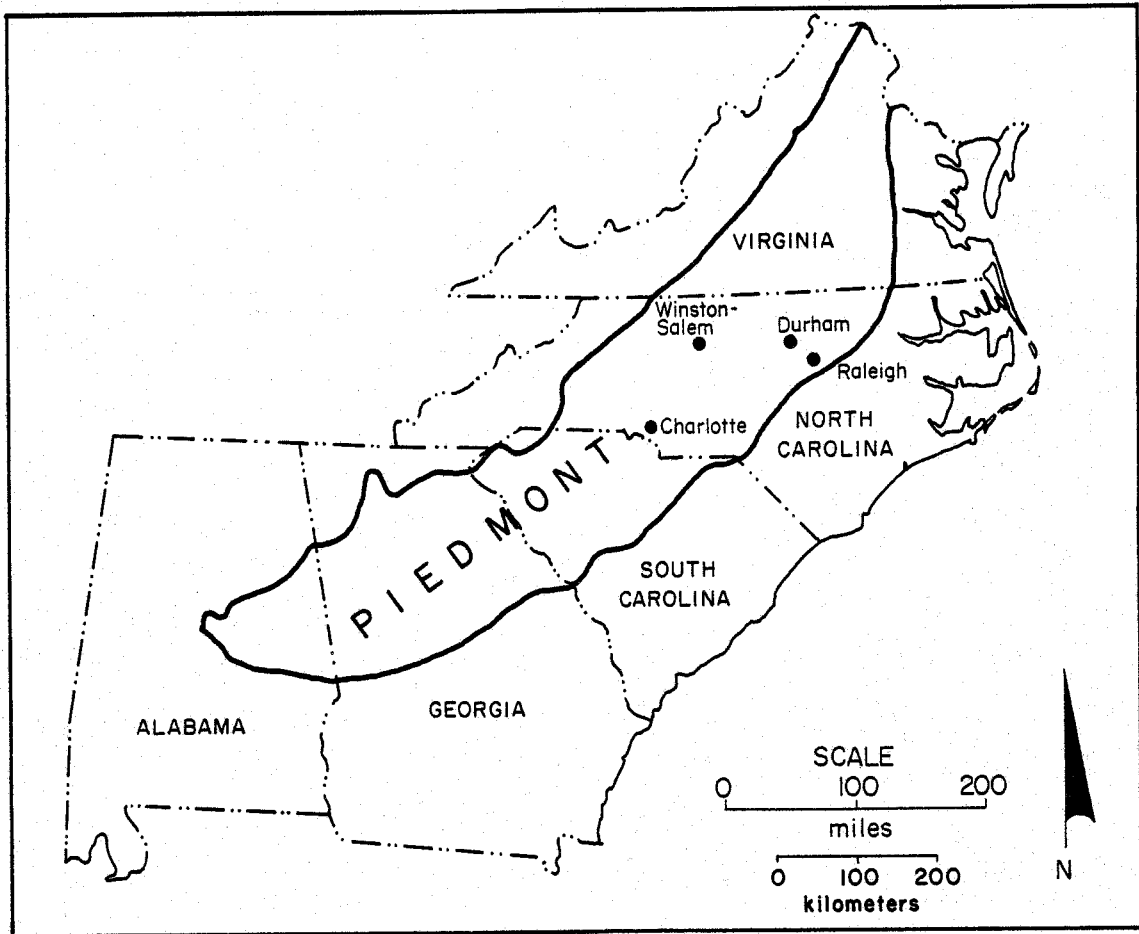
5. Colluvial deposits - accumulations of sediment via sheet erosion on valley walls and occasionally mixed with sediment from down-hill creeping or rolling. Such sediment was found at the flood plain margins.

The bulk of the flood plains investigated by Happ, Rittenhouse and Dobson are composed of vertical accretion deposits interlayered with splay deposits (reddish), overlying older flood plain deposits (grayish color). The post-European age, reddish sediments contained almost no lateral accretion deposits and little channel fill or lag deposits. They noted that channel changes were due to avulsion, i.e. abandonment of a channel in favor of the development of a new one elsewhere in the flood plain. Avulsion presumably occurred because of channel-plugging or levee-overtopping during repetitive flooding.

Project Locus

This study was completed in four North Carolina cities (Fig. 2): Charlotte, Durham, Raleigh and Winston-Salem. Most of the work was completed in Charlotte during 1979 and 1980. Most of the stream reaches studied are identified in the text. Sufficient descriptive detail is given so that a reader wishing to locate a particular stream segment may find it on a local city-engineer's map or a standard U.S. Geological Survey 7.5' topographic map (such maps were used for data compilation for the project).

Fig. 2 Project Location. Piedmont urban streams were studied in four North Carolina cities.



CHARACTERIZATION OF PIEDMONT URBAN STREAM BANKS

Most Piedmont urban streams are tributary or headwater type streams of first- through third- or fourth-order. First- or second-order streams show a veneer or flood sediments, lag deposits and colluvium over saprolite (Fig. 3). For third- or fourth-order streams, the banks are usually composed of red-brown, vertical-accretion deposits of post-European settlement age overlying gray pre-European, flood-plain sediments (Fig. 4). Most of the third- or fourth-order streams have their beds in gray fluvial sediment (pre-European) but occasionally they cut into solid rock ("bedrock") or weathered rock ("saprolite"). Test borings for civil works do not distinguish between various types of gray alluvial sediments. However, borings show that occasionally there is five feet or more of gray fluvial sediments between stream base and rock. Fill deposited from channel dredging is common at the top of the banks. Near the flood plain margin, or at bridge or utility-line crossings, thick deposits of fill may occur (Fig. 5).

Fig. 3 Saprolite. Fine-grained fluvial deposits over saprolite. The saprolite (weathered bedrock) shows the original structure (color bands) of the metamorphic bedrock. A. wet sediment (Winson-Salem); B. dry condition (Charlotte). Hoe handle is marked in decimeters.

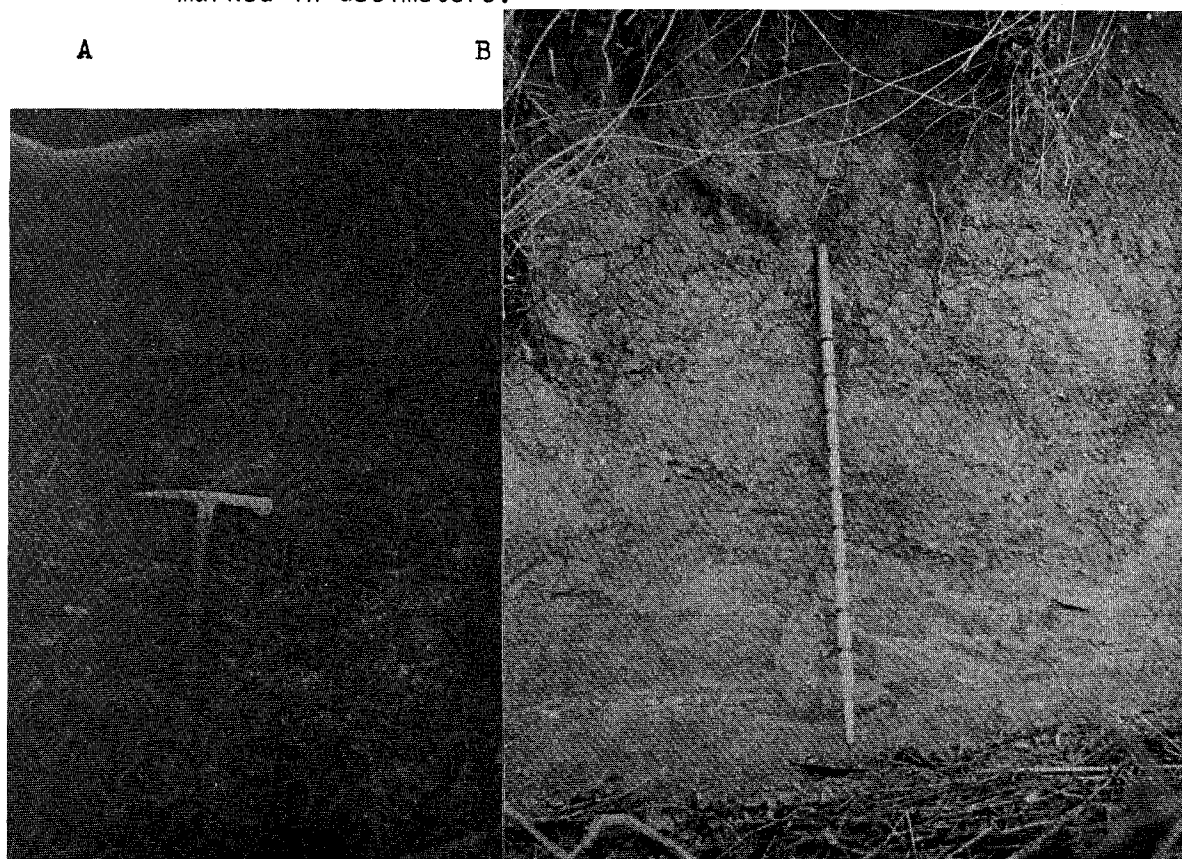


Fig. 4 Red Soil Overlying Gray. Left bank of Briar Creek near its juncture with Little Sugar Creek, Charlotte. Note erosion, and old tree stump at lower left.



Fig. 5 Fill Overlying Gray Sediment. Dashed line on photo is at base of fill. Briar Creek at Plaza Road, Charlotte.



Color

Post-European deposits are reddish brown in color, and usually compose the upper half of the bank on third- or fourth-order streams. These fluvial deposits are red because they are sufficiently coarse grained to permit drainage and maintain an oxidizing environment. To the contrary, the pre-European sediments and the saprolite are fine grained to the point that a wet reducing condition is maintained. Both colors of fluvial sediment were deposited initially on swampy flood plains. Recent stream entrenchment and/or channelization have generally lowered the water table in the flood plains, nevertheless the grays remain wet. For convenience, pre-European-settlement age fluvial deposits (prior to approximately 1700 A.D.) will be referred to as gray and post-European as red.

Red Fluvial Sediments

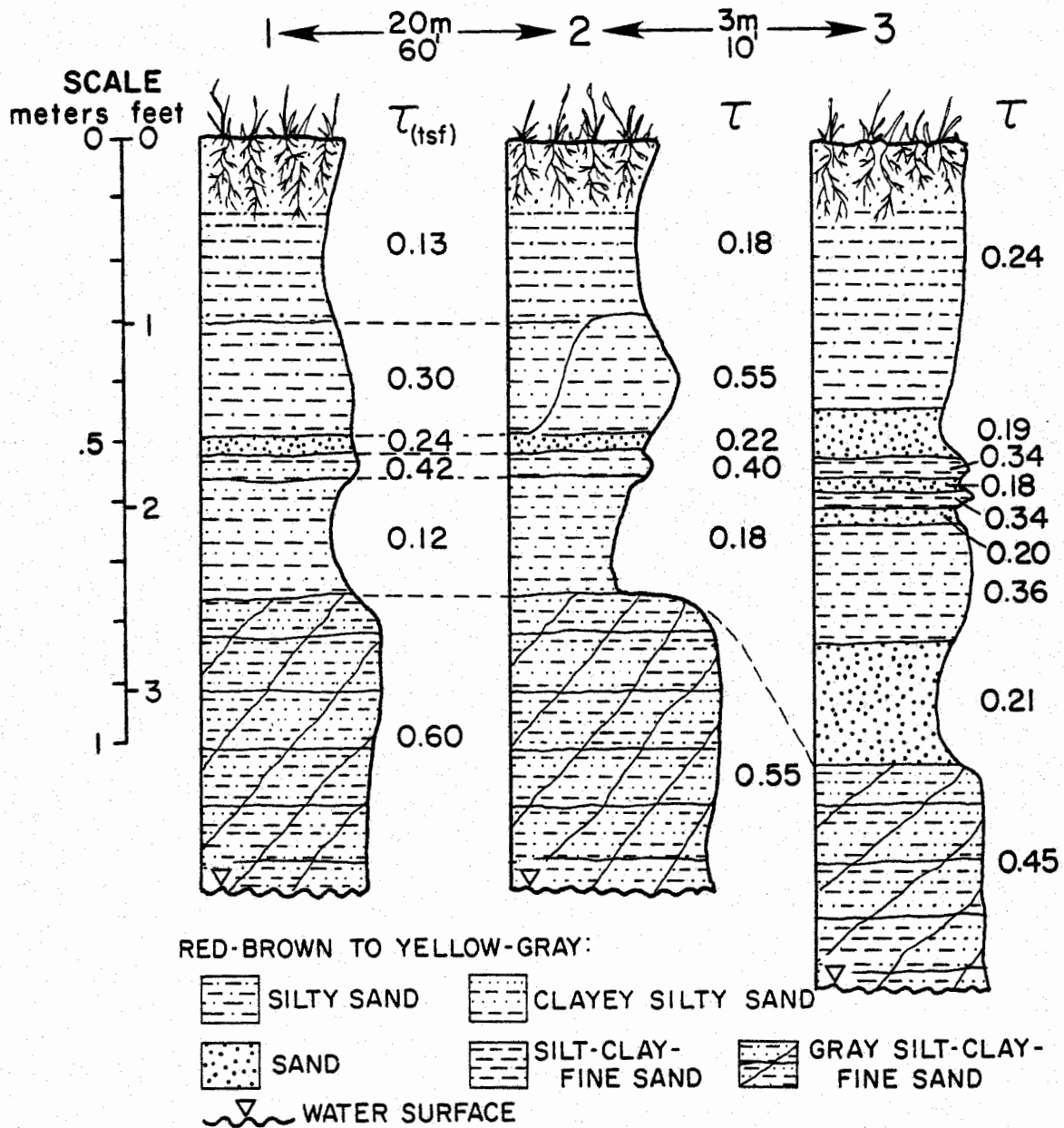
Red fluvial sediments are vertical accretion deposits mixed with splay deposits. Figure 6 indicates the range in properties of these materials. Banks of third-order streams are commonly composed of dozens of sheet-like or lenticular deposits ranging from clayey or silty sands to clayey silt. A well-sorted (poorly graded) layer is rare. Individual layers can sometimes be traced for a hundred feet or more but in other places there is significant change in a few feet. No lateral accretion deposits or channel fills were observed in the red sediments.

Gray Fluvial Sediments

The gray sediments are very fine grained vertical and lateral accretion deposits. Little or no layering was observed in the vertical accretion deposits (grays of Fig. 6 for example); root or stump casts were common near the tops of the deposits. Lateral changes from clayey to more sandy vertical accretion deposits were noted along several banks. Such changes may have been caused because the modern bank was cut diagonally across an old channel such that the observer traversed from slack-water deposits to natural levee deposits. However, the actual observation of an old filled channel was quite rare. Another explanation is that a tributary brought coarser sediment to the flood plain and produced an alluvial fan.

Cross-stratified lateral accretion deposits are uncommon. Lateral accretion deposits are coarser grained than the vertical accretion deposits, but not much so. In three localities, a filled channel was observed in the vertical accretion deposits. The channels contained cross-bedded sand but were partly filled with vertical accretion deposits. Considering current-direction indicators in the sands, the modern channel cut the older one at an oblique angle. These old channels had width-depth ratios of about ten to fifteen (roughly, widths of twenty to thirty and depths of two to three feet). Channel side slopes were approximately 3:1 or 4:1. These ancient channels were observed in the Briar Creek and Mallard Creek flood plains in Charlotte.

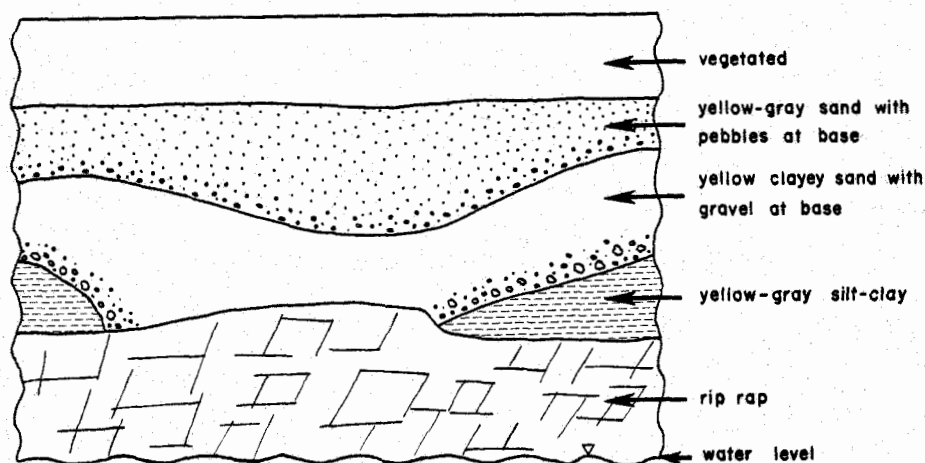
Fig. 6 Variable Properties of Red Alluvial Soils. An example of lateral and vertical variability in red alluvial sediments overlying gray alluvial sediments. Toby Creek, Charlotte.



Paleosols developed on the grays and buried by the reds were observed along more than half of the banks. Usually the organic-rich, top-most horizon (A-horizon) was preserved. In some places the gray sediment became bleached and increasingly yellowish toward the interface with the red sediment. Root casts were prominent in some areas but not in others, with no apparent cause for localization; however, where root casts did occur, they were a foot or two below the organic-rich horizon. Root casts were filled with gray vertical-accretion deposits.

Several peculiarities were noticed regarding the gray sediments. A remnant of a terrace was discovered along Briar Creek (at Myer's Park Country Club, Charlotte). The sandy deposit is sketched in Figure 7. The terrace formed a knoll several feet above the flood plain with well-defined side slopes. Due to vegetative cover the relationship between this terrace and other flood plain sediments could not be examined. The shape and isolation of the knoll imply that it is an erosional remnant.

Fig. 7 Terrace Remnant. Exposed in eroded bank of Briar Creek, Charlotte. Height of view is ten feet.



Another type of oddity, found along Ellerbe Creek in Durham and Briar Creek in Charlotte, was the type of sediment ordinarily found in lakes (fine-grained, composing one thick layer). In both locations this sediment was about one or two feet thick and located between the grays and reds. In each case the sediment is probably an accumulation from an early mill pond.

In the left bank, where Briar and Little Sugar creeks join (Charlotte), the pre-European age flood-plain (marked by the paleosol at the top of the gray sediment) drops about five feet in elevation over a horizontal distance of about twenty feet. The top of the modern flood plain (red sediments) remains level. No faulting or igneous dikes are observed. The cause of the disparity in elevations between the Briar Creek and Little Sugar Creek pre-European flood plains is not obvious. Possibly the present course (channelized) of Briar creek is cutting an old terrace buried by the red sediments.

Fig. 8 Fill. Red sediment over gray showing disturbance of upper red sediment. Chunks of gray sediment are incorporated into the red soil by dredging and dumping. The contact between red and gray soils has been deformed, perhaps by the weight of heavy machinery. Briar Creek at Methodist Park, Charlotte.



Saprolite and Bedrock

Saprolite refers to rock that has chemically decayed to sands (quartz and feldspar minerals), clays and oxides (iron and aluminum). Great lengths of time are required for the solid rock of the earth's crust, bedrock, to decay to saprolite...time measured in tens or hundreds of thousands of years. In a warm, humid environment chemical weathering dominates over physical processes such as frost activity. As a consequence, saprolite retains many of the structural features found in the original bedrock, prior to decay, so long as roots or burrowing organisms haven't excessively reworked the soil. So, one can usually distinguish the presence of saprolite from other soils by noting the characteristic structures of bedrock (as in Fig. 3). Bedrock itself is obvious so long as it is a well consolidated and cemented mass, i.e. hard. All of these conditions are met in the Piedmont where rocks are very durable and saprolites retain rock structures and fabric.

The bedrock presents, in the short run, a barrier to stream erosion. Saprolite's erodability depends mainly on its degree of cohesiveness. Upland Piedmont streams (such as first-order streams) are usually cut into saprolite and sometimes into rock. Lowland Piedmont streams, including those not urbanized or channelized, are cut into the gray fluvial sediments. Lowland streams occasionally bottom in rock, very rarely in saprolite. Where a stream encounters rock in its bed and banks, it will erode little; where it encounters rock in its bed, it will tend to widen if its water or sediment discharge is increased. Owing to the types of rocks present, saprolites in the Charlotte area tend to be erosion-resistant (intrusive igneous rocks decaying to clayey, cohesive soil), whereas those in the other cities studied have variable erosion resistance (weathered metamorphic gneisses and schists may form particularly granular saprolite).

Fill

Fills are artificial deposits related to man's constructions (Fig. 8). Stream beds rarely encounter fills; but stream banks are often composed partly of fill if the stream has been channelized. When streams have been excavated or dredged and the spoil spread over the banks, fill may compose five to fifty percent of the bank height. On third-order streams, more than six feet of dredge spoil is rare, one to three feet is common. Conduits for cables, water, sewer, gas, etc., cross Piedmont urban streams. Some conduits are buried below the stream bed, others cross the channel at various levels. Of course, the fills over or around the conduits are exposed in the banks. Fills around sewer lines usually parallel the streams, but lateral migration or widening of the stream in rare instances exposes the fills. Fills from highway and bridge construction are exposed in the banks. Occasionally, fills from parking lots, foundations, landfills, or subdivisions may be exposed. In some instances the exposure of fills in the banks is the result of poor choice of alignment during channelization.

Fills can be identified by their lack of primary sedimentary structures, such as stratification and cross-bedding. Some fills contain human artifacts. Some fills show signs of mechanical mixing,

such as drag-line or dredge spoils wherein gray and red colored fluvial sediments are admixed as chunks or are squeezed together like toothpaste. Fills can be identified by the presence of many, sharp steep boundaries between chunks or lenses of different grain sizes. Fill may contain a mixture of widely varying sizes or compositions of particles similar to glacial till deposits or mudflow deposits but in a setting not likely to have had a glacier in the past two hundred years!

In all instances fills were observed to be more erodible than other bank materials. In some cases the erodibility may have been due to erosive seepage through the fill.

Cohesiveness, Strength and Particle Size

Particle size, strength, and cohesive properties vary in Piedmont urban stream banks. Figure 9 presents examples of grain size analyses by standard sieve and hydrometer techniques, and strengths measured by the "Torvane" apparatus (Soil Test, Inc., Evanston, Illinois, USA).

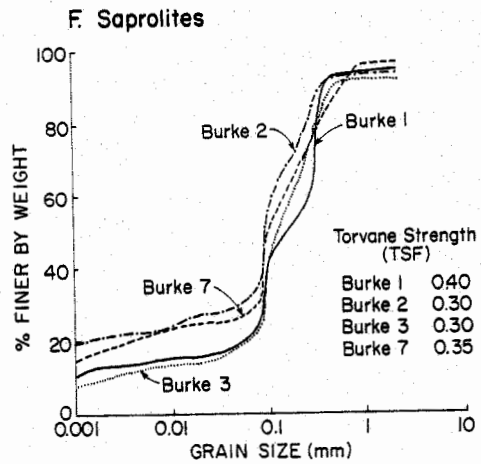
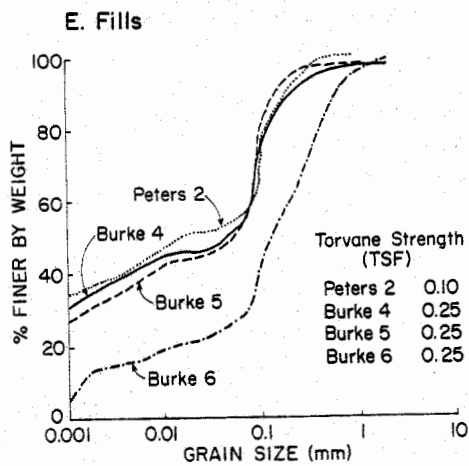
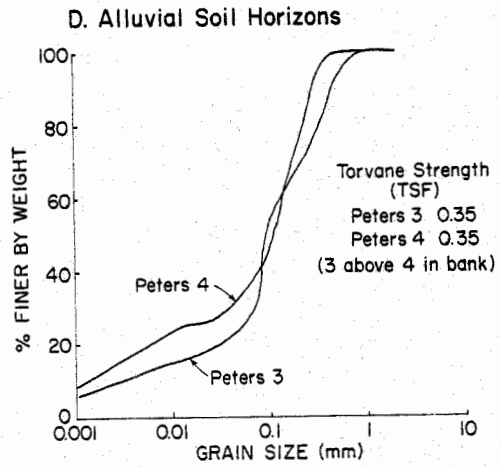
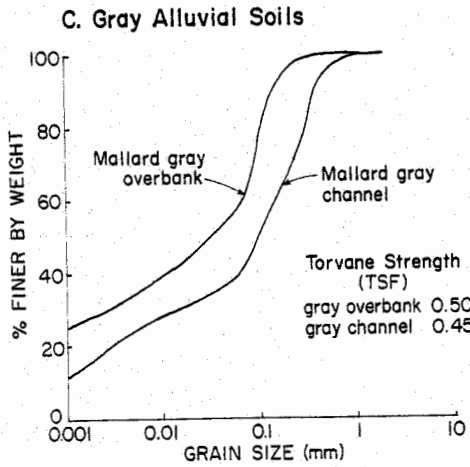
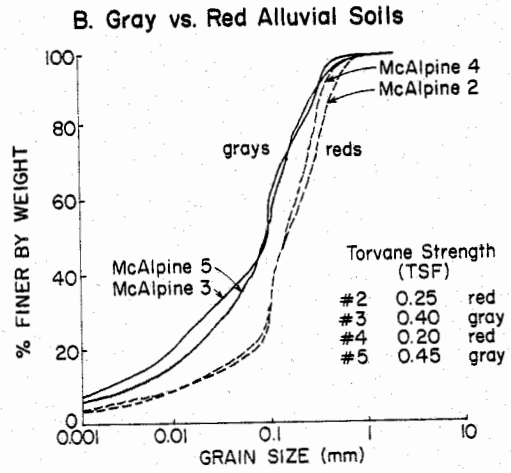
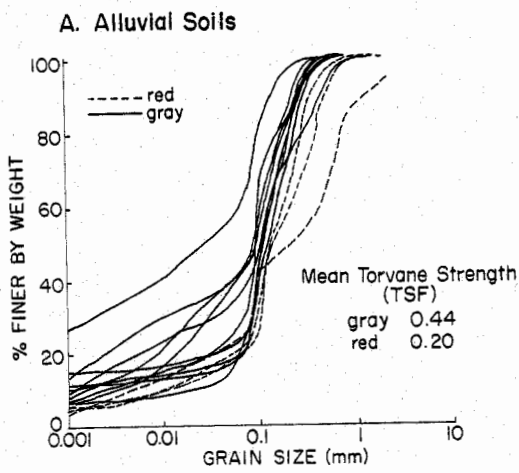
In a plot of a random sample of alluvial soils (red and gray bank sediments) from Piedmont streams (Fig. 9A), the size components of the reds and grays overlap but the reds are generally coarser than the grays. The reds have much lower strengths than the grays. When red and gray alluvial soils are compared along a single stream (Fig. 9B), the grain size disparity between reds and grays is more obvious.

Variability of properties within the red alluvial soils has already been mentioned with regard to figure 6. Variability within the grays is more subtle. Figure 9C displays grain size variation between a gray overbank deposit (vertical accretion) and a gray channel deposit (lateral accretion). However, both are fine-grained and have high strengths. Within a gray vertical-accretion deposit, there may be variation (coarsening upward) due to position in the soil profile (Fig. 9D).

Fills are highly erratic in their grain size distributions (Fig. 9E). Strengths are variable but tend to be low. Saprolites are also variable in terms of their size distributions and strengths. But their grain size curves are much less variable than fills and their strengths are generally higher. Grain size distributions in saprolites and fills are often multimodal.

The cohesiveness of bank sediments varies in a manner similar to the particle size distributions. Fills and saprolites are highly variable within and between deposits. Red and gray alluvial sediments are predictable. Atterberg limits for gray sediments are higher than for reds. Liquid limits of thirty to sixty, plastic limits of eighteen to thirty, and plasticity indices of eleven to forty for gray sediments compare to non-plastic red sediments with liquid limits of twenty to thirty.

Fig. 9 Grain Size and Strength for Several Alluvial Soils.



CONDITION OF PIEDMONT URBAN STREAM BANKS

Most urban areas in the Piedmont are located along the headwaters or tributaries of large drainage basins. Piedmont streams may be subjectively grouped into five categories that reflect their size and basin conditions. These groups help to simplify discussion in this report. The categories are: 1) non-urbanized, 2) central business district, 3) urbanized upland tributary, 4) urbanized lowland tributary, and 5) urbanized main branch. The non-urbanized and central business district streams form a standard of comparison for the other categories. The following paragraphs present a travelog of stream conditions.

Non-urbanized Piedmont Streams

Terms such as "natural stream" or "rural stream" are misleading. For many readers these terms imply a stability, or equilibrium, and a simple history and setting that is erroneous. The rural streams have suffered from deforestation, then erosion from uplands and deposition in lowlands due to agricultural practices, followed by erosion and entrenchment due to agricultural conservation and/or reforestation. Urbanization is a phenomenon largely superimposed on the previously mentioned events. Except for fill materials, urbanized and rural stream banks contain the same types of sediments. However, because channelization is mainly an urban phenomenon, gray sediments are more deeply exposed in the urban environment.

Non-urbanized Upland Tributaries

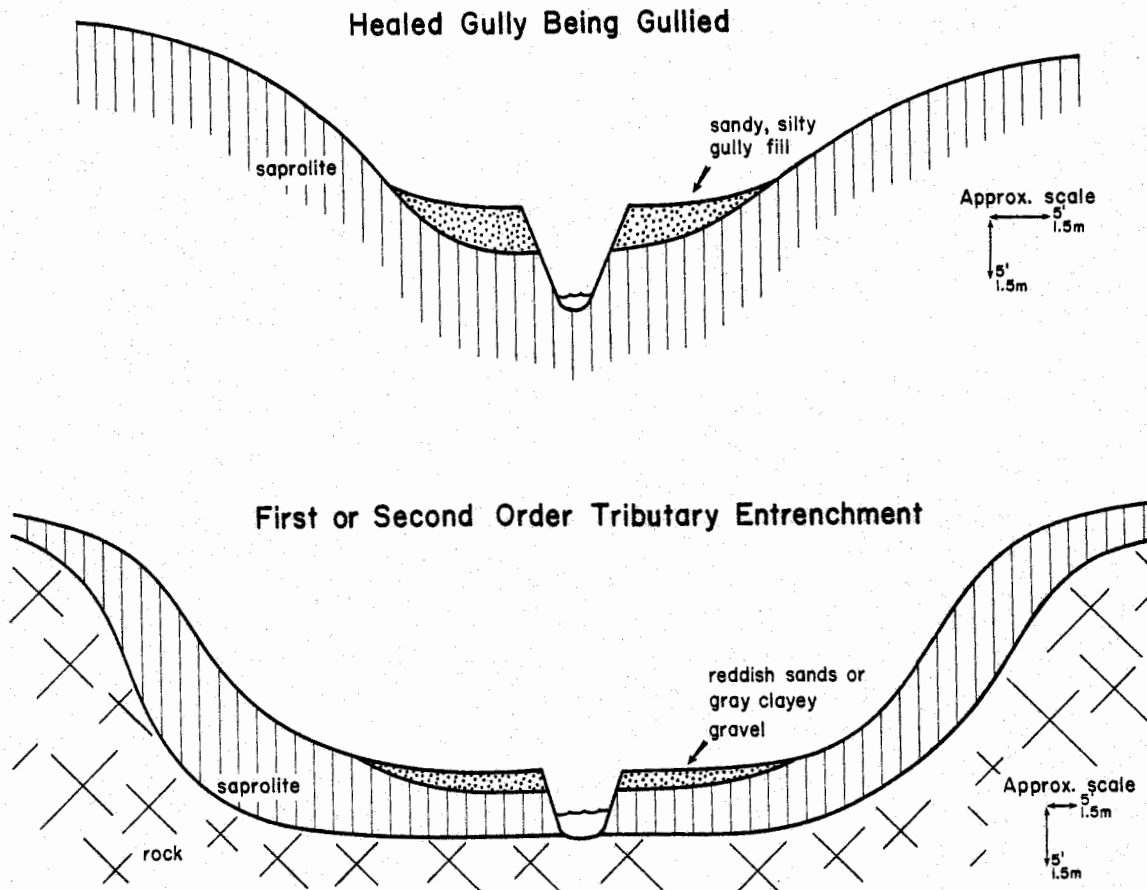
The upland tributaries to Mallard Creek (Charlotte) are often non-urbanized and reforested. About fifteen of these were traversed. Also, tributaries were traversed in Union and Stanly counties, where the underlying rocks were slates (argillites and volcanic rocks of the Slate Belt). The Mallard Creek tributaries are underlain primarily by igneous rocks (diorite and granodiorite intrusives of the Charlotte Belt). About fifty percent of upland tributary banks were eroding by scour.

Upland streams are often entrenched several feet, occasionally ten feet, through alluvium into saprolite (Fig. 10). Bedrock is often exposed. Other streams flow underground for much of the year through cavities carved by erosive seepage through alluvium beneath root mats. Rarely, these cavities are large enough for a person to crawl into. Judging by vegetation growth and kinds of sediments eroded, the entrenchment and the erosive seepage are phenomena of the past one or several decades. Entrenchment and seepage can occur along the same stream; erosive seepage seems to dominate where tree roots form a dense mat.

Once the upland streams degrade to bedrock they may widen, meander, or scour rock. They usually do all three at once, but broad active meanders are not seen. Much of the upland streams energy is dissipated on irregularities in its bed. These irregularities are either inherited due to variability in saprolite erodibility

(variation in original rock structure) or relate directly to varying rock resistance when bedrock is encountered.

Fig. 10 Schematic Profiles of First- and Second-Order Valleys.



Non-urbanized Perrennial Streams

Much of the Mallard Creek drainage basin has not been urbanized. However, as Charlotte grows northward, urbanization of Mallard Creek progresses. Mallard Creek and several of its lowland tributaries, including Toby and Doby Creeks, have been channelized for approximately half their lengths. These streams represent the early stages of urbanization; most of the basin land use is rural or park land.

Several non-channelized, non-urbanized tributaries of Mallard Creek were accessed at bridge crossings. A 1500 foot reach of Mallard Creek was observed at Harrisburg, North Carolina where it has not been channelized for several miles of its length. All of these stream segments were entrenched into the gray sediments.

The reach of Mallard Creek at Harrisburg is the one cited by Keller and Swanson (1979, p. 372) in their paper on vegetative effects on channel form. They noted that log jams created a 230% increase in stream width due to scour around the jams. Bank protection by root wads was also noted. Conditions similar to their mapping (1976) persisted at the time of this study (1980, 1981). Most erosion along this reach is by scour. Root wads provide natural bank protection. When most of the soil under a tree is scoured, the tree and remaining soil mass fail as a coherent block. Such failures can be likened to slab or beam failure. The top of the block remains horizontal or rotates forward. Once a tree-soil block has failed, the bank scarp formed above the block will be subject to scour or deposition during high flows.

The flood plains of Mallard Creek near Harrisburg and its non-urbanized, non-channelized tributaries show many flood features. Scour pockets, small sand bars, occasional flood channels and flood debris attest to frequent inundation of the flood plain. Such features are inconsequential on the flood plains of the channelized segments, either because flooding is decreased or because of flood plain maintenance (such as parks, golf courses).

Central Business District

Streams in the central business district (CBD) of Piedmont cities are usually subject to extreme structural control. The economy of the CBD is such that streams can be totally concrete lined or entirely routed through conduits. Remember that most Piedmont urban streams are headwaters to larger basins.

Tar Branch in Winston-Salem is a CBD stream similar in size to upland streams or lowland tributaries. Most of Tar Branch is under pavements and foundations. About 1000 feet of Tar Branch and another 1000 feet of its main (unnamed) tributary were available for observation. Approximately twenty percent of the banks were actively eroding by scour. The bed is formed by gravel composed of construction debris and other urban materials along with some gneisses and other rock fragments. Some locations exhibit bed and lower bank exposures of gneissic bedrock. Some lower banks are composed of gneiss bedrock. Fine sand and silt stream sediments, post European settlement in age, but not strongly red in color, compose most of the banks. Where the fluvial sediment overlies the rock in the bank, a pebble lag deposit occurs at the base of the fluvial sediment. Fill is present near bridges.

Where kudzu heavily lines the banks of Tar Branch, erosion seems to be impeded. However, where kudzu spans the stream by attachment to trees on opposite banks, it does not protect the banks and it kills other protective vegetation by cutting out the sunlight. Currently the stream is reworking its banks and forming a new flood plain at a level lower than the previous flood plain.

Little Sugar Creek was observed in the vicinity of Memorial Hospital, Charlotte. At this location the straight channel is about sixty feet wide and twelve feet deep with gray sediments composing the lower half of the bank. Approximately 500 feet of channel on the fringe of the CBD contained sixteen failed masses of red sediments translating over gray sediments in the lower banks. The failed soil-masses resembled blocks of sediment gliding down inclined planes rather than slabs rotating away from the bank or rotational slumps. Several of the blocks were scoured around their periphery. Many blocks were heavily vegetated with weeds and vines - as were the banks generally. Although observations were made at low flow, no other scour holes were observed. Incipient meandering was not observed. The failed blocks appeared to be piling-up at the base of the bank forming part of an inner-channel terrace. The terrace is about one-third to one-half the bank height.

The Urbanized Upland Stream

The headwaters of Pidgeon House Creek in Raleigh are eroding slightly weathered bedrock (gneiss and schist) and saprolite. Due to the mineralogy and structure of the rock, a grainy texture is present. Sand and pebble size fragments can be entrained in flow as non-cohesive sediment. Lithology and structure are conducive to the development of potholes in the bank. Erosion of such non-cohesive particles is rapid.

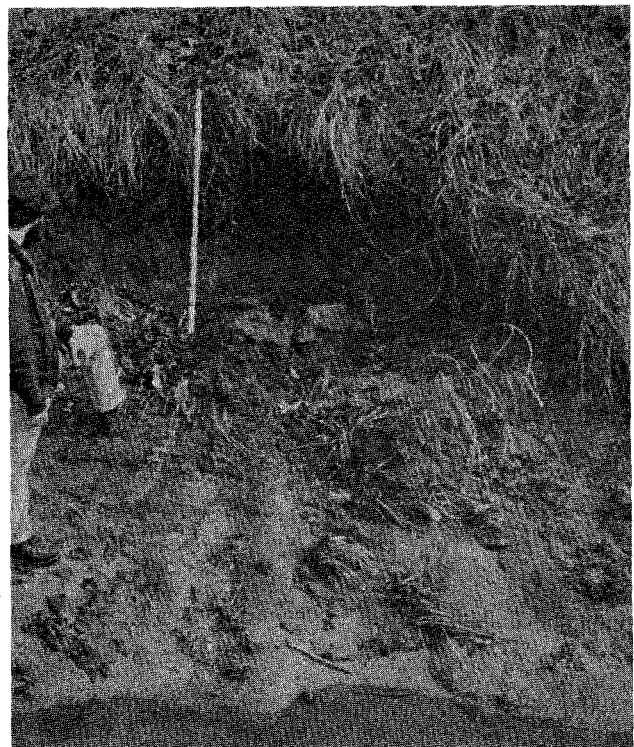
At another location the left bank of Pidgeon House Creek is in fill. Visits between 1979 and 1980 revealed more than two feet of lateral erosion in one year. There is no reason to believe this rate will decrease and the local street is threatened by eventual undercutting or bank failure. Structural protection is inevitable.

A portion of the southwest prong of Beaver Dam Creek was visited in Raleigh. The banks are composed of: one-foot thick grass-root-mat with silt and fine sand, over two or three feet of red fine sand grading into gray fine sand, over a lag deposit of durable pebbles and cobbles. The stream bed and bank bottom was composed of moderately to unweathered rock. The bedrock substrate forces this stream to adjust to urbanization by widening and meandering rather than downcutting.

Much of Burke Branch in Winston-Salem is an upland stream. About 6000 feet of channel in the upper reaches was investigated. Land use is residential and park. Most of these reaches were cut into saprolite and fill with twenty percent of the banks eroding mainly by widening. The headwaters of this stream are formed by several tributaries with flows of perhaps one cubic foot per second. Most of these tributaries lie in or near Miller Park and are partly fed by storm drains from adjacent residential streets. Immediately downstream from these reaches the stream carries a heavy load of sand which is temporarily trapped at a chemical monitoring site (Dick Casper, personal communication). The streams are downcutting in Miller Park. Rapid erosion is taking place in sand that fills abandoned, concrete-dammed ponds. These ponds were originally small and shallow: the dams are only a few feet high and occur in step-like fashion up the stream. These features were buried by sediment and are being exhumed.

A 1000 foot segment of Doby Creek was investigated north of Harris Blvd. in Charlotte. Most of its drainage basin is park land with scattered buildings (research park), interstate highway and woodland. The channelized, grassed banks are subject to translational failure. Blocks of red sediment, often matted with roots, glide over the sloping gray-sediment banks into the channel. As the gray alluvial sediments become scoured more blocks fail and the stream widens. In 1980 this stream segment had dozens of small, failed blocks (one to fifty cubic feet) translating slowly down the banks. Some banks were still completely grassed; others showed bare soil for the lower half of their height (Fig. 12).

Fig. 12 Two Views of Doby Creek Showing Small Vegetated Blocks Gliding Over Gray Soil.



Upper Briar Creek downstream of Plaza Road could be classed as urbanized lowland. Twenty-two hundred feet of channelized stream was observed. Much of this length was stable. Land use is mainly residential. There were three slab failures and three locations where root-mat blocks were sliding into the stream.

Briar Creek in the Methodist Park was observed in 1979, 1980, 1981 and 1982. The stream was suffering from retaining wall failure by lateral earth pressure, scour above and below the walls, failure of rip-rap, and mechanical failure (slabs). Later, banks were smoothed and rip-rap placed along the whole section. Prior to rip-rap placement, this section showed highly variable bank materials: thick fills from previous channelization, an old sand-filled channel

Briar Creek, upstream of Plaza Road, Charlotte, is an upland stream cut into clayey saprolite with tree-line banks. The stream is ten to fifteen feet wide and six to eight feet deep. The stream has cut downward and now is mainly widening. Land use is residential.

Urbanized Lowland Tributaries

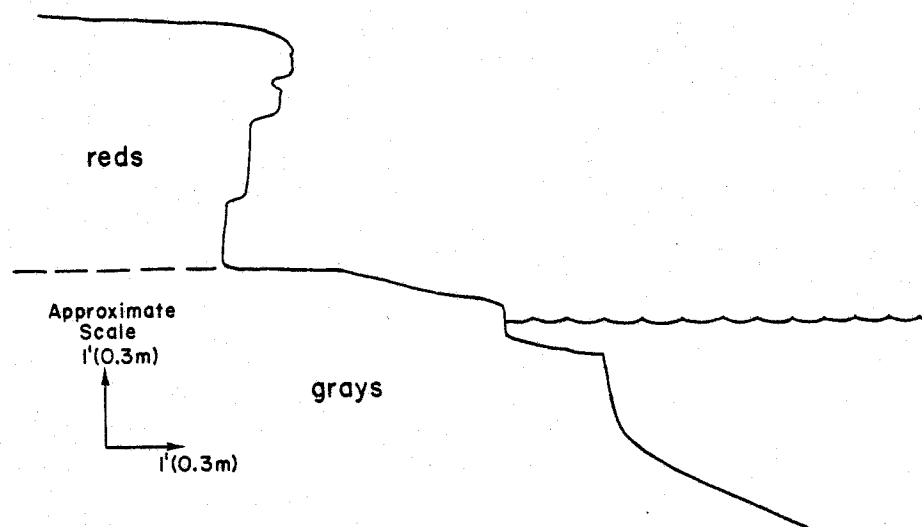
Urbanized lowland tributaries are perennial streams that connect upland tributaries to the main branch streams. Four channelized streams, lower Burke Branch in Winston Salem, lower Toby and Doby Creeks and upper Briar Creek in Charlotte, were observed.

The lower 2200 feet of channel of Burke Branch, Winston-Salem, exposes gray alluvial sediment. About five percent of the banks are eroding by scour. The tributaries are in residential land use, while the lower flood plain is undeveloped grassland. This reach represents a situation where the tributary is channelized across the flood plain of a large trunk stream.

Three thousand feet of banks were studied along lower Toby Creek, Charlotte. Part of the reach is in park land with no trees on the bank and part is forested. Banks are maintained free from shrubs or trees along the entire segment, including forest.

In a 1400 foot reach of Toby Creek, six eroding sections of bank totaled 240 linear feet, i.e. eight percent of the banks were eroding. Width-depth ratios were two to three; cross-sectional areas were fifty to seventy-five square feet. Erosion was caused by scour around small stumps or on the outside of incipient meanders. Occasionally, cubic-foot size blocks of sediment had tumbled into the stream from undercutting. Some blocks were composed of root mats; others were formed from stiff clayey lenses. A handful of slab failures (less than six by four by one foot) were noted. Most interesting was the observation that the red sediments in the upper bank were susceptible to scour as evidenced by steps in the channel cross-section (Fig. 11). Channel fills (both natural and artificial), saprolite, and bedrock were also noted at places in the channel banks or bed. Fills were relatively erodible. Igneous rock dikes and quartz veins formed riffles in the bed.

Fig. 11 Profile Showing Variable Erodibility by Scour. Left bank of Toby Creek, Charlotte.



subparallel to the present channel, saprolite, and red and gray fluvial sediments. Observations in the Spring of 1981 showed several places where children had dismantled, or were disturbing, the rip-rap. During 1982 the reach was stable with silt and grass covering much of the rip-rap.

Main Branch Streams

Seven channelized trunk streams, Elerbe Creek in Durham, Salem and Peters Creeks in Winston-Salem, and Little Sugar, Mallard, McAlpine and Briar Creeks in Charlotte, were studied. Their cross-sectional areas range from approximately 300 to 1000 square feet. Channel depths are eight to fifteen feet.

Ellerbe Creek

Several portions of Ellerbe Creek, Durham, totaling 2800 feet were observed. The channel is cut into gray clayey sand and clayey silt. The straight reaches near Midland Road and Albany Street form a striking contrast. Banks near the Midland Road segment are at forty degrees with channel bed twenty feet wide while the Albany street segment has banks sloping twenty degrees with channel bed eight feet wide. The Albany Street segment shows no erosion of the grass and low shrub lined channel. The Midland Road segment is scouring its banks and small grassed blocks are gliding into the channel.

Salem Creek

Salem Creek (Winston-Salem) was observed in Washington Park (1200 foot section) and Central park (1600 foot section). These sections are channelized straight. This stream was visited in the summer and heavy vegetation covered the banks. Some of the weeds and grasses are probably swept away during the winter leaving more of the banks exposed to erosion. Less than five percent of the banks were eroding during the summer.

The Central Park section looks quite stable. The stream width doubles and the depth halves in a downstream direction. No obstructions to flow were noted in the channel.

Erosion was spatially associated with every obstruction to flow in the channel in Washington Park. At six points widening of Salem Creek was noted. In each case small failed blocks were accumulating to form an inner-channel terrace.

Peters Creek

About ten percent of the banks of Peters Creek, Winston-Salem were eroding along the 8000 feet of stream surveyed. Width-depth ratios were about two and a half. A stable reach was in natural alluvial sediments with minor fill topping the bank near Brunson Elementary School. Along an unstable reach near the high school, fills were involved in bank failure. Moving blocks were developing inner-channel terraces.

Little Sugar Creek

Two thousand feet of Little Sugar Creek was observed in Freedom Park, Charlotte, before and after a recent channelization project. The stream was also channelized previously. Because this is one of Charlotte's most popular parks, the recent channelization procedure included many aesthetic amenities. At the downstream end of the park a dam was constructed such that water and sediment discharge during floods could be transmitted over and under the dam crest thus eliminating upstream siltation. The lower bank is now composed of an inner-channel terrace of rip-rap, partly covered by a sidewalk. Banks are lined with trees, grass and shrubs, rip-rap, wooden bulkheads, concrete, etc.. Prior to channelization the stream possessed many large failures similar to those described in the preceding section of this report on the CBD (a half mile upstream of Freedom Park). The cost of this type of channelization is far beyond what can normally be assigned.

Mallard Creek

Three sections of channelized Mallard Creek near the University of North Carolina at Charlotte were surveyed. Of one 1600 foot reach, 700 feet of banks (22%) were eroding. Five hundred feet were involved in scour and 200 feet in scour and slab failures. Fourteen separate failures were noted.

A stable 2800 foot section is crossed by Route 29. This section is heavily vegetated in summer. In winter frost heave and ice crystal growth are observed. Thin slabbing occurs on some steep banks. The channel is about fifteen feet deep, fifty feet wide. The base of the banks are rip-rapped for several hundred feet. The banks contain several feet of channel material dumped as fill, over thinly-layered red sediments over gray sediments.

Erosion of 450 feet of banks occurs in a 1400 foot channel section upstream of Route 85. Gray sediments tend to be more sandy than on other reaches studied and the red sediments tend to compose half to three-fourths of the bank height.

Briar Creek

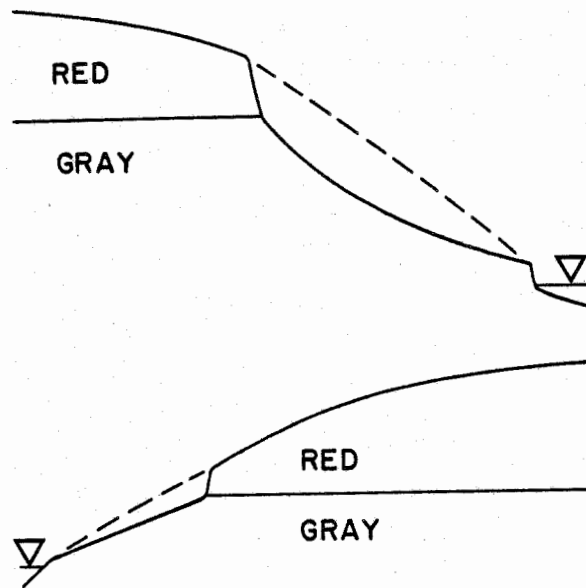
Along Briar Creek, from Little Sugar Creek to north of Providence Road (19,000 feet of stream), 7200 feet of banks were eroding (eighteen percent). Erosion occurs in straight reaches or on the outside of bends. Mechanical failure was noted in eighteen locations. Thirteen large failures occurred and five reaches contained many small slab failures, mainly composed of grass-root mats. The large failures were either slab failures or were indeterminate forms (situations where it was not possible to determine the form of the failure surface).

McAlpine Creek

McAlpine Creek was studied in the Springs of 1980 and 1981. About 5000 feet of straight channel was walked. Dozens of failing

blocks of root-mats were noted, but their total volume was minor. Scour of the lower banks was evident. This stream segment had been channelized a few years previously. Sections with rip-rap in the lower bank were most stable. Twenty percent of the banks were experiencing minor erosion. A few percent of the banks without rip-rap were developing distinctive profiles as shown in Figure 13.

Figure 13. Profiles of McAlpine Creek. Dash line shows approximate profile following channelization but prior to erosion.



PROCESSES OF BANK EROSION

Major Phenomena

Piedmont urban streams respond to urbanization or channelization by widening of lowland channels, and widening or degrading of upland channels. One instance of aggradation was noted upstream of a culvert, possibly caused by sediment deposition during high-flow ponding. One instance of downcutting (as much as five feet) was noted on a main branch stream as a knickpoint, created by a channelization project, migrated upstream.

Stream widening is achieved by a combination of scour and slab failures. Although many mechanical failures include gray sediments, most mechanical failures are in the red soils, and in fills. Several types of slab failures are common: 1) small slabs up to a cubic foot or two in volume, equidimensional or tall and thin, formed of cohesive soil in either red or gray sediments; 2) blocks involving grass root-mats, one to tens of cubic feet in volume; 3) large slabs, trapezoidal or triangular prisms with long axis parallel to the bank, or arcuate-shaped in plan view, similar to a rotational slump but with translational movement on a relatively flat, sloping base, tens to hundreds of cubic feet, rarely two or three thousand cubic feet; and 4) slabs similar to #3 but also composed of tree roots. Failure types 2 and 3 usually move intermittently for periods of a few years once initiated. Failure type 1 occurs during a storm or two. The duration of movement of type 4 is variable. At least some movements are initiated during flooding. The relative contributions of scour and slab failure to erosion are not obvious. The two processes are often interdependent. Scour initiates slab failure, but once failure begins then the failed block acts as an obstacle to flow producing scouring secondary currents.

Scour of composite banks produces composite profiles. As erosion proceeds the gray sediments in the lower banks produce gentle slopes such as 4:1, but the red soils produce steep profiles. The most rapid scour takes place in fills.

Channelized streams with straight alignment undergo a common sequence of events. If banks are less than six feet high, the stream displays the beginnings of meanders several years or a decade following channelization. If banks are greater than six feet, channel meandering is inhibited by the development of berms (inner-channel terraces) composed of remnants of failed blocks and the gray sediments of composite profiles. Straight reaches with bank slopes of 3:1 or 4:1 are often stable.

The outside of bends do not become stabilized until some relatively unerodible object is encountered (such as tree roots, bridge abutments, or bedrock).

Any irregularities in channel profile or any obstacles in the path of flow lead to scour from erosive secondary currents.

Minor Phenomena

Frost activity is an important minor phenomenon. Occasionally, frozen slabs of sandy sediment inches thick fall from banks. More

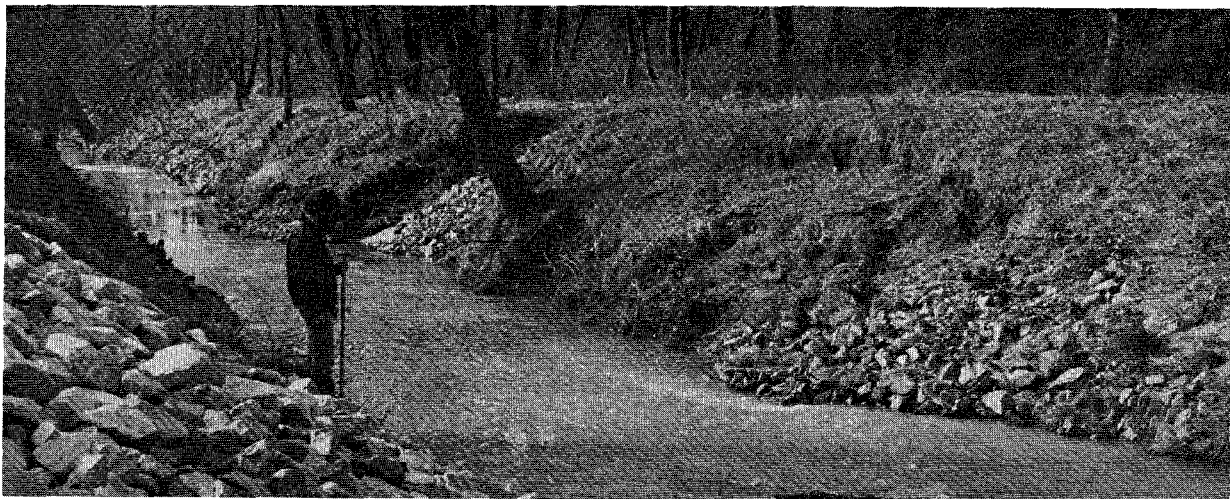
often, needle ice growth loosens soil crumbs which cascade from the bank during thaw. A few inches of bank erosion may be accounted annually from frost activity. Observations indicate that frost activity is much more common in the red sediments than the lower bank gray soils.

No positive identification has been made of a rotational slump. However, several indeterminate forms of bank failure might be slumps. A large subaqueous failure along Briar Creek near Harbinger Court in Charlotte may have been rotational. The slump occurred downstream from a tree growing in the channel bank during a bankfull flood. The vortex downstream from the tree was powerful enough to omit audible sounds heard by a local resident standing about a hundred feet away. The slide mass was removed during the flood. An arcuate scar remained (Fig. 14). But a scar modified by scour is an indeterminate form.

Where Little Sugar Creek joins Briar Creek the upstream migration of a knickpoint and the direction of flow of Little Sugar Creek against its right bank have produced a bank nearly fifteen feet high. Part of the bank has collapsed. The toe of the failure has been pushed up and into the stream bed. This collapse may be a rotational failure. This location involves the deepest cut observed in gray sediments - approximately the lower ten feet of the bank. The cohesive fine-grained gray soils do not achieve a sufficient height of bank to fail by rotation under common channelized conditions.

Of the streams observed, only in a single fifty-foot reach were features observed that might be subaqueous, lower-bank, rotational-failure scars. However this stretch of Briar Creek had several trees growing in the bank, an irregular channel profile and variable alignment; these bank scars could be just from irregular scour. Subaqueous failures observed by investigators in other regions involved cohesive over cohesionless composite bank profiles. In the Piedmont, the sequence is the reverse: somewhat cohesionless sediments (reds) over cohesive sediments (grays).

Fig. 14 Slide Scar and Slide. Viewed From Harbinger Court, Briar Creek, Charlotte.



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