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A MINERAL-MAGNETIC ASSESSMENT OF URBAN SEDIMENT SOURCES AND DRAINAGE BASIN PROCESSES

By
Dan Royall

Department of Geography
University of North Carolina at Greensboro
Greensboro, North Carolina

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ABSTRACT

Many assessments of urban stream quality, and in particular sediment dynamics are costly and time consuming. In contrast, magnetic characterization of sediment is cheap, easy and fast, and may also provide important water quality information including heavy metal concentrations. In this project, the use of mineral-magnetic measurements in applied urban sedimentation studies was evaluated in the context of heavily urbanized North Buffalo Creek watershed in Greensboro, North Carolina. Sediment samples were collected from a variety of impervious surface types with different traffic densities, material types and ages; urban soils were sampled as well. Three types of magnetic measurement on bulk and fractionated samples from these surfaces were evaluated for their discriminatory ability. The results were compared with magnetic profiles from streambanks and streambed traverses at five stream reaches spanning the urban to rural transition to explore the prospects for downstream tracing of urban sediments. Impervious surface sediments, particularly from roadway asphalts, concrete sidewalks and other surface types adjacent to high vehicular traffic areas were found to be consistently more magnetic than urban soils. Mineral debris from parking lots of all materials tended to exhibit magnetism values in between high traffic zones and soils. Vehicular exhaust emissions, which are often highly magnetic, are presumably causal. Streambank and bed sediments increase in magnetism downstream, a pattern which, taken together with the types of magnetic measurement employed suggest more local control of sedimentation than downstream translation. The relatively strong particle-size dependence of magnetism may be useful for rapid mapping of hydraulic habitats, but may obscure magnetic patterns associated with downstream translation of urban sources. Suspended sediment sampling would likely produce better information on the downstream movement of urban-origin sediment, particularly because magnetism was often observed to be inversely related to particle-size in these samples.

(keywords: sediment, urban, magnetism, stream)

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SUMMARY AND CONCLUSIONS

Urban surface sediment sources, a combination of weathering residues from the construction materials themselves, vehicle exhaust particles and incidental soil and other aerosols are magnetically distinctive enough to be discriminated in mixed sediment in this case study from the Piedmont province of North Carolina. Impervious surface sediments, particularly from roadway asphalts, concrete sidewalks and other surface types adjacent to high vehicular traffic areas are consistently more magnetic than urban soils in samples from the North Buffalo Creek watershed. Mineral debris from parking lots made from raw asphalt, sealed asphalt and concrete exhibit magnetism values in between those of high traffic zones and soils. Strongly magnetic vehicular exhaust emissions, in the pseudo-single domain magnetic grain sizes, appear to be influential in determining the magnetic signatures of street residues.

Streambank historical overbank sediments generally increase in magnetism downstream. Streambed sediment magnetism displays a parallel pattern particularly beginning just outside the urban edge which, taken together with the types of magnetic measurement employed, suggest more local control of sedimentation than downstream translation. Presumably local bank failure is a large contributor of this sediment.

The relatively strong particle-size dependence of magnetism may be useful for rapid mapping of hydraulic habitats, but may obscure magnetic patterns associated with downstream translation of urban sources. Suspended sediment sampling would likely produce better information on the downstream movement of urban-origin sediment, particularly because magnetism was often observed to be inversely related to particle-size in these samples. However, the current state of knowledge regarding controls on urban magnetism, sedimentary processes influencing it, and the the sedimentological history of the study site is insufficient for making such applications simple at this time. Although the total mass contribution of urban surface sediment to sediment input in stream channels is small relative to bank and bed sources in all stream reaches, this material may have distinctive attributes such as low SIRM/κ_{lf} relative to soil or pre-industrial, pre-automotive sedimentation, most of which is likely to have been agriculture associated.

Particulate sediments of all types travel discontinuously downstream, potentially mixing with local sediment sources which may be of various origins (even earlier upstream deposits) and attributes. The rapid magnetic identification of urban-origin sediment impacts on downstream sites is a difficult challenge at this time. Such determinations must be made prior to any magnetism-based consideration of future impacts of urban sediment pollution on downstream channel habitat and water quality outside the urban zone. Such impacts, however, are likely to occur given enough time for their translation, and at some point conceivably may impact nearby rural and downstream urban communities. This is particularly true, considering the City of Greensboro's interest in expanding the city eastward in the future. If this occurs, the currently rural areas in this study may rapidly transform into urban and extra-urban communities with potential concomitant impacts on environmental quality along the North Buffalo Creek corridor and possibly points downstream which have already been realized within the headwater reaches.

RECOMMENDATIONS

As a pilot study, this project relied on a small sample size; the analysis of a larger number of samples would be an important first step in understanding the true degree of variation in magnetic characteristics for urban sediments. A spatial correlation analysis of traffic patterns and urban street residue magnetism would also be useful in testing assumptions regarding the influence of vehicular emissions on urban surface magnetism.

Isolating fine sediments which would more likely move with heavy metal and other pollutants, especially in stormflow suspension, would be another important step in the development of magnetic fingerprinting and monitoring in urban stream environments. Other major needs relevant to the use of magnetism in urban sediment budgeting, water quality and habitat studies include the development of better techniques for reliably separating the influences of source and particle size variation on magnetism, and the explicit determination of relationships between water quality and magnetism for the North Buffalo Creek watershed.

Last, the apparent importance of local bank failure to sediment inputs in reaches downstream of urban zones needs to be further tested. Although the late stages in particular of Simon and Hupp's (1986) incised channel evolution model may not be wholly appropriate for incised streams in urban environments, the earlier stages of critical bank height attainment and channel widening via bank collapse may have implications for downstream rural siltation. Conceivably, headwater (urban) areas first acutely experience high stormwater discharges and rapid channel incision, followed by bank collapse, with the final aggradation and quasi-equilibrium phase uncertain. Because aggradation might then be restricted to areas immediately downstream of urban headwaters (in this case, perhaps near the Latham Park or Church Street reaches), channels even farther downstream could still be incising under the influence of stormwater flows, with critical bank height being reached along some reaches. Apparently similar states have been observed in non-urban basins elsewhere in the Piedmont (Ruhlman and Nutter, 1999) and midwestern US (Knox, 1987; Trimble, 1993). Because floodplains are usually better developed in lower portions of basins and channel boundaries more deformable, rural reaches might be predicted to better fit Simon and Hupp's (1986) model in later stages. A larger sample of cross sections, bank magnetism profiles and streambed magnetic surveys is needed to clarify these possibilities.

1.0 INTRODUCTION

The once largely agricultural landscapes of the southeastern U.S. are experiencing rapid population growth focused in the region's cities. With this growth has come similarly rapid increases in hydrologically impervious land area and deforested area both within cities and along the suburban fringe, as new neighborhoods and service areas are constructed. The hydrologic consequences of such urbanization have been well studied, and feature most prominently the alteration of flood frequencies and peak discharges in streams (Booth, 1991; Booth and Jackson, 1997). The attendant geomorphic phenomenon of induced stream channel instability (Trimble, 1997, Downs and Gregory, 1995; Chin and Gregory, 2001; Knighton, 1998) is also increasingly of interest as the applied science of stream restoration matures. In addition to these structural effects are the associated influences on water quantity and quality related to point and non-point source pollutants including sediment from urban infrastructure and disturbed soil. In addition to being a source of stream and lake impairment itself, sediment from both upland and lowland sources is also often a carrier of adsorbed chemical pollutants like heavy metals, fertilizer compounds, and in some cases radionuclides.

Reducing the impairment of streams and reservoirs by excess sediment (popularly referred to as siltation) and adsorbed pollutants is a great challenge for water resource managers throughout North Carolina and the rest of the increasingly populated Southeast, east of the Appalachian Mountains. This challenge can be rendered tractable by a quantitative knowledge of sediment sources, storages, and their residence times in the fluvial system. Although an approximate knowledge of these can be postulated, the inherent spatial and temporal complexity of fluvial processes, and continually evolving urban influences can cause substantial departures from predictions. For example, because of storage potential, sediment yield rarely equals gross erosion, a phenomenon reflected in the concept of sediment delivery ratio (SDR; the ratio of gross watershed erosion to contemporaneous downstream sediment yield; Walling and Webb, 1983). A poor understanding of SDR in urban stream networks has been cited as a key problem for environmental planners (Stow et al., 2002). Some method is needed for more rapid and accurate evaluations of the different sources of sediments and bound pollutants in urban stream water, and their residence times at different locations. In addition, it is important to understand the downstream dilution of such pollutants, and in the case of particulate sediment, the likelihood of storage and concomitant benthic habitat modification, as they move downstream.

In this study, the potential for using relatively new mineral magnetic techniques for urban sediment tracing is explored (Thompson and Oldfield, 1986; Walden et al., 1993; Walden et al, 1997; Dearing, 1999; Dearing, 2000; Royall, 2003; Evans and Heller, 2003). Although it has received little scientific attention to-date, particularly in the US, densely concentrated urban activities like automobile use and various industrial energy-related processes involving the combustion of fossil fuels produce magnetic byproducts or residues which either travel independently (in the air or water) or become adsorbed onto other sediment particles in transport (Shilton et al., 2005). In addition, several prior studies have noted apparent correlations between sediment magnetism and heavy metal content (Revitt et al., 1981; Beckwith et al., 1984; Hunt et al., 1984; Beckwith et al., 1986). Thus, it may be that the magnetic properties of soils and sediments in the urban environment may be useful as tracers within the aquatic environments downstream, and possibly also as surrogate indices of water pollution.

In the current research, this idea is pursued within the context of a small (50 km^2; 3rd-order) drainage basin spanning the urban boundary of Greensboro, North Carolina, the North Buffalo Creek watershed (Fig. 1). As a typical growing Piedmont city sharing geohydrological properties and human history with most of this large heavily populated province from Pennsylvania to Alabama, Greensboro provides a representative environmental example for a much larger area. The goals of this study are 1.) to test the discriminatory power of mineral particle magnetism with regard to urban sediment sources, 2.) to determine the circumstances, if any, under which mineral magnetic properties of urban sediment may be used for understanding sediment sources and urban sediment budgets, 3.) to determine the circumstances, if any, under which mineral magnetic properties of urban sediment might be used for predicting other water quality and stream habitat variables, and 4.) to evaluate the dilution of any urban sediment signal as streams flow beyond urban boundaries and into adjoining rural areas with much lower or negligible impervious land cover and fossil fuel residue production. The broader objective of these analyses is to enable the more accurate and rapid assessment of urban watershed sediment budgets with applications in water resources planning and modern stream rehabilitation.

2.0 BACKGROUND

2.1 Urban Drainage Basin Sedimentology

Sediment dynamics in drainage basins are of concern to a variety of applied scientists and water resource management agencies. Understanding the origins and movement of materials through the fluvial system is prerequisite for assessing the stability of streams and the past, present and future degradation of stream channels and the water they transport. Such knowledge in turn is mandatory for success in the various endeavors related to mitigating the harmful impacts of human resource use on streams. Urban environments (including suburbs), where population density and thus land use pressures are greatest, represent one extreme in the spectrum of human impacts on the fluvial system (Chin, 2006; Gregory, 2006; Kang and Marston, 2006). Although industrial processes and landscapes may achieve even greater impacts, the long-term ongoing migration of people from rural to urban areas beginning in the 20th century has made the impact of urbanization at once intensive and widespread, with high cumulative impact across the US and similarly developed countries (Chin, 2006). Thus, urban drainage basins have been the focus of increasing physical study in the last few decades.

The sedimentation status of all drainage basins can be assessed within the context of the sediment budget concept. A sediment budget, at its most developed state, is a full quantitative accounting for the sediment sources, sinks (storages) and sediment output (yield) from a drainage basin (Dietrich and Dunne, 1978; Dietrich et al., 1982), and the dynamic linkages between these. Of these components, sediment yield, the mass of sediment exported out of the basin per unit time (usually one year), is easiest to obtain, although suspended sediment output is more readily evaluated than bed material output.

Wolman (1967) presented the classical statement of sediment yield changes in small watersheds of the Piedmont, focusing on observations from Maryland. In his model, sediment yield starts off low (perhaps 10-20 t $km^{-2}yr^{-1}$) prior to extensive agriculture beginning around 1840. Sediment yield rises to a peak of ~275 t $km^{-2}yr^{-1}$ in 1900 due to extensive agriculture as well as poor conservation practices, then begins to fall as conservation programs are implemented and land goes out of production. Urbanization ensues around 1960 at which time a large (800 t $km^{-2}yr^{-1}$) sediment pulse is generated as a result of preconstruction surface disturbance, with heavily disturbed soils often left uncovered for long periods prior to construction of impervious cover. Subsequently, sediment yields drop precipitously as upland soils are paved over and no longer available for erosion. Although Wolman's (1967) model indicates very low sediment yields in subsequent years, it now apparent that the altered flood frequencies of urban streams often remobilize older sediment through increased streambed and bank erosion, resulting in higher yields than might ordinarily be expected (Gregory, 2006; Trimble, 1997).

Sediment sources can often be readily identified, but still difficult to quantify in terms of percent contribution to total sediment input and output. Sediment storage can be very difficult to accurately quantify, and stored sediment bodies are doubly difficult to date and determine residence times for. Yet for much applied work, such detail is ideal because more conceptual sediment budgets give little more than an appreciation of the possible process states for streams, a useful but ultimately inadequate background for the application of mitigation measures.

Sediment sources in most drainage basins include upland soils (the pervious land surface), subsoil input from gully erosion, and within the channel itself, sediments input as a result of stream bank failure and streambed erosion. For urban streams, weathering debris from impervious surfaces like asphalt, concrete, and roofing materials, and from the machinery in use on such surfaces is another potential source. In addition, the products of fossil fuel combustion output as exhaust from vehicles principally, alighting on both impervious and pervious surfaces, constitutes a third general type. Both of the latter types are often overlooked from the sediment budget viewpoint, because in most urban environments, other sources appear to be far more important volumetrically. However, because of the potential for correlations between such materials and chemical pollutants from vehicular emissions, they may be disproportionately important. Such considerations have been more typically found in water chemistry research in the past.

Stream bank sediments themselves are, for some 2nd and most 3rd and higher order channels in the North Carolina Piedmont, prominent sediment storage sites which may receive sediments from other upstream and upland sources during overbank flooding. Because such floodplain sediments have variable but potentially long residence times (periods between deposition and later remobilization by bank erosion and levee crest erosion), the historical conditions of overbank sedimentation influence modern sediment budgets as well as long-term water quality.

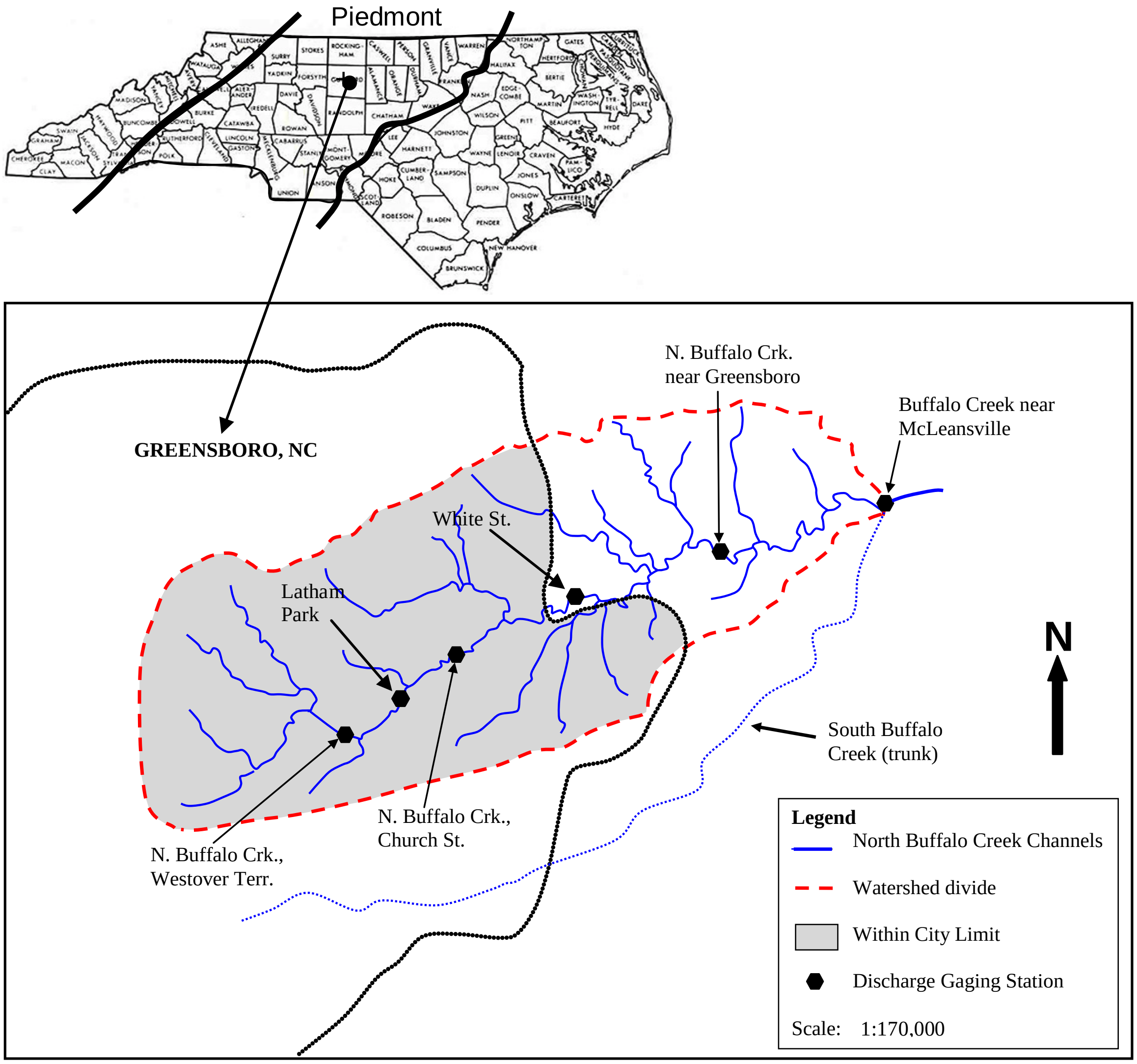
2.2 Environmental Magnetism

Beginning in the mid-1970s, the application of the natural magnetic properties of materials to the solution of environmental problems began to establish itself as the subdiscipline of geosciences known as Environmental Magnetism or Enviromagnetics (Thompson and Oldfield, 1986; Evans and Heller, 2003). The field of environmental magnetism is based on the fact that all substances exhibit a measurable reaction to being placed in a magnetic field, and that these reactions vary substantially and systematically enough to allow discrimination of materials.

2.2.1 Magnetic Measurements

There are several different types of magnetic measurement useful for evaluating sediments (Table 1). The most common measurement is low frequency magnetic susceptibility, which gages the degree to which a sample placed in a moderate-magnitude low frequency magnetic field reinforces or reduces that field. It is thus often thought of as the “magnetizability” of a substance. However this is not entirely accurate because some sizes of magnetic mineral grain exhibit very high susceptibilities but are incapable of maintaining any inherent magnetism once outside of a magnetic field. Magnetic susceptibility can be expressed either on a sample volume basis (the volume susceptibility, in which case it has the symbol: κ_{lf} and is a dimensionless ratio) or on a sample mass basis (the mass-specific, or simply “specific” susceptibility: χ_{lf}, with density units inverted (m^3kg^{-1}) by dividing the dimensionless ratio κ_{lf} by sample density. The variation in susceptibility in relation to the frequency of magnetic field applied can also be a useful measurement, indexing the presence or absence of fine clay-sized magnetic minerals often of

Figure 1. North Buffalo Creek location map



secondary origin. This measure is known as the frequency dependent susceptibility, and has the symbol: κ_{fd} or χ_{fd} with units of percent difference (%). Volume susceptibility can be measured rapidly in the field using a variety of sensors (search loops, point probes, wafer, and core scanner bridges). The other measures require sampling and laboratory measurements.

Saturation isothermal remanant magnetization (SIRM) is a measure of the acquired artificially-induced and self-sustaining magnetism imparted to a material after it has been placed within a high (~1 Tesla) magnetic field. The ratio SIRM/κ_{lf} can be useful in ascertaining the dominant magnetic grain size in a sample. Table 1 contains a summary of the major magnetic measurements and their meaning.

2.2.2 Magnetic Behaviors of Materials

Systematic variation in magnetic properties is a product of three major factors 1.) elemental composition of materials (organic vs. inorganic; mineral species), 2.) magnetic grain size, and 3.) magnetic grain shape (elongate vs. equant; often related to mineral structure class). Organic matter including macro debris like leaves and twigs as well as humic susbtances typically found in soils exhibits either zero or weakly negative magnetic susceptibility (approximately, the "magnetizability" of a substance; Dearing, 1999) an are categorized as diamagnetic. Among minerals, most iron oxides are moderately to highly magnetic, and most others, including the typically dominant mineral of stream sediments quartz, exhibit zero or weak magnetic properties similar to those of organic matter and are also diamagnetic. Water also is diamagnetic in behavior and thus the magnetism of more magnetic materials in or packed with water can be sensed with little interference. Of the common spinel structured iron oxides, those exhibiting ferrimagnetic behavior like magnetite (Fe_3O_4), a common constituent of many igneous rocks and residues, and the common soil constituent maghemite (γFe_2O_3), are the most magnetic (Thompson and Oldfield, 1986; Dearing, 1999). Other soil constituents, especially in the common soil orders of the southeastern US like Ultisols, include hematite (αFe_2O_3) and goethite ($\alpha FeO \cdot OH$), both of which are weakly to moderately magnetic, displaying canted (imperfect) antiferromagnetic behavior.

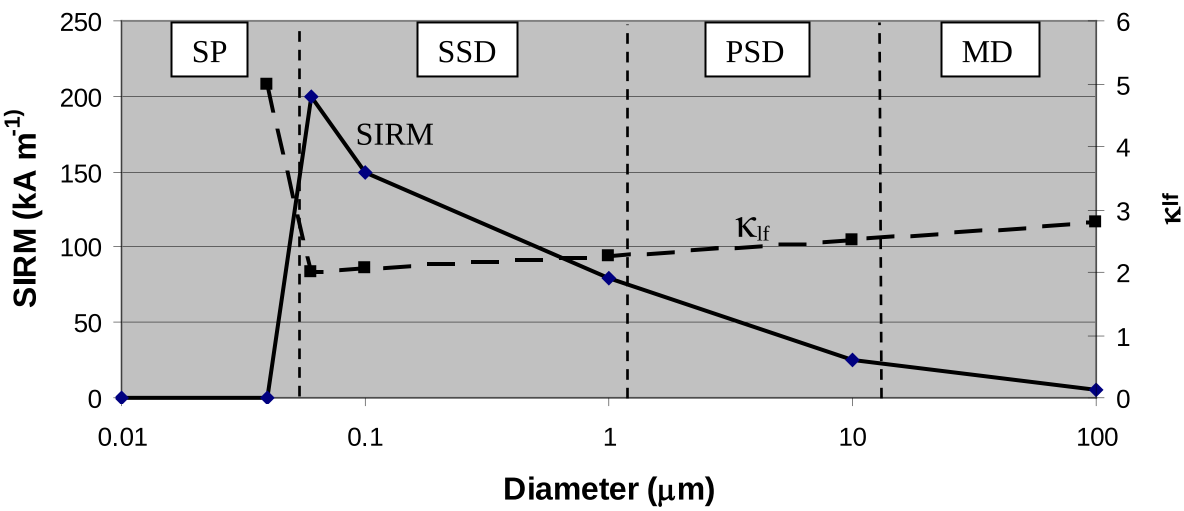
The sizes of magnetic iron oxide grains constitute a continuum associated with specific magnetic behaviors (Fig. 2). From largest to smallest, these are: 1.) Multidomain (MD) grains that contain more than three independently magnetized zones ("domains"), 2.) Pseudo-single domain (PSD) grains that contain two or three domains, 3.) Stable single domain (SSD) grains, and Superparamagnetic (SP) grains which cannot maintain a remanent magnetization at room temperature due to molecular vibrations in these fine clay-sized grains. MD grains are characterized by low SIRM and high volume and specific susceptibilities. PSD grains have moderate SIRM and moderate susceptibilities. SSD grains have high SIRM and low/moderate susceptibilities. SP grains have zero SIRM and very high susceptibilities. Thus, ratios of SIRM/κ_{lf} can be used to judge magnetic grain sizes which may be associated with particular sources.

The shapes of magnetic grains exercise a degree of influence on sample magnetism slightly less than or roughly equivalent to that of grain size. However, the shapes of magnetic grains may not vary across as large a range as particle size, and thus as a source of sample magnetic variation may often be of lesser importance than grain size.

Table 1. Magnetic measurements and their interpretation

κ_{lf}	low-frequency volume magnetic susceptibility; concentration of magnetic minerals; secondary influences are particle size, shape, and species; these secondary influences hold for all measures of susceptibility; often described loosely as how magnetizable a substance is; high in SP grains, relatively low in SSD, and increasing slowly with larger sizes thereafter.
κ_{hf}	high-frequency volume magnetic susceptibility; concentration of magnetic minerals; insensitive to magnetic grains sizes near the SP/SSD boundary; used only in the determination of κ_{fd} (frequency dependent susceptibility).
κ_{fd}	frequency dependent magnetic susceptibility; calculated as the percentage change from κ_{lf} and κ_{hf}; gages quantity of superparamagnetic (SP) (fine clay size) magnetic grains, lying near the SP/SSD (stable single domain) boundary; often such grains are secondary in origin in soils and sediments.
χ_{lf}	mass-specific low-frequency magnetic susceptibility; κ_{lf} divided by sample density; adjusts for mass of sample; like κ_{lf}, a concentration measurement.
SIRM	saturation isothermal remanant magnetization; alternative measure of concentration; amount of magnetization induced, then sustained in a sample after being placed in a high (1 Tesla) field, then removed from it; insensitive to SP grains (zero SIRM); high in SSD grains, decreasing with increase in magnetic grain size.
SIRM:κ_{lf}	SIRM divided by κ_{lf}; according to magnetic grain size trends for SIRM and κ_{lf}, this ratio is low for large multidomain (MD) grains, low to moderate for pseudo-single domain (PSD) grains (i.e., apparently like vehicle exhaust particles; Booth, 2006), and high for SSD grains.

Figure 2. Magnetism variations with magnetic grain size and magnetic domains. SP – superparamagnetic; SSD – stable single domain; PSD – pseudo-single domain; MD – multidomain. (after Thompson and Oldfield (1986), Figure 4.7)



2.2.3 The Magnetism of Mixed Soils and Sediment

From a pedological or sedimentological perspective, a 4th factor, the concentration of magnetic minerals in a population (sample) of grains is of great importance. In soils, it is common to observe magnetic differentiation of soil profiles (Dearing et al., 1985; Royall, 2001). A-horizon materials which are frequently darkened by organic matter additions (which includes "topsoil" where present) are often found to have a higher concentrations of magnetic mineral grains than subsoil B-horizons. This is attributable to both primary sources (magnetites from parent materials that are residual from weathering), and sometimes also the secondary synthesis of magnetite or maghemite within the soil via pedologic processes. The magnetic difference between topsoil and subsoil has permitted the unmixing of hillslope sediments (Dearing et al., 1986; deJong et al., 1998), suspended sediment samples (Walden et al., 1997) and lake sediment deposits (Royall, 2000; 2003).

Most sediment grains in alluvium are of mineralogy resistant to weathering and transport-induced particle size diminution. Quartz is the primary resistant mineral in alluvium, and being diamagnetic, dilutes the total sample magnetism which is almost completely derived from those few iron oxide grains present. Thus, for samples enriched in quartz or other diamagnetic material at the expense of magnetic iron oxides, magnetic susceptibility and SIRM values will be lower in magnitude. However, the spatiotemporal variations in magnetism are frequently of more interest to the water resources specialist, due to their potential linkage to parallel changes in source area, and thus the insights offered into sediment budgeting.

Because of the grain size dependence of magnetism, hydraulic factors which result in particle-size sorting of stream sediment are capable of obscuring the source signal with respect to those measures primarily dependent on concentration; low frequency susceptibility (κ_{lf} and χ_{lf}) and SIRM. However, the ability to gain grain size information by ratioing SIRM and κ_{lf} allows for some control over hydraulic sorting, frequency dependent susceptibility is unaffected by concentration, and further insight into the effects of hydraulic sorting can be easily obtained through fractionation of samples for independent measurements, or for comparing a single size fraction (usually the finer) between samples. However, the application of the latter measure to all samples is very time consuming.

Sediments derived from urban impervious surfaces include splashed soil materials from adjacent pervious areas, weathering debris derived from the surface itself, rusts and other iron-rich debris from vehicles and metallic drains, and airborne particulates, most notably combustion products from exhaust pipes. In urban environments, most or all of the topsoil has likely been removed during construction, leaving often less magnetic subsoil materials as the likely natural contributor to road sediment. The nature of weathering debris from impervious surfaces depends on the material used (usually asphalt and/or concrete), the age of surface (time available for weathering), and possibly the amount of traffic contributing to physical weathering of the surface material. Rusts from vehicles is likely to be paramagnetic, and thus only moderately magnetic compared to fully metallic debris, which however might occur less frequently on roads than the former, although there are few data to judge by. Vehicle exhaust contains iron-oxide microspherules in the PSD size range which may accumulate between rainstorms that wash them into storm drains and thence into urban streams. Beckwith et al. (1984, 1986) found that heavy metals derived from vehicle exhaust occurred in concentrations in roadways correlated with street dust magnetism, thus opening an alternative pathway for monitoring.

Magnetic measurements are easy, fast, safe, cost effective to acquire, and nondestructive to the sample (allowing for further analyses). In addition, volume susceptibility can be measured in the field using a number of sensor types, and can be coupled with data loggers. As a result, to the extent that magnetic measurements can serve as indices or proxies for chemical and physical attributes of samples that are much more difficult to acquire, their use offers great advantages. In addition to the potential for studies of heavy metal pollution in stormwater demonstrated by Beckwith et al. (1984, 1986) for example, more recent studies by Shilton et al. (2005) may provide a means of rapid particle size determinations in spatial and vertical sediment sequences, and the production of air quality risk maps.

2.3 Current Project

For meeting the goals of magnetically discriminating sediment sources, determining the conditions for applying magnetism to sediment transport and water quality research, and delineating the extent of downstream urban sediment impacts, a set of conditions is required. First, a variety of different surface types need to be sampled, and the range of values given by each need to be sufficient to permit reliable associations to be made. Second, the influences of particle size variation on magnetism need to be understood, and these influences accounted for in an interpretive model of magnetism. Last, sampling of fluvial deposits downstream outside of the urban boundary are required and their attributes need to be assessed within this interpretive model. The interpretive model itself is largely provided by a series of flow charts for interpreting magnetism from Dearing (1999). These coupled with existing knowledge of sedimentation in North Buffalo Creek are sufficient to permit judgments of best practices for mineral magnetic sediment budgeting approaches.

3.0 STUDY SITE AND METHODS

3.1 Study Site Description

Greensboro, North Carolina (36°04'45", 79°48'46"; Fig. 1) is a typical growing Piedmont city with a population of about 230,000. Most of the city's water supply is derived from a nested series of shallow reservoirs north of town center which currently mark the interface of urban/suburban growth and the formerly agricultural countryside. Although not part of the city's water supply system, North Buffalo Creek is the most prominent urban stream in Greensboro. West and north of the central business district (CBD) in a heavily urbanized landscape lie the headwaters for North Buffalo Creek (Fig. 1), which, as delimited by the North Buffalo Creek at Church Street USGS gaging station (Fig. 1) are entirely contained within the densely urbanized area of the city. Total impervious area in this watershed ranges from ~15 to 40%. In addition to the Church Street gage, two other gages, one upstream (North Buffalo Creek at Westover Terrace) and one downstream (North Buffalo Creek near Greensboro) provide real-time streamflow data.

North Buffalo Creek throughout almost its entire watershed exhibits characteristics noted as typical of urban streams in humid temperate climates in a large number of areas (Booth, 1991; Chin, 2006; Gregory, 2006). These are : 1.) enlarged cross-sections relative to rural streams of similar drainage area, 2.) presumed disconnection from former floodplains due to deep incision, and the stranding of former floodplains as terraces, and 3.) "flashy" discharge behavior, with rapid rises and falls of hydrograph limbs, and high peak discharge. Several typical urban pollutants have been noted in the stream, including heavy metals (Comito and Lutz, 1993). Incision of the streambed has exposed hard rock ledges in several locations, particularly within the urbanized area. Further downstream, bedrock if often found below low water in the streambed. Presumably, this bedrock prevents further bed degradation, causing a transfer of erosive power to the high banks instead. As a result, bank collapse is a common phenomenon along most reaches, and stream widening is indicated by comparison with regional curves (plots of channel width, depth, and cross-sectional area) for the rural Piedmont. Although great caution must be used in judging the actual departures of these characteristics from some reference state, North Buffalo Creek appears to reflect conditions of having reached critical bank height for failure, channel widening and at least sporadic aggradation in some reaches, as exemplified in models like that of Simon and Hupp (1986) in the latter stages of adjustment to perturbation.

The waters of North Buffalo Creek are listed as impaired by sediment and pathogens (EPA, 1998 survey). The creek exits the urbanized area of Greensboro, flowing abruptly into pastureland and fallow fields, patches of forest with scattered subdivisions and house lots, and generally larger amounts of riparian forest vegetation. Prior and ongoing research on the North Buffalo Creek ecosystem includes studies of nitrogen cycling, riparian buffers, hydraulic habitat, woody debris dynamics and downstream propagation of urban hydrologic effects on channel sedimentation and geomorphology.

3.2 Methods

Surface samples from roadside and other soils, and sediments from urban surfaces were collected after an extended (>4-day) dry period, to allow the accumulation of recent exhaust particles. In addition, soil samples (both A horizon, and the subsoil (B) horizon, which is more likely to be the one exposed in urban environments after construction) from the same series, but outside the urbanized area, were collected to provide baseline magnetism values against which the urban samples can be judged. For soils, surface samples were collected using a plastic trowel; for hard surfaces like asphalt, a synthetic painter's brush was used to sweep sediments and other urban residues into a plastic dustpan for transfer to plastic ziploc baggies. Sample bags were labeled with date, location coordinates, and type of surface, while notes regarding the age, weathering features, and other characteristics of the surface were recorded. Care was taken to sample locations that contain a single ground cover type. For example, an asphalt parking lot will contain a weathering residue related to asphalt tar and mineral compositions, in addition to the potential for magnetic exhaust particles. Using a parking lot that combined two ages of asphalt, or one area of sealed and one area of non-sealed, would unnecessarily add a variable, and impede source classification. Sample sites included asphalt parking lots of various ages, concrete structures like some smaller parking lots and sidewalks, downspout outflows from houses and businesses, and roadside and culvert soils. All sources were collected from within the North Buffalo Creek watershed (Fig. 1).

Samples of stream sediments were collected primarily from channel bank exposures because most sediment input appears from preliminary studies and recent observation to be derived from this source. This accords with the observations of Trimble (1997) for urban streams in subhumid climates where channel bank sources constituted grater than 60% of sediment inputs in incised urban streams. Five bank exposures were magnetically profiled, photographed and described along three urban stream reaches and two rural reaches downstream. Entire profiles were sampled because streambank failure results in the input of sediment from the entire profile. In addition, magnetism was expected to vary through each profile in association with historical changes in fossil fuel combustion, types of fuel, other technological impacts like railroads, as well as particle size variability due to changing hydraulic conditions and source material characteristics. At three of the five reaches, in-situ κ_{lf} measurements were obtained for each soil/pedostratigraphic horizon delineated in the field. At each bank exposure sampled, cross-channel variations in in-situ streambed κ_{lf} were measured using a Bartington Instruments MS2 magnetic susceptibility meter with a submersible search loop sensor.

All samples were air dried at room temperature (to avoid changes in the magnetic characteristics of samples when subjected to high temperatures; Dearing, 1999) at the regolith analysis laboratory in the Geography Department of the University of North Carolina at Greensboro. A selection of impervious surface samples were fractionated by sieving for measuring trends in the relationship between particle-size and magnetism (Thompson and Oldfield, 1986; Royall, 2001). Samples were packed into preweighed 10 cc plastic cylindrical pots with caps, and massed in preparation for magnetic measurements. The following laboratory measurements were made: low-frequency volume magnetic susceptibility (κ_{lf}), high frequency volume magnetic susceptibility (κ_{hf}), and SIRM. From these basic measurements the following measurements were calculated: low-frequency mass-specific magnetic susceptibility (χ_{lf}), frequency dependent susceptibility (κ_{fd}), and SIRM/κ_{lf} ratio. Magnetic susceptibility measurements were made using a Bartington Instruments MS2 magnetic susceptibility meter employing a Bartington MS2B dual frequency sensor. For SIRM determinations, samples were saturated in a 0.9 Tesla field using an ASC Scientific IM-10 Impulse Magnetizer, and SIRM was then measured using a MOLSPIN Minspin portable spinner fluxgate magnetometer (MOLSPIN Instruments, Ltd.). Some bank exposures were also profiled at smaller depth increments using a Bartington MS2E precision core scanning sensor.

4.0 RESULTS

4.1 Particle Size and its Influence on Magnetism

The abundance of sample available for collection was typically greatest for older asphalt surfaces upon which weathering residues had accumulated despite sheetwash removal over years. However, there was no difficulty obtaining large amounts of sediment from any surface except sidewalks and a few weakly weathered road asphalts. Particle size sorting by sheetwash has doubtless strongly influenced particle size distributions of street weathering residues. Coarse materials were particularly easy to obtain (Figs. 3, 4 and 5). Most often the size fraction of 2 to 4 mm diameter was greatest in mass, although its mass value was typically found to be only slightly greater than the next larger and smaller classes (Figs. 4 and 5). However, finer materials were typically mixed in with these, and perhaps protected from erosion by them in some circumstances.

Figure 3. Particle size distribution of residues collected from an older street asphalt sample (#11).

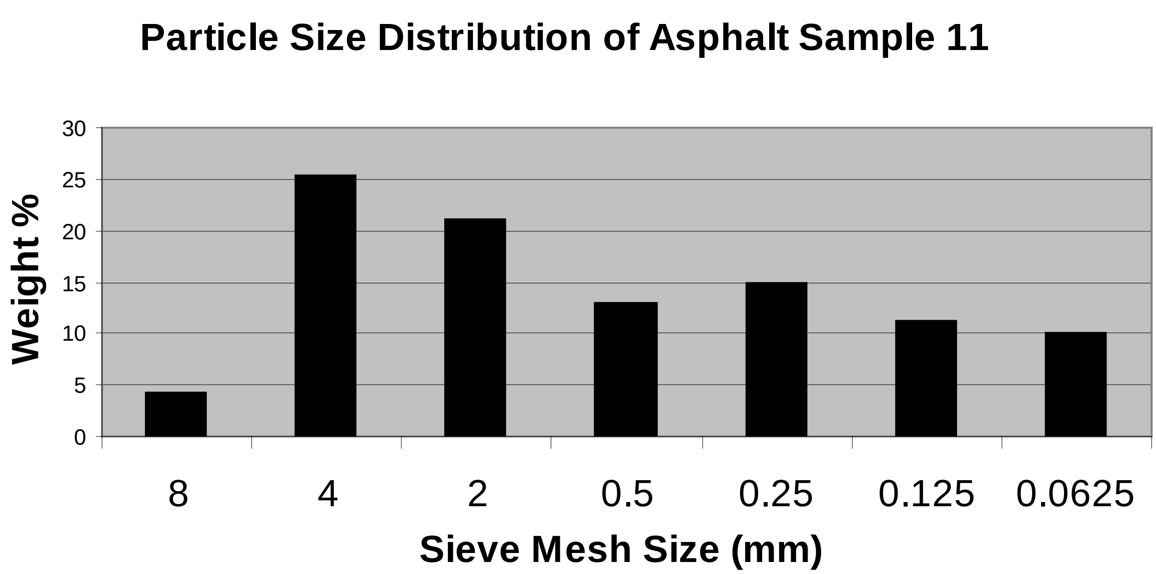


Figure 4. Mass of particle size fractions in impervious surface sediments. Size fractions measured are restricted to particles retained on 4, 2, 0.25 and 0.0625 mm meshes. Ranges are then: >4 mm, 2-4mm, 0.25-2 mm, and <0.25 mm. Legend gives sample designation numbers.

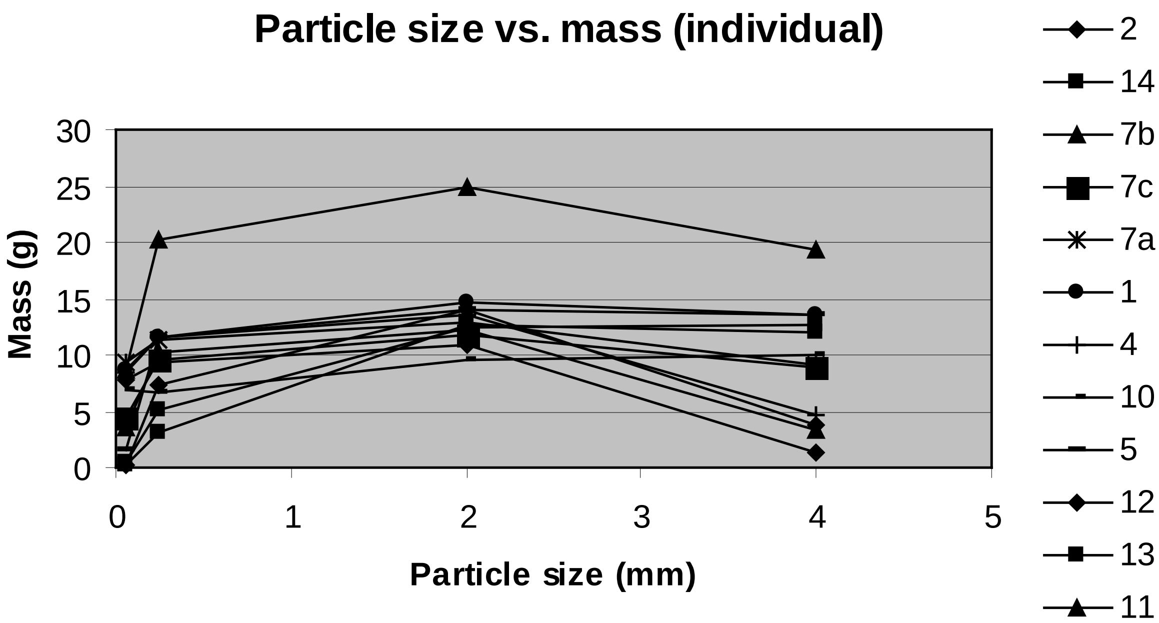
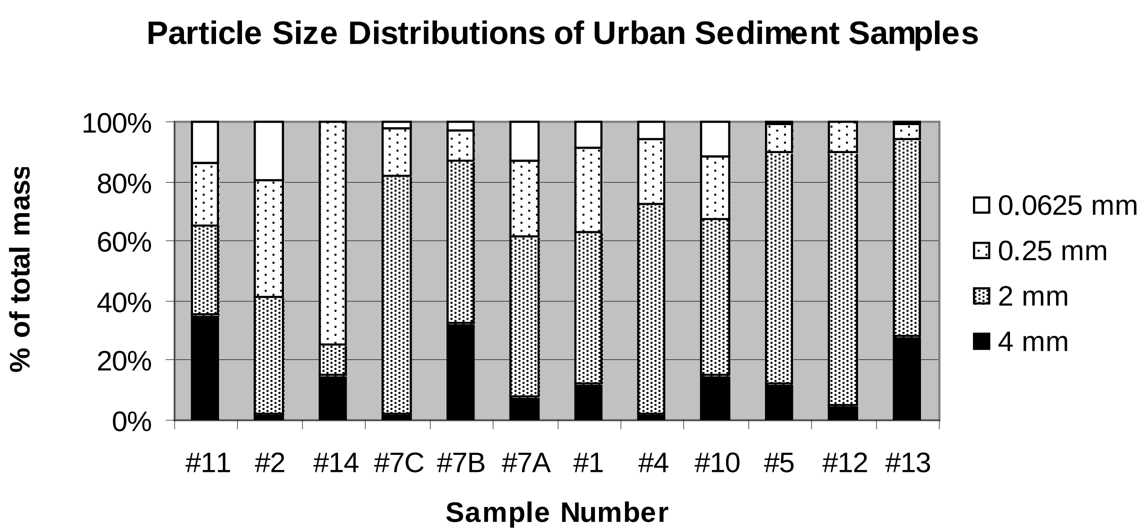


Figure 5. Percent by mass of different size fractions for impervious surface residues. Sample origins: 11, 2, 5 - old weathered asphalt; 1, 12, 13, 14 – young less weathered asphalt; 4, 7a, 7b, 7c ; 10 – recently sealed moderately weathered asphalt.



Both χ^{lf} and κ^{fd} were generally found to exhibit an inverse relationship with particle size (Figs. 6, 7, and 8), which is highest in magnitude (slope) for particle sizes smaller than 1 mm diameter. In interpreting these data, it is important to consider that 1.) magnetic grain size is not the same as particle size of a bulk sample, which is largely composed of quartz, 2.) magnetic iron oxides are more dense than most silicate minerals, and thus are more likely to move with larger size fractions of the latter, and 3.) in road sediments, it is possible that some small magnetic grains adhere to or are trapped by tar on larger silicate particles. However, the general trends observed in the bulk samples compare favorably to those expected for the grain size – magnetism relationships observed for pure iron oxide samples in the laboratory: an inverse relationship between magnetism and particle size.

4.2 Magnetism and Source Area

The surface samples exhibit a broad range of magnetism values for χ_{lf} and SIRM, and a relatively narrow range for κ_{fd} (Figs. 9-12). With only two exceptions (Figs. 9 and 10), κ_{lf} values are below 4%, suggesting that clay-sized SP grains are unimportant as a control of overall sample magnetism in urban street residues. Such ultrafine materials would likely be largely removed by sheetwash during rainstorms, or even air currents if they do not cling to or are sheltered by larger particles, if in fact they are accumulating at all. Except possibly in one case (asphalt roadway sample 12), χ_{lf} values appear too low to reflect iron debris that is not fully oxidized.

Figure 6. χ_{lf} , SIRM/κ_{lf}, and κ_{fd} trends with particle size for sample 11.

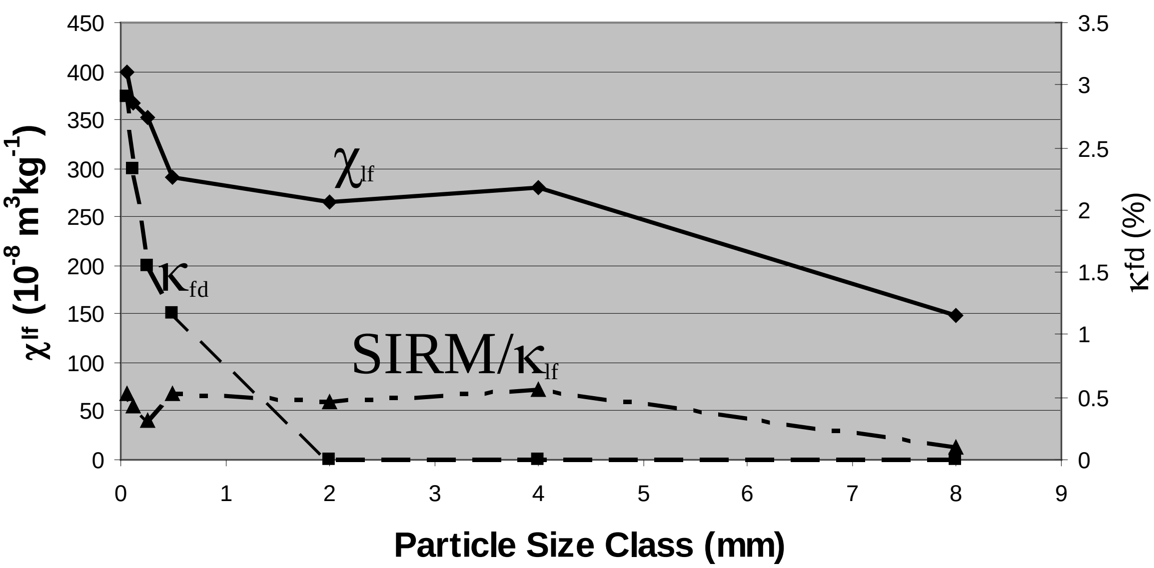


Figure 7. χ^{lf} trends with particle size for all samples at mesh sizes of >4, 2, 0.25, and <0.25mm. Legend gives sample designation numbers.

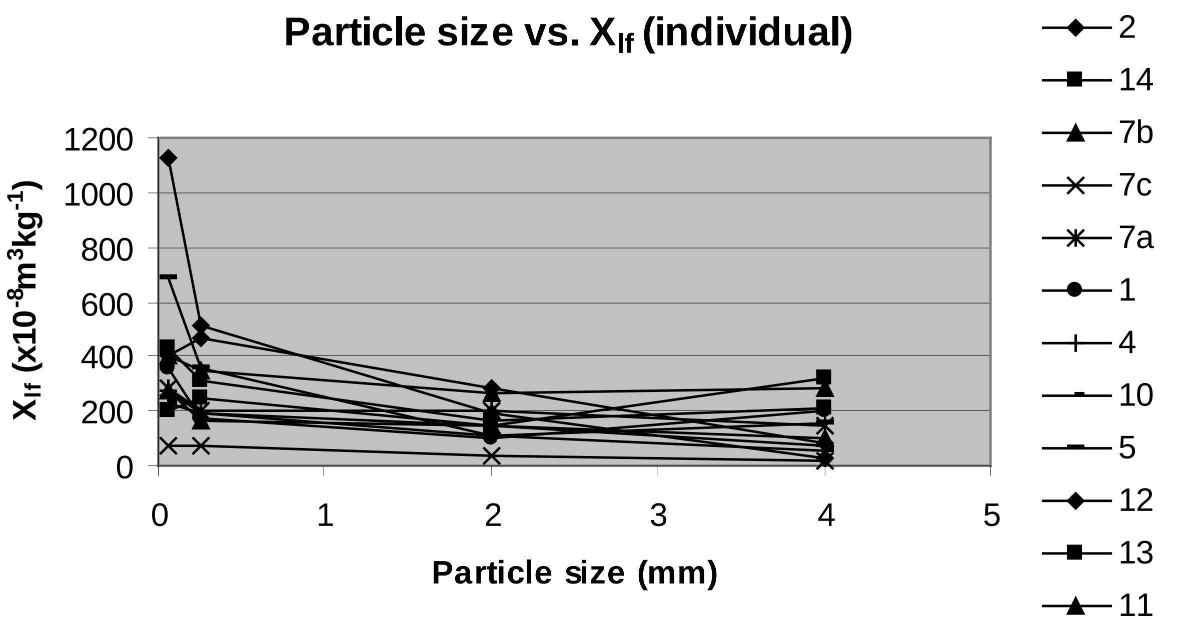
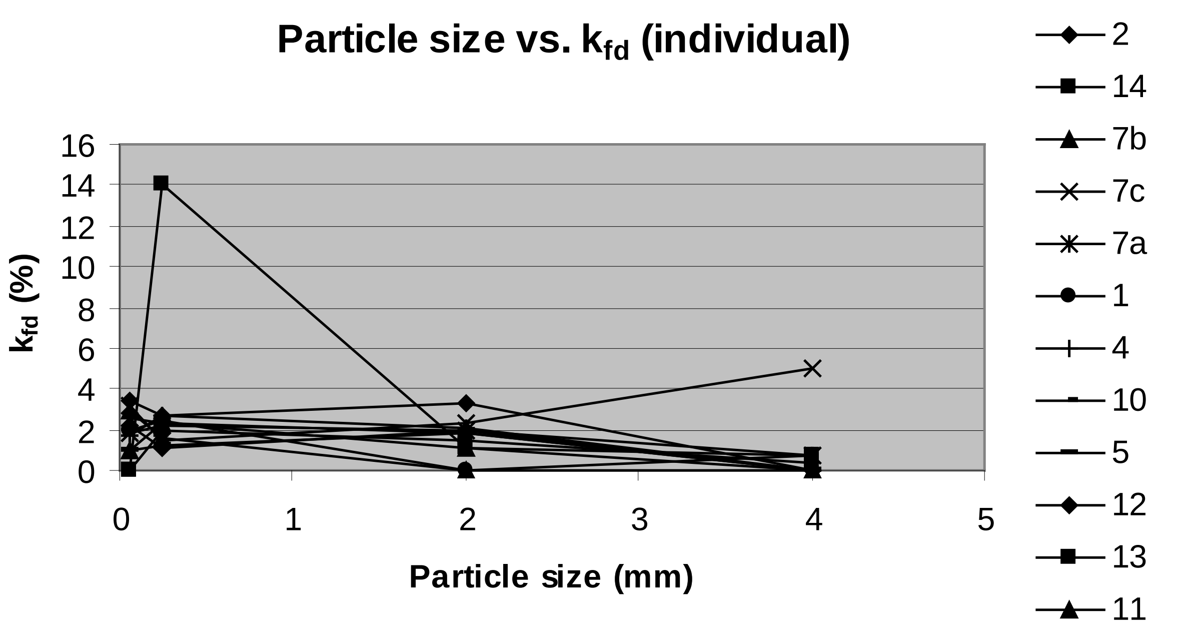


Figure 8. κ^{fd} trends with particle size for all samples at mesh sizes of >4, 2, 0.25, and <0.25mm. Legend gives sample designation numbers.



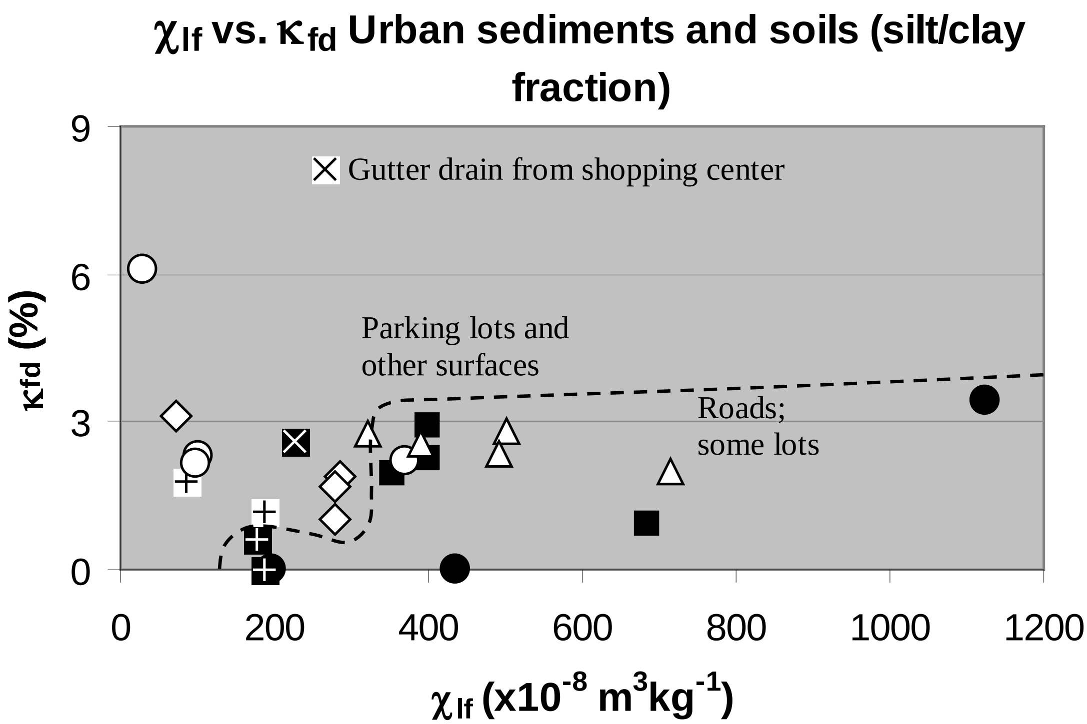
All soil samples (red points in Figs. 9-12) from urban areas are principally of subsoil derivation; this includes those older engineered soils that have become darkened with organic matter additions, but which do not exhibit magnetic enhancement, which is likely to require much longer time periods than have elapsed since construction. Although all measures of soil magnetism vary substantially in those sample obtained, soil magnetism values are almost always less than values for road asphalt residues for both coarse (Fig. 10) and fine (Fig. 9) fractions. Because soil samples were measured as bulk samples (i.e., they were not fractionated) the particle-size influence is not expressly accounted for in these relative values. However, subsoils of soil series in the Greensboro area are typically dominated by the fine sands, silts and clays which represent the size fractions from which magnetic measurements were acquired from fractionated urban surface sediment samples. This is also true of materials in the other samples analyzed in bulk (see Fig. 9 caption). Thus, all samples used for magnetic analyses in Figs. 9, 10 and 11 are comparable in grain size.

Asphalt residue samples in general range broadly in magnetism; however, three populations are discernible: 1.) fresh asphalts which exhibited the maximum χ_{lf} value, but also the largest range of values (black points), 2.) old highly weathered asphalts with moderate χ_{lf} (gray-blue points), and 3.) moderately youthful asphalts from shopping center parking lots (orange points) and clean (low residue) roadways (turquoise points). Low values of the SIRM/ κ_{lf} ratio in all samples suggest that combustion-derived iron oxides of PSD size are possibly important as a control on magnetism in these and many other samples. If so, this further suggests that parking lots of even busy shopping centers are likely to be less important contributors of magnetic spherules and possibly the often associated heavy metals than are roadways of any age.

Concrete surface residues sampled (yellow points) generally exhibit magnetism values between those of the most weakly magnetic asphalts and the moderate values from old weathered asphalts roads (Figs. 9-12). Because concretes are mixtures of cement (essentially crushed limestone and sand) and aggregate (a variety of rock sources), magnetic grains weathered out of this material may be primary (from aggregate) or secondary (formed within the original sedimentary rocks making up the cement).

In most cases, it is likely that high concentrations of magnetic minerals will not occur in either material. If so, much of the magnetism of concrete surface residues may be derived from fuel combustion of vehicles traveling over it. However, concrete residues exhibit relatively high SIRM/κ_{lf} values, suggesting a greater component of grains with SSD magnetism instead of the PSD sizes believed to be more typical of exhaust (Shilton et al., 2005). In addition, it is perhaps more logical to expect higher exhaust concentrations on roadways rather than on the concrete parking lots which form the bulk of the samples in this study. However, despite the variations observed, none of the samples analyzed had high enough SIRM/κ_{lf} ratios to clearly indicate a non PSD source.

Figure 9. Magnetism plots for urban sediment samples. Note that all soil samples, the gutter drain sample, and 4 asphalt samples (black cross and white cross in box points) are bulk samples. The remainder are from measurements on fractionated materials. Dashed line separates road samples from parking lot and other non-road surface samples. Legend from this figure applies also for Figs. 10 and 11.



LEGEND

● Fresh and moderately weathered asphalt from roads and parking lots (samples 14, 12, 13)

■ Older, more weathered asphalt from roads and parking lots (samples 11, 2, 5)

Bulk samples, moderately weathered busy roadway, and storm drain (samples 8 & 9)

⊠ Recently sealed, moderately aged/weathered asphalt (sample 10)

△ Sidewalk dusts

◇ Concrete parking areas of various ages (samples 7a,b,c, and 4)

⊞ Bulk samples from asphalt parking lots of modern shopping complex (samples 15 & 17)

⊠ Bulk sample from (metal) gutter drains off roof of modern shopping complex (sample 16)

○ Bulk soil samples from road and walkway edges

Two final types are unaccounted for in the foregoing: 1.) new sealed asphalt, and 2.) downspout gutter. In the former, sealed asphalt residue in a parking lot appears to be magnetically indistinguishable from other parking lot residues (Figs. 9-12). The residue from the shopping center downspout gutter is similar in χ_{lf} to parking lot residues samples, but is clearly elevated in κ_{fd} (Figs. 9-12). There appears to be no clear explanation for this observation. Because these two types are represented in the sample set by single observations, and do not exhibit markedly divergent values with regard to all other samples, little is gained by further evaluation of them at this time.

Figure 10. Dashed line has same meaning as in Fig. 9, but excludes two road samples.

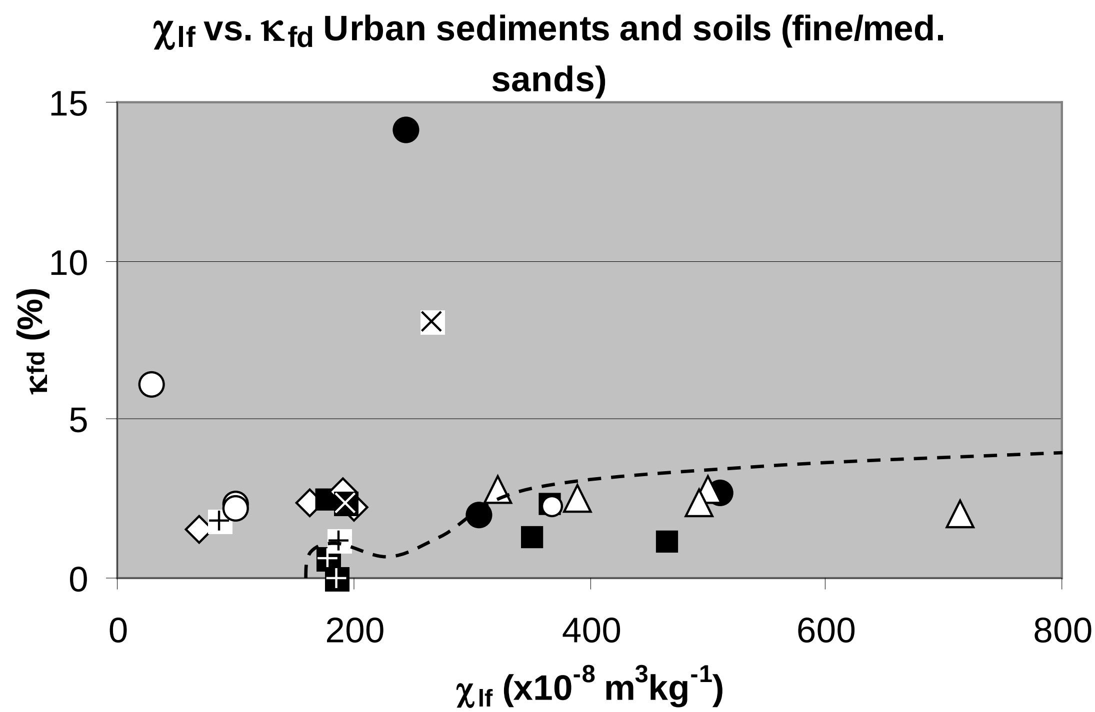
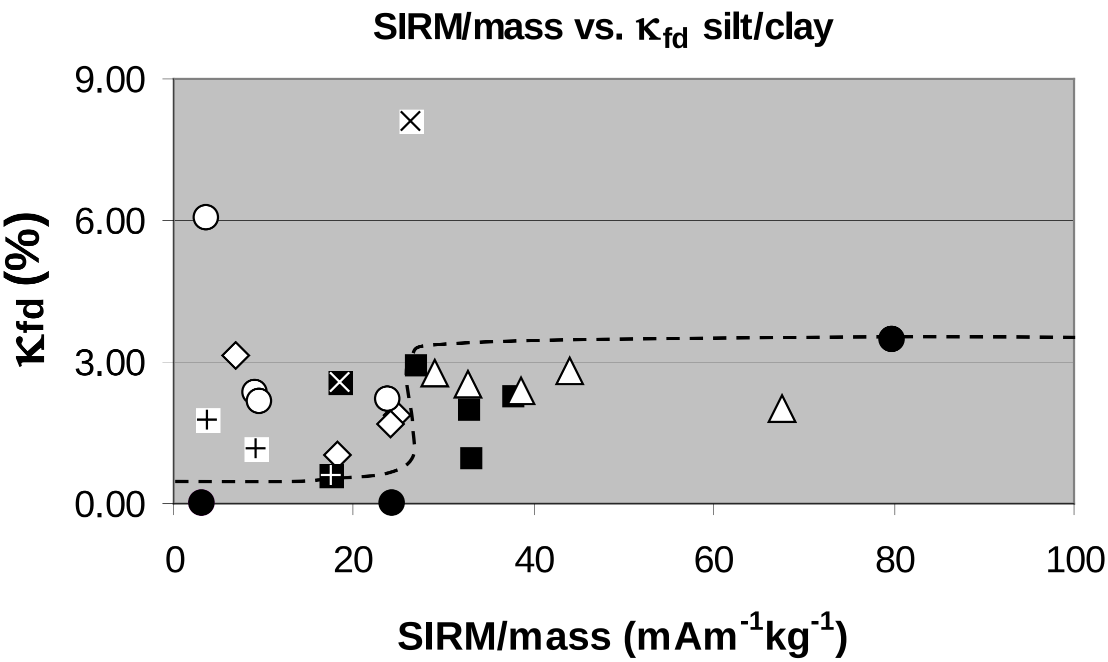


Figure 11. Mass adjusted SIRM vs. κ_{fd} for the fraction smaller than silt.

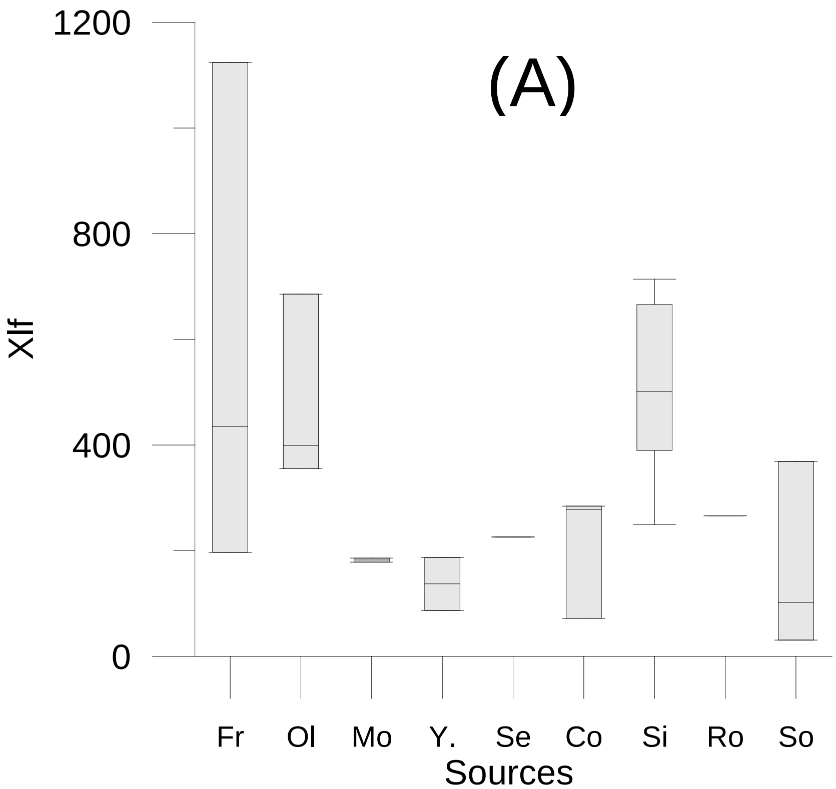


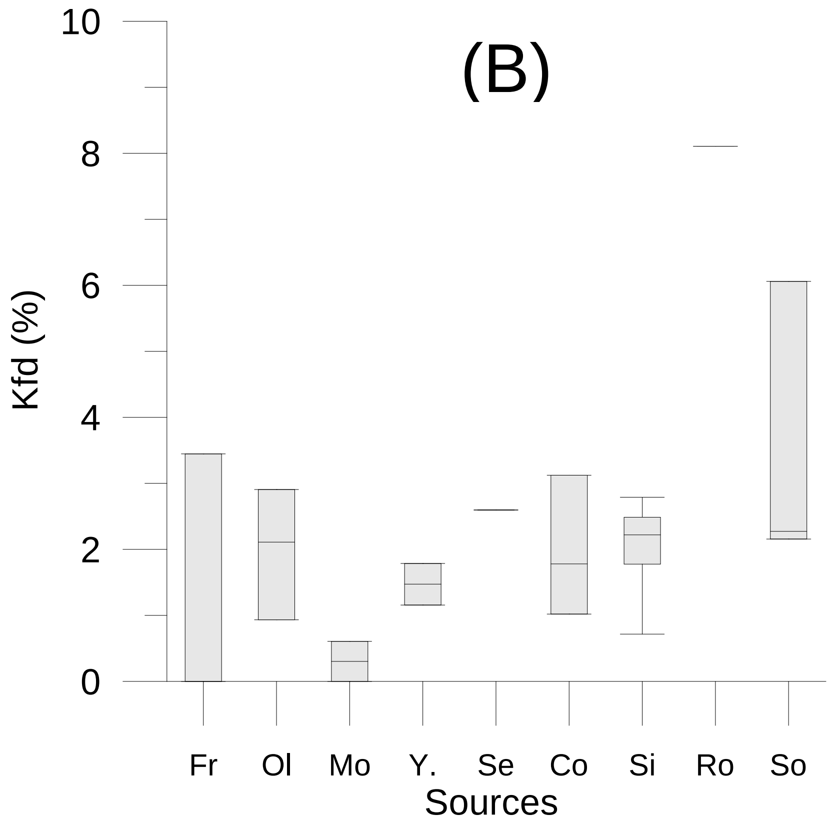
In summary, the general trends observed for the magnetism – source area relationship are: 1.) highest χ_{lf} values are found in residues from asphalt roads. Freshly paved roads exhibit the largest range in χ_{lf} values, older weathered asphalt roads exhibit mid-range values, and lowest values occur for roads surfaces having sparse residue accumulation. Parking lot of all kinds appear to contain residues exhibiting lower magnetism values than those from roadways, a difference that may be attributable to differences in exhaust accumulation. Other trends are not apparent, a result which may partly derive from the paucity of samples.

4.3 Channel Bank Magnetism

With the exception of the Church Street reach, all channel bank profiles exhibit magnetism changes in association with horizon differentiation (Fig. 13). The profile at Church Street is a very young section as indicated by the presence of plastic trash less than 35 years old within basal profile sediments. Magnetically, the Church Street profile resembles the uppermost sediments of the two urban reaches upstream, which exhibit high SIRM/κ_{lf} ratio relative to χ_{lf} (Figs. 13A-C). Rural reaches downstream are reversed in this characteristic (Figs. 13D,E). Like the majority of urban sediment sources analyzed, bank sediment profiles in almost all cases

Figure 12. Box and Whiskers plots of the major urban residues sampled. Fr – fresh asphalt; Ol – old weathered asphalt; Mo – moderately weathered asphalt; Y. – youthful asphalt in shopping lot; Se – recently sealed asphalt lot; Co – concrete lots; Si – sidewalks; Ro – roof downspout in shopping center lot; So – upland soils.




(B)
10
8
6
4
2
0
Kfd (%)
Fr
Ol
Mo
Y.
Se
Co
Si
Ro
So
Sources

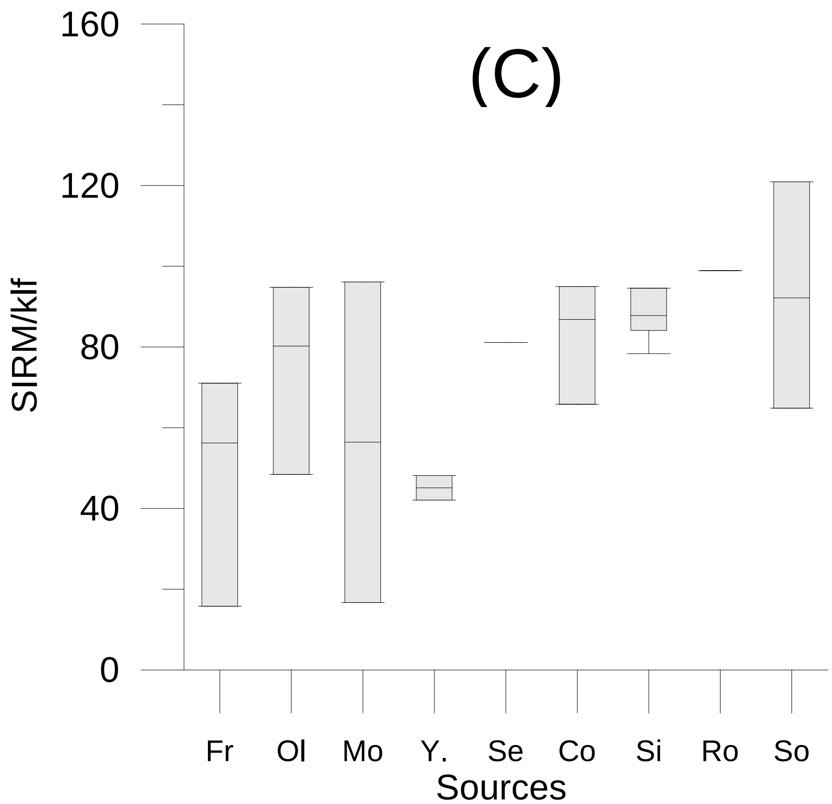
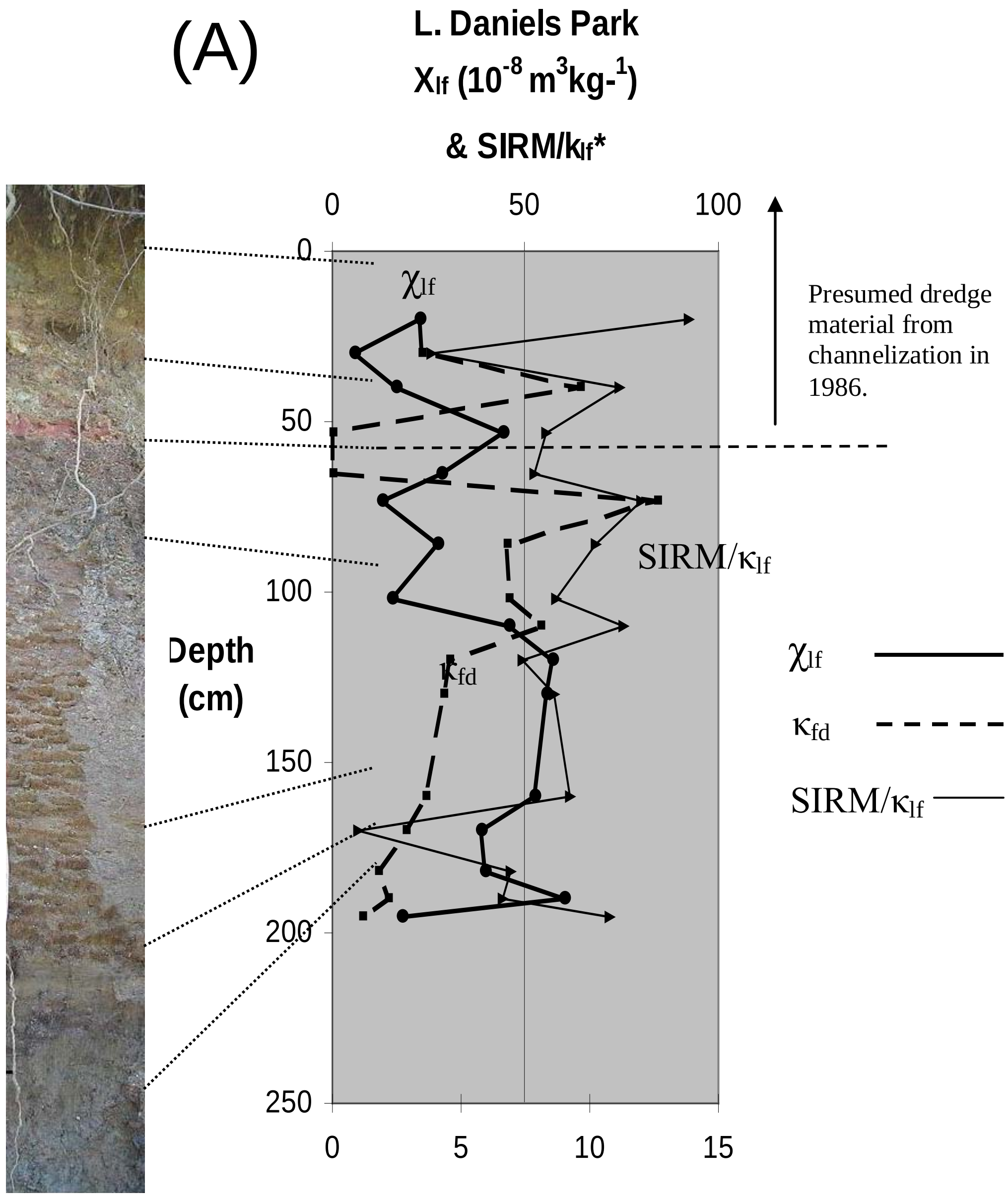
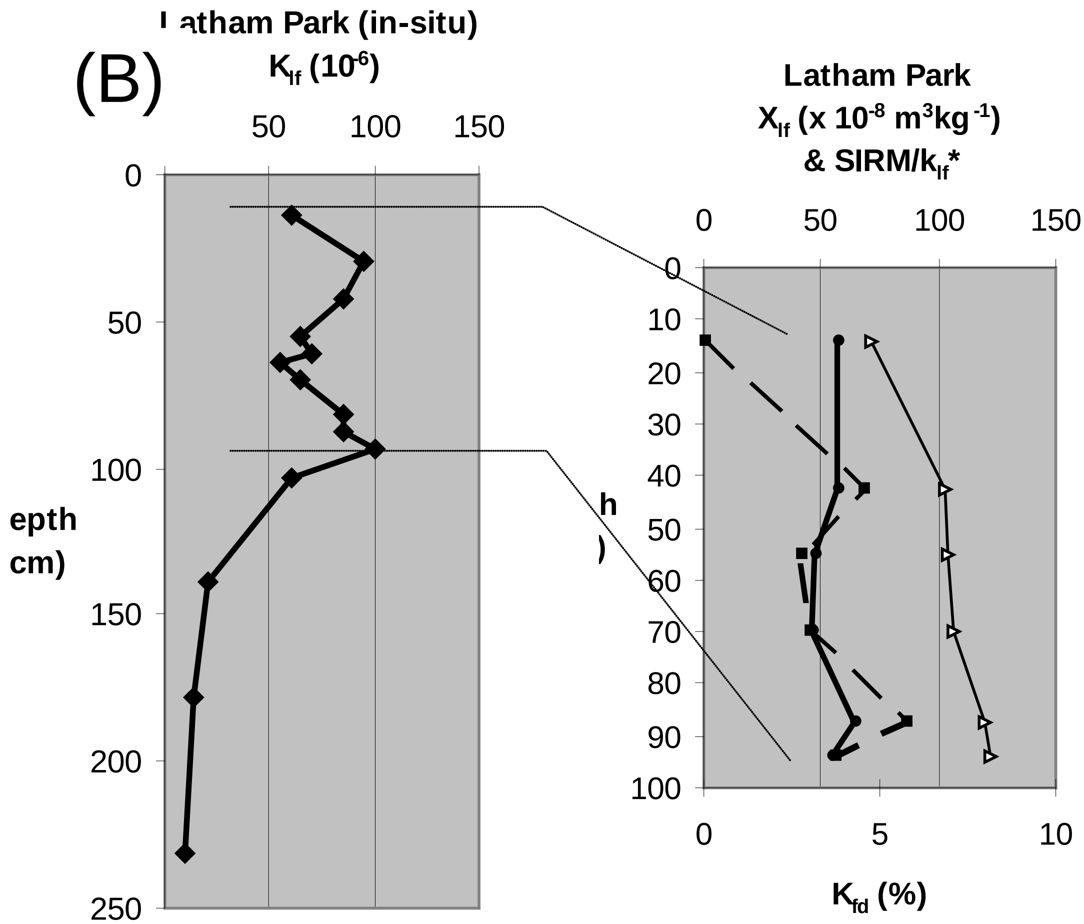

(C)
160
120
80
40
0
SIRM/klf
Fr
Ol
Mo
Y.
Se
Co
Si
Ro
So
Sources

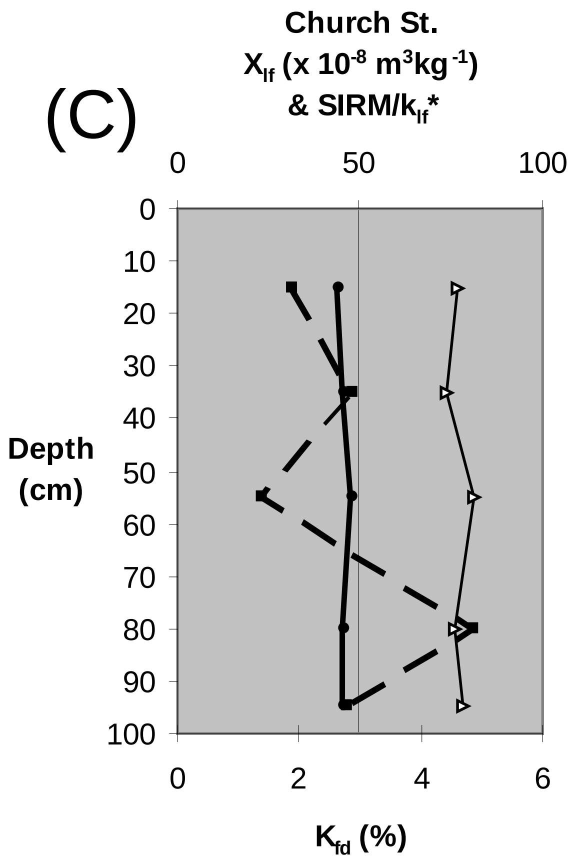
Figure 13. Magnetic profiles for five stations along North Buffalo Creek. A.) Lake Daniels Park (24.6 km^2); B.) Latham Park (31 km^2); C.) Church Street (36.8 km^2); D.) White Street (57 km^2), and E.) North Buffalo Creek near Greensboro (NBCnG) (USGS gaging station at 96 km^2). A through C are urban sites; D and E are rural reaches downstream. In-situ κ_{lf} profiles are based on magnetic core scanner measurements directly from fresh (i.e., dug) surfaces on banks, at depths corresponding to midpoints of field-delineated soil/pedostratigraphic horizons. Triple curve plots display χ_{lf} (black), SIRM/κ_{lf} (yellow; on same scale as χ_{lf}, but dimensionless), and κ_{fd} (red).



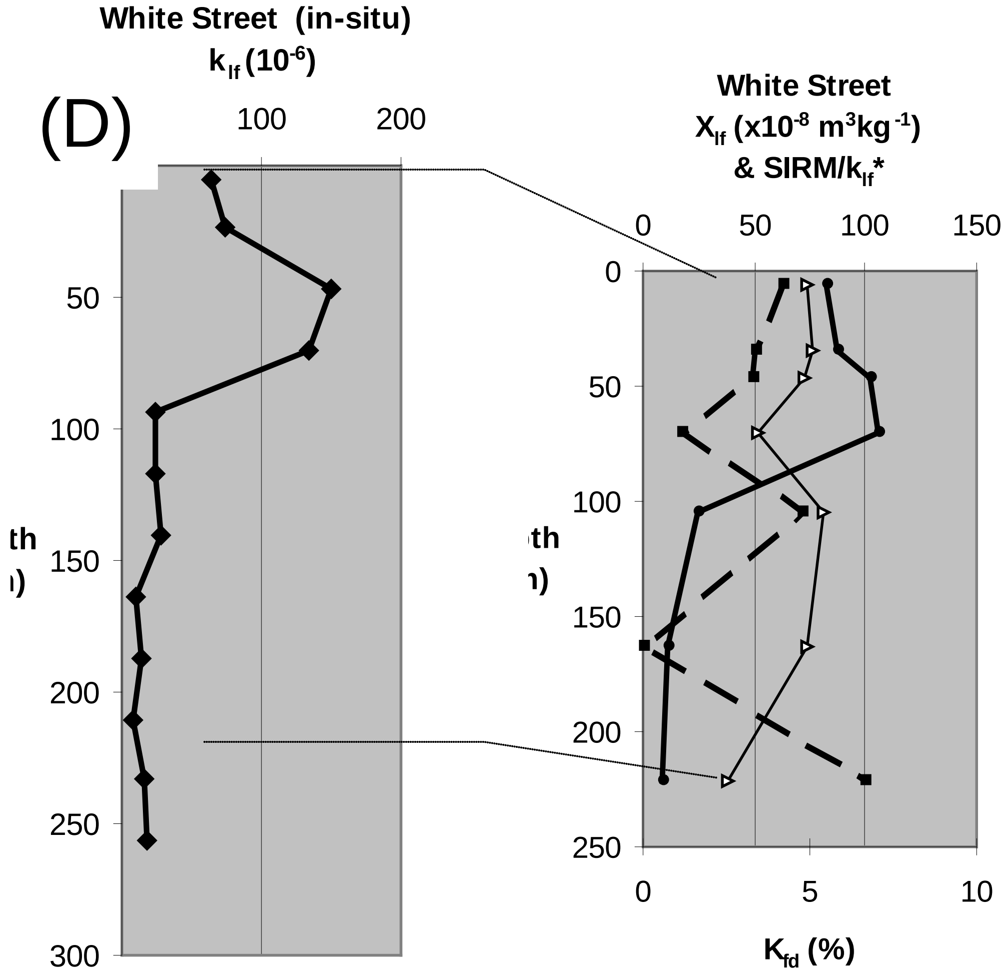
(B)


Latham Park (in-situ)
Klf (10-6)
50
100
150
0
50
100
150
200
250
epth
cm)
Latham Park
Xlf (x 10-8 m3kg-1)
& SIRM/klf*
0
50
100
150
0
10
20
30
40
50
60
70
80
90
100
h
)
0
5
10
Kfd (%)

(C)



Church St.
X_{lf} (x 10^{-8} m^3kg^{-1})
& SIRM/k_{lf}*
0
50
100
Depth
(cm)
0
10
20
30
40
50
60
70
80
90
100
0
2
4
6
K_{fd} (%)


White Street (in-situ)
klf (10-6)
(D)
100
200
50
100
150
200
250
300
th
)
White Street
Xlf (x10-8 m3kg-1)
& SIRM/klf*
0
50
100
150
0
50
100
150
200
250
th
)
0
5
10
Kfd (%)

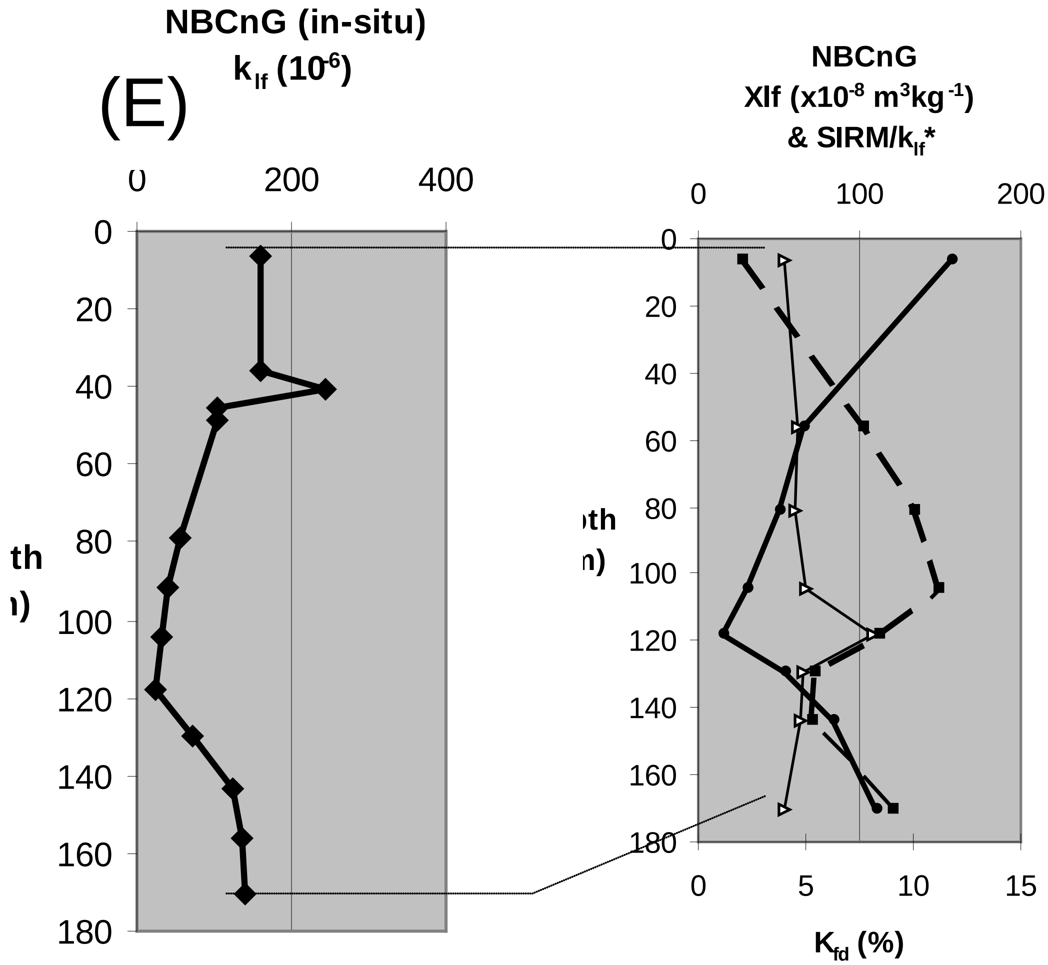


exhibit very low frequency-dependent susceptibility (κ_{fd}), indicating a paucity of magnetic mineral grains of sizes near the superparamagnetic (SP)/ stable single domain (SSD) boundary. Unlike the urban sources, however, streambank sediments are characterized by relatively weak magnetism (χ_{lf} and κ_{lf}). Urban surface sources most commonly display χ_{lf} values of 200 to 400 (x10^{-8} m^{3}kg^{-1}), with the lowest values being those for urban soils (~100 x10^{-8} m^{3}kg^{-1}), whereas bank sediment χ_{lf} rarely rises above 50 in urban areas and 100 in downstream rural areas (Figs. 12A and 13). There are two important factors that may give rise to these observations. First, the highly magnetic upland impervious surface sediments volumetrically make up a small proportion of the total upland soil and older streambank sediment available for erosion. As a result, they are strongly diluted. However, even upland soils are much more magnetic than most streambank sediments, especially in the urban zone. Second, although soil erosion need not be particle-size selective (Royall, 2004), the transport of eroded soil within stream channels is certain to be.

Soil magnetism typically increases inversely with soil particle-size (Thompson and Oldfield, 1986; Dearing et al., 1985), thus sand-sized particles which are most common in channel-marginal overbank deposits would impart a lower magnetic susceptibility to these.

The very low susceptibilities observed in the lowermost, relatively non-friable, and presumably prehistoric portions of all profiles excepting that at Church Street are likely to be caused by reducing conditions which destroy ferrimagnetic grains near the seasonal high baseflow elevation, and possibly ferrimagnetic grain destruction over centuries or millennia of weathering for higher zones immediately below historical materials. Due to recent channel incision (itself probably caused by impervious area growth upstream), these lower materials, although relatively resistant to erosion, do contribute sediment to the channel via scour, and thus suggest a third possible explanation for low susceptibilities in the upper banks.

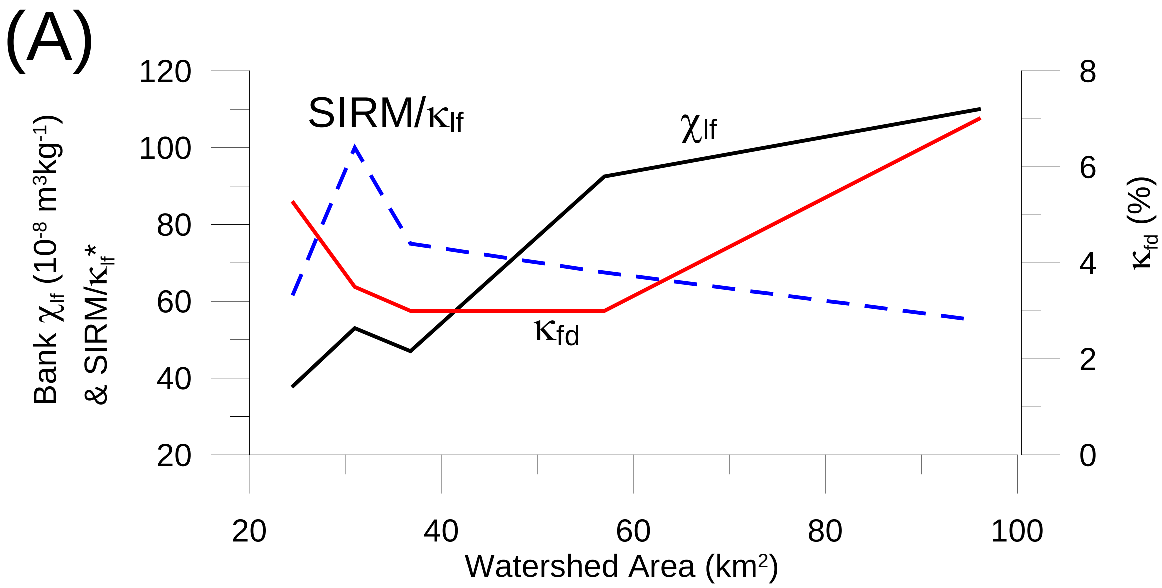
Although the geomorphic history of North Buffalo Creek is still under study, it appears that between 80 and 110 cm of historical sediment lie above older alluvium at these five sites. The lower portion of this would presumably represent agricultural phase top- and subsoil erosion (Trimble, 1974), and the uppermost portions a more urbanization influenced sedimentation during overbank flooding. Historical sediment along North Buffalo Creek is variable in magnetism, but is generally characterized by higher magnetism for all measures in upper sections of the profiles, although the uppermost portion of the Lake Daniels profile below dredge material displays the opposite trend (Fig. 13A). It is possible that this relatively weakly magnetic material represents a veneer of lake sediments that would have been deposited during a brief phase of inundation by Lake Daniel early in the 20^{th} century, but this has not yet been established.

Upper bank χ_{lf} and SIRM/κ_{lf} display opposing trends downstream (Fig. 14A). Although downstream decrease in the latter could indicate an increasing urban sediment influence, downstream increase in the former may be unrelated to urban proximity. Instead, χ_{lf} values may represent a larger historical contribution of local eroded topsoil which often displays magnetic enhancement due to a variety of natural causes. κ_{fd} values, which may also be elevated in original topsoil (much less so in regenerated topsoil; Landgraf and Royall, 2005), are also far higher in the mid- and lower portions of the upper (presumably historical sediment) profile at the NBCnG reach than at any other reach or in any portion of the upstream profiles (Figs. 13, 14).

4.4 Stream Channel Bed Magnetism

Pools (see Fig. 15 caption for term usage), typified by fast and deep flows, along with relatively coarse (granules, gravels) substrate at the study reaches exhibit higher κ_{lf} values (range 125-250 $\times10^{-8}$ m^3kg^{-1}) than shallower areas of sand bedforms or sand-rich mid-channel bars (range ~50-125 $\times10^{-8}$ m^3kg^{-1}) (Fig. 15). This large variation in magnetic susceptibility is thus apparently attributable to textural variations associated with hydraulic environment. This appears contrary to the fact that magnetic susceptibility otherwise exhibits an inverse relationship with particle size (Figs 5 and 6; although note that only impervious surface sediment, and not soils is included in these figures. Similar tendencies are generally the rule for soils as well however, across a broad range of environments (Dearing et al, 1986, Thompson and Oldfield, 1986)). However, the bulk densities of fine sediments (i.e., recently deposited sands and silts) are lower than those of gravel-sand mixtures due to relatively high porosities in the fine deposits. In-situ κ_{lf}, a measure that incorporates a fixed material volume instead of mass, would thus obtain a higher signal for the same sediment volume in coarse sediments.

Figure 14. Downstream changes in magnetic characteristics of banks (A), and channel bed (B). Water is too deep at the NBCnG site to allow in-situ κ_{lf} measurement in the bed, thus its value is missing in plot (B).



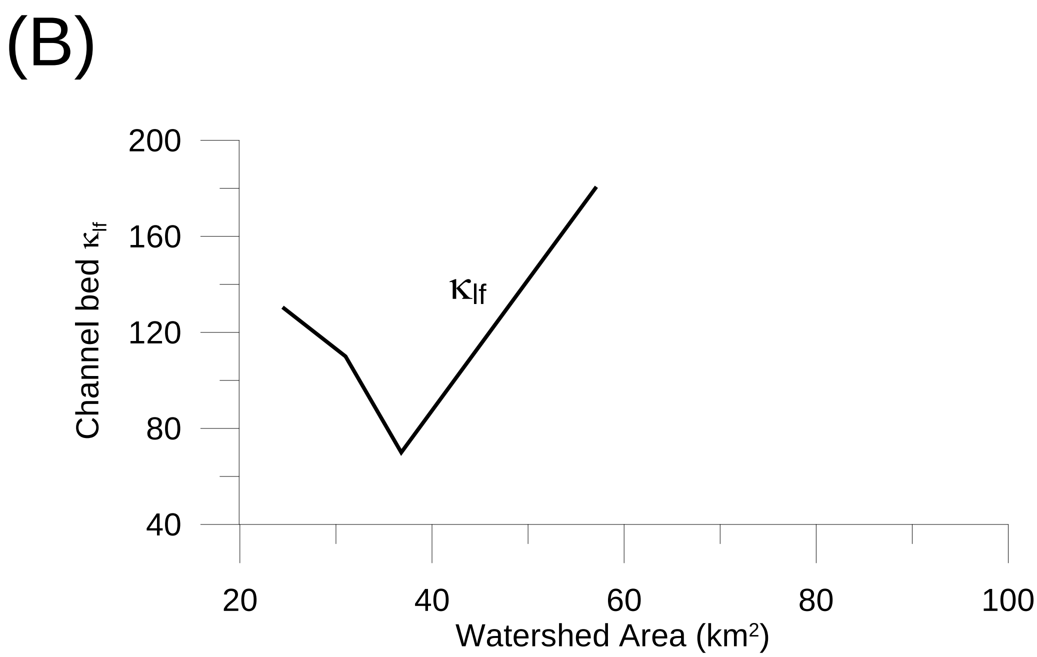
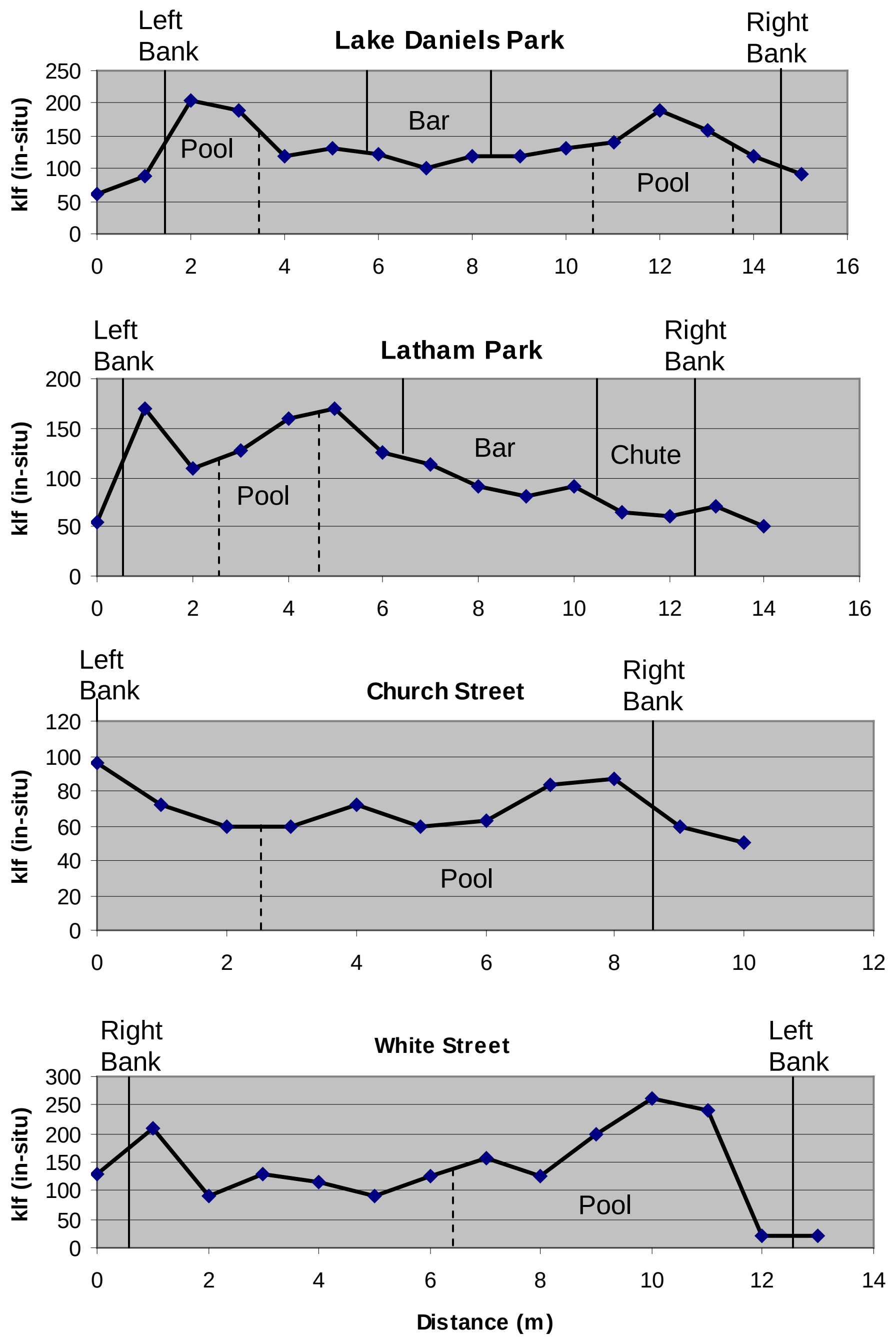


Figure 15. Channel transect in-situ κ_{lf}. Vertical lines delimit channel banks (left and right banks as noted), large-scale bedforms (i.e., bars), and other hydraulic/morphologic features. The term “pool” as used here refers to deeper water zones of at moderate-to-rapid flow velocities (as in a “riffle-pool sequence”; Knighton, 1998), as opposed to a hydraulic reference to usually deeper, but very slowly moving flow.



Average channel bed magnetism values are observed to decrease downstream within the urban environment, and increase rapidly with further distance outside of it (Fig. 14B). This trend parallels that in bank χ_{lf} (Fig. 14A), suggesting an extra-urban bank source for channel bed sediment along the rural reaches. However, the lack of data from the NBCnG reach, and the generally small number of sites is limiting for such interpretations.

5.0 INTERPRETATIONS AND DISCUSSION

This research constitutes a pilot or preliminary study to establish the usefulness of magnetic approaches to water quality, habitat and related sediment budgeting studies in a typical urban Piedmont environment. The stated goals reflect the concept establishment theme.

5.1 The Magnetic Discrimination of Urban Sediment Sources

There is ample evidence supporting the differentiation of some important urban sediments on the basis of rapidly, cheaply, and easily obtained magnetic measurements. In particular, three major groupings are suggested in order of increasing χ_{lf}: 1.) upland soils (primarily subsoil or Bt horizon), 2.) concrete surface residues and parking lots, particularly from shopping centers, and 3.) fresh asphalts, particularly from roads, and sidewalk dusts. Although these three groups are also distinguishable by the magnetic parameters κ_{fd} and SIRM/κ_{lf} (both inversely related to the above sequence), χ_{lf} is the better discriminant. This is fortunate because κ_{lf}, the volumetric measurement serving as a proxy for χ_{lf}, can easily be determined in-situ in the field, whereas the other measures require subsampling and lab analyses to determine. Thus, mapping by κ_{lf} probe or search loop, as in the case of the channel bed surveys, may be almost as useful as the more time intensive lab determinations.

Upland soils in urban environments are likely to be exposures of subsoil, rather than original topsoil, which has in most cases long since been eroded away during earlier agricultural phases, or removed (or buried) during construction. Original topsoil may have been highly magnetic due to enhancement over long time periods, and some of this material may be currently stored in floodplain sediments exposed in streambanks. However, subsoil materials sampled here are only weakly magnetic, and furthermore show no signs of enhancement either by pedologic processes (topsoil regeneration), or by accumulation of iron-oxide aerosols from vehicle emissions. Wolman (1967), Gregory (2006) and Trimble (1997) assert that uplands soils, while still eroding, possibly as a result of accumulated sheetwash transfer from impervious surfaces, are not as important sediment sources in the urban environment as they were during prior agricultural phases, with the emphasis now on channel erosion sources.

Concrete surface residues are potentially of importance volumetrically due to the high degree of weatherability of limestone cements. However, the cement itself is fully soluble in acidic rainwater, so that only liberated granular non-soluble components (incorporated sands and gravels) are particulate contributors to sediment budgets, although this does not dismiss the importance of dissolved limestone cement in changing water chemistries. The magnetism of concrete residues is partly controlled by particulate components; but these may vary from region to region as construction materials source availability varies. Perhaps of primary importance to residue pollutants and magnetism on concrete lot surfaces is vehicle exhaust residues of pseudo-single domain grain size. Residues from concrete sidewalks bordering roadways are highly magnetic (source category 3 above), most likely not because of concrete weathering residues but because of proximity to busy roads. Parking lots are less intensively traveled than roadways because automobile exhausts are not emitted by parked cars, suggesting one reason why concrete (and the asphalt lots sampled) have only moderately magnetic dusts.

In contrast, well traveled asphalt roadways apparently accumulate larger amounts of vehicular exhaust particles, despite the drafts of the moving cars. In addition, exhaust particles and weathering residues from these surfaces can be moved easily into stormwater drains through roadside curb drainage. Older asphalts also may contribute more weathering residues, which have had the opportunity to be generated and possibly accumulated for longer periods. Very high χ_{lf} observed for some fresh asphalts (Fig. 9) is conceivably a result of recent heating during the paving process. Forest fires are commonly observed to strongly enhance the magnetism of soils via the conversion of more weakly magnetic iron oxides to highly magnetic ferrimagnetic minerals (Thompson and Oldfield, 1986). Such enhancement might occur during the heating of tars and included asphalt gravels. However, this has not yet been established and remains conjecture at this time. Alternatively, the fact that sidewalk dusts and asphalt residues are similarly magnetic suggests that construction materials or processes may be less important than vehicular exhaust in determining magnetism. The very high magnetism observed for a few freshly laid asphalts may wane through time as road weathering converts the heating induced ferrimagnetic minerals to less magnetic forms.

5.2 The Use of Magnetic Properties in Sedimentation Assessments

Sedimentation assessments rely on an understanding of both upland and bottomland sources including streambank sources resulting principally from the storage of historical overbank sediments and streambed materials currently being eroded as urban channels continue to incise. According to Simon and Hupp (1986), streambed degradation causes banks at some time to achieve a threshold height beyond which bank failure and channel widening become major sediment sources leading ultimately to channel aggradation and the establishment of a new quasi-equilibrium channel. This model is based on watershed systems (western Tennessee agricultural drainages) that may be able to adjust to bed degradation resulting from channelization over the long term.

This model may not be fully applicable to urban drainages because the disturbance producing channel incision in urban streams derives from permanent upland changes (impervious area growth) rather than originating within the deformable channel bed itself. Bank failure appears to be highly localized in upstream areas with high banks (Lake Daniels) partially resulting from channelization, yet downstream in Latham Park where banks are lower, bank failure and channel widening are common, perhaps as a consequence of maintaining channel margins vegetation-free. As a result, Lake Daniels channel sediments might be expected to reflect a larger component of upland sources compared to those at Latham Park. This might also be expected as a result of closer linkages between uplands and stream channels often cited for headwater areas (Knighton, 1998). At Lake Daniels, bank sediments have low χ_{lf} and SIRM/κ_{lf}, and channel bed sediments have high κ_{lf} relative to the other urban channel reaches downstream (Fig. 14). This pattern suggests a greater proportion of upland sediment source control on channel bed sedimentation than points downstream. Downstream at Latham Park, bank χ_{lf} and SIRM/κ_{lf} are higher and channel sediment κ_{lf} only slightly lower, suggesting that channel bank inputs are indeed more important along this widening reach.

Farther downstream at Church Street, bank χ_{lf} and SIRM/κ_{lf} are decreased and channel bed sediment at its minimum value for all reaches sampled (Fig. 14). The youth of this still thick, sand-rich and well stratified sediment profile here (less than 35 years old according to trash debris enclosed) indicates a high sedimentation rate under high velocity flow, possibly linked upstream to bank failure sediment from the widening Latham Park reach. The very low κ_{lf} for channel bed sediments suggests another control which has major consequences for the magnetic interpretation of sedimentation regime: particle size. Stream incision has been held up somewhat at Church Street by a concrete weir-like structure (pipe stabilizer) which slows flow rates down at non-storm period flows. Sediment deposited in this relatively low energy setting is finer than at other channel bed locations sampled, has low bulk density, and thus would exhibit lower search loop κ_{lf} as observed. As noted earlier, a similar particle size control on magnetism is found in cross-channel magnetic transects at the other reaches, albeit, with coarser sediments.

It is instructive to compare the ranges of magnetism associated with particle size variations alone. If magnetism variations related to simple hydraulic/particle size controls are greater than variations due to source, then the ability to trace urban sediments in stream beds is reduced. For urban impervious surface residues, χ_{lf} ranges from 100 to 400 ($x10^{-8}$ m^3kg^{-1}) for sand size and finer particles typically making up the majority of overbank and channel bed sediments (Figs. 9-12). Variations in channel bed κ_{lf} (Fig. 15) maximize at 60 to 250 and thus span a magnitude of variation comparable to that for upland sources, but the ranges are not necessarily overlapping. In addition, the actual range of magnetism for channel bed in-situ κ_{lf} is probably less than 60-250 once translated into mass specific values, which are usually up to 50% lower. Particle-size variations thus do not pose an irresolvable problem for magnetic sediment tracing.

5.3 The Use of Magnetic Properties in Water Quality and Habitat Assessment

Water quality is integrally related to water quantity in a number of ways. Not all water uses require the standards of water quality set for drinking water for example (Thompson, 1999; Cech, 2003). Most of the prior discussion focuses on bed material load. Bed material load is important from a water supply vantage because sedimentation reduces reservoir capacities and must be filtered from water before use. However, magnetic exhaust particles from roadways, which have been shown to be correlated with heavy metals in urban street dusts in at least one study (Beckwith et al., 1984; 1986), are sufficiently small that they are likely to move as wash load during storm events. Their occurrence in coarser overbank and channel deposits might stem from settling during waning flows, especially after aggregation with other small particles, scavenging by settling coarser particles, and subsequent bioturbation. More direct links between wash load magnetism, stormflows and other sediment particles might be obtained through analysis of suspended sediment samples. Bartington makes the κ_{lf} sensor MS2G for 1 ml powder or liquid samples, which would reduce the amount of water sample required to obtain sufficient sediment sample for analysis.

Stream habitat can refer to a large number of environmental variables. Magnetic measurements, in addition to being linked to heavy metals and possibly serving as proxies for other water quality variables, are also linked to hydraulic habitat (including substrate density characterizations and substrate thickness in some cases) via sediment transport and budgeting applications as discussed in section 5.1. In-situ measurements of channel bed κ_{lf} using the search loop are capable of rapid estimation of particle size variations and their mapping. Visual observation is also useful for this purpose. However, magnetism offer some advantages over visual observation. First, magnetism is a quantitative index of sediment characteristics including particle size that could conceivably be calibrated to give specific particle size distribution data. Second, the measurement of in-situ magnetism in channel beds is very rapid; individual measurements, once the loop is in place, require about 1 second either on continuous operation or button control. In addition, data from the meter can be output to a portable data logger for the rapid acquisition of large data sets. Third, the search loop sensor measures a volume of sediment within a sphere extending downward from the loop into the bed. As a result, it is capable of determining where in bedrock channels sediment cover exists as only a thin veneer. At the White Street reach, the low κ_{lf} value at the twelfth meter (Fig. 15; near the left bank) was taken from sediment cover, but detected the presence of non-friable old basal sands which form a shelf along both banks. The ability to detect such features, which clearly mark a different type of benthic habitat relative to that in the mid-channel, is limited by the sensory depth for the search loop which declines exponentially away from the loop to 50% after a few centimeters. Finally, water turbidity does not impact observations with the loop as it would with visual assessments.

5.4 Downstream Magnetic Tracing

Studies of channel cross-sections downstream through North Buffalo Creek (Royall and Henderson, in prep.) suggest that channel cross-section morphology makes a transition from urban to rural with regard to size over a small distance after exiting urbanized area. It might be expected that urban sediment sources would similarly fail to be recognizable in rural reaches downstream. However, the transition in cross-section form may not be fully finished at the NBCnG site (more data are needed for this determination). The hydrologic regime at the NBCnG gaging site may still maintain a vestige of urban influence. Suspended sediment originating within the urban zone might be magnetically identifiable at this distance, further exemplifying the need for suspended sediment sampling in future magnetic work.

Bed material load originating in the urban environment may also still be identifiable downstream, both in the channel bed, and stored in the floodplain. The downstream decrease in SIRM/κ_{lf} observed in historical overbank sediment could reflect historical accumulation of exhaust origin PSD particles. If this is so, however, it is difficult to explain why upstream sites closer to urban surfaces do not also exhibit low SIRM/κ_{lf} in banks which presumably contain historical sediments of similar or even more urban origin. Higher bank χ_{lf} with downstream distance is perhaps more likely to be related to historical topsoil erosion sources, as also evidenced by increases in κ_{fd} (Fig 14).

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