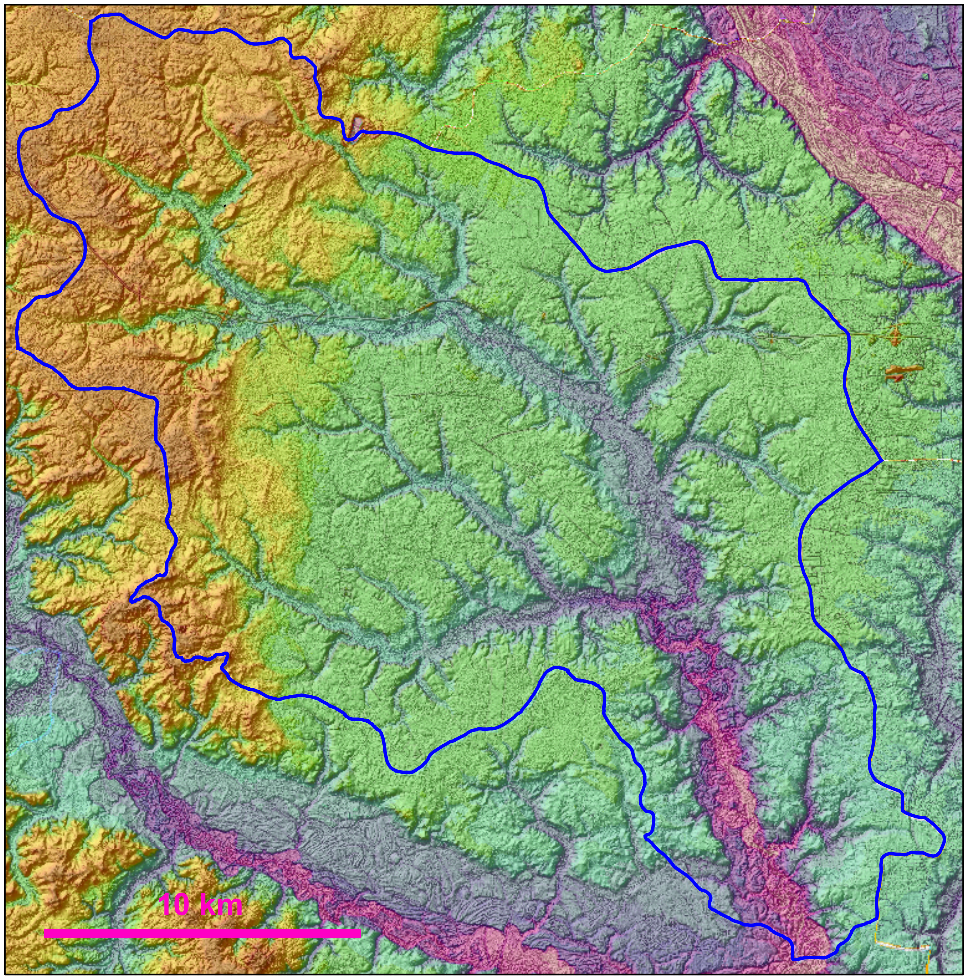
Surficial geology and shallow aquifer system of the Little Contentnea Creek Watershed, Neuse River Basin, North Carolina



Carolina Geological Society Annual Field Trip November 14–16, 2003

Guidebook Editors:

Kathleen M. Farrell and Amy J. Keyworth

Contributors
(in reverse alphabetical order)

Anthony J. Tesoriero, Timothy B. Spruill, Douglas G. Smith, H.E.Mew, Jr., Stephen R. Kraemer, Amy J. Keyworth, Steve L. Harden, Kathleen M. Farrell, and Timothy W. Clark

Acknowledgments and Credits

John Warlick, Martin Marietta Aggregates, Fountain, NC

John Stevens, Martin Marietta Materials, Raleigh, NC

U.S. Environmental Protection Agency
Clean Water Act Section 319(h) Nonpoint Source Grant Program

James D. Simons
Director, Division of Land Resources and State Geologist
North Carolina Department of Environment and Natural Resources (NC-DENR)

Carl Bailey
NC-DENR, Division of Water Quality, Groundwater Section

Tonya Merritt, North Carolina Geological Survey (NCGS-DENR)
Phil Bradley, Amy Ward, Cindy Phillips (NCGS-DENR)

Sponsorship of CGS-2003 (received prior to printing) by:

Martin Marietta Materials
2710 Wycliff Road
Raleigh, North Carolina 27607-3033

Vulcan Materials Company
Mideast Division
4513 Creedmore Rd
Raleigh, NC 27612

Patterson Exploration Services
P.O. Box 3008
Sanford, NC 27331
919-744-3770
Russ@pattersonexploration.com

Cover Figure:
Lidar map of the Little Contentnea Creek Watershed. (Created by Amy J. Keyworth)

Layout by Amy J. Keyworth

Surficial geology and shallow aquifer system of the Little Contentnea Creek Watershed, Neuse River Basin, North Carolina

Carolina Geological Society
Annual Field Trip
November 14–16, 2003

Guidebook Editors:

Kathleen M. Farrell and Amy J. Keyworth

Collaborators (in reverse alphabetical order):

H.E. Mew, Jr. and interdisciplinary collaborators:

Anthony J. Tesoriero
Timothy B. Spruill
Douglas G. Smith
Stephen R. Kraemer
Amy J. Keyworth,
S.L. Harden
Kathleen M. Farrell
Timothy W. Clark

Carolina Geological Society

http://carolinageologicalsociety.org/

2003 Officers

President ……. Randy Cumbest
Vice-President ……. John Dennison
Secretary-Treasurer ……. Duncan Heron

Board Members

Randy Cumbest
1015 Richardsons Lake Rd
Warrenville, SC 29851
803-952-8336 (W); 803-663-0512 (H)
Email: randolph.cumbest@srs.gov

John Dennison
Department of Geological Sciences
University of North Carolina
Chapel Hill, NC 27599
919-962-0686 (W); 919-929-1701
Enail: palteach@mindspring.com

Neil Gilbert
Zapata Engineering
1100 Kenilworth Avenue
Charlotte, NC 28204
704-358-8240 (W) Fax, 704-358-8342
Email: ngilbert@zapeng.com

Duncan Heron
Division of Earth and Ocean Science
Box 90230, Duke UniversityDurham, NC 27708-
0230919-684-5321 (W); 919-489-4402 (H)
Email: duncan.heron@duke.edu

Jim Hibbard
Box 8208 MEAS
NC State Univ
Raleigh, NC 27695
919-515-7242 (W), 919-859-3752(H)
Email: jhibbard@ncsu.edu

Bill Powell
Carolina Geological Consultants
619 Garmony Road
Columbia, SC 29212
803-750-4917 (W); (H)
Email: wepowell@sc.rr.com

Alex Glover
Feldspar Corporation
PO Box 99
Spruce Pine, NC 28777
Email: aglover923@aol.com

2003 Guide book Contributors

Anthony J. Tesoriero
U.S. Geological Survey
Raleigh (District Office)
3916 Sunset Ridge Road
Raleigh, NC 27607
tesosier@usgs.gov

Timothy B. Spruill
U.S. Geological Survey Survey
Raleigh (District Office)
3916 Sunset Ridge Road
Raleigh, NC 27607
tspruill@usgs.gov

Douglas G. Smith
U.S. Geological Survey Survey
Raleigh (District Office)
3916 Sunset Ridge Road
Raleigh, NC 27607
dgsmith@usgs.gov

H.E. Mew, Jr.
NC Department of Environment and Natural Resources
Division of Water Quality-Groundwater Section
1636 Mail Service Center
Raleigh, NC 27699-1636
Ted.Mew@ncmail.net

Stephen R. Kraemer
US Environmental Protection Agency
Office of Research and Development
National Exposure Research Laboratory
960 College Station Road
Athens, GA 30605
Kraemer.Stephen@epa.gov

Amy J. Keyworth
NC Department of Environment and Natural Resources
Division of Water Quality-Groundwater Section
1636 Mail Service Center
Raleigh, NC 27699-1636
Amy.Keyworth@ncmail.net

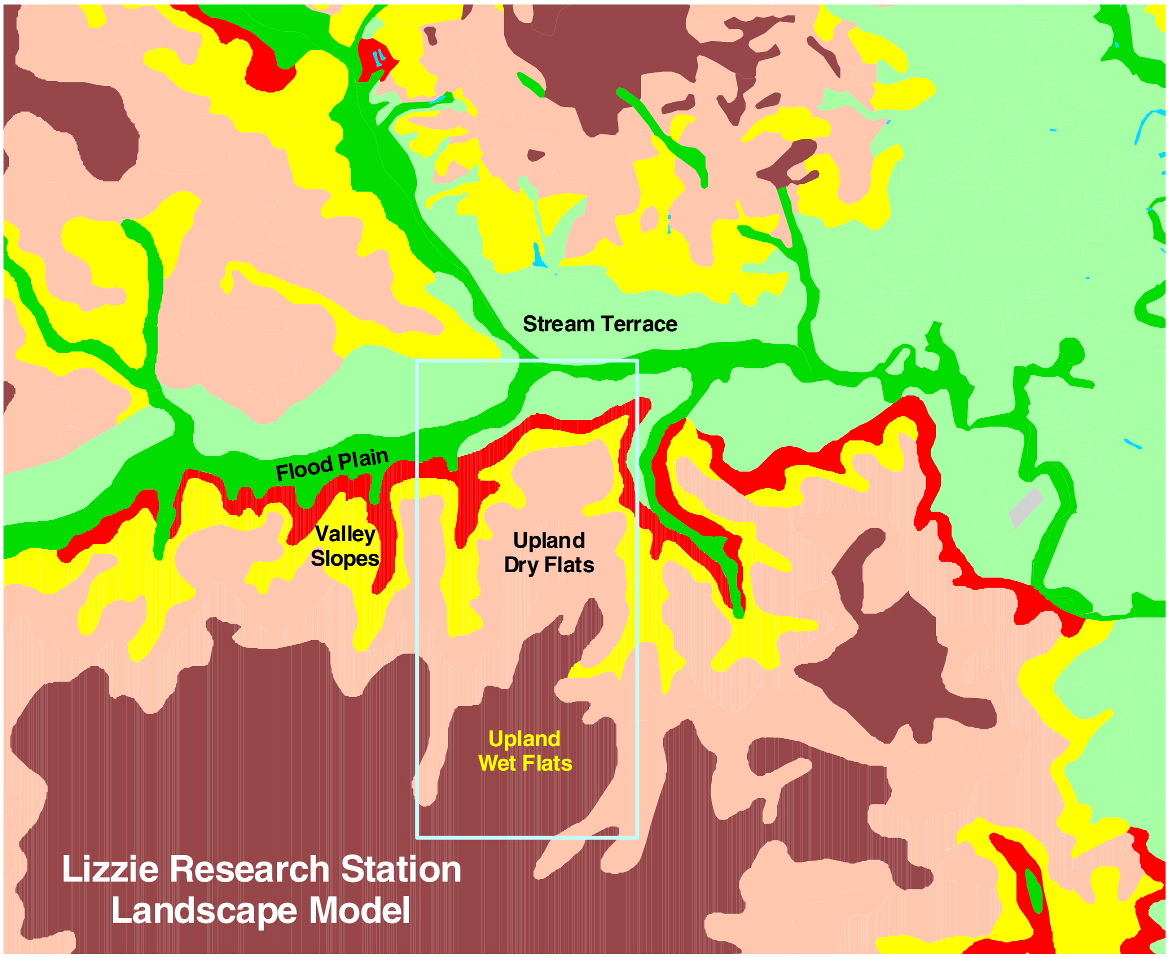
S.L. Harden
U.S. Geological Survey - Water Resources Division
Raleigh (District Office)
3916 Sunset Ridge Road
Raleigh, NC 27607
slharden@usgs.gov

Kathleen M. Farrell
North Carolina Geological Survey
Coastal Plain Office
1620 Mail Service Center
Raleigh, NC 27699-1620
Kathleen.Farrell@ncmail.net

Timothy W. Clark
North Carolina Geological Survey
1612 Mail Service Center
Raleigh, NC 27699-1612
Tyler.Clark@ncmail.net

Contents

We dedicate this guidebook to our friend and colleague, H.E. Mew, Jr. (Ted) for forming this interdisciplinary collaboration – comprehensive landscape analysis, geomorphology, stratigraphy, hydrogeology, geochemistry, water quality, modeling – and introducing us all the Lizzie Research Site.



For more information on landscape analysis and recharge see:

Mew, H.E.,Jr., Hirth, D.K., Lewis, D.V., Daniels, R.B., Keyworth, A.J., 2002, Methodology for Compiling Ground Water Recharge Maps in the Piedmont and Coastal Plain Provinces of North Carolina: Ground Water Bulletin Number 25, N.C. Department of Environment and Natural Resources, Goundwater Section, Division of Water Quality, Raleigh, NC.

Carolina Geological Society
Annual Field Trip
November 14-16, 2003

Comprehensive landscape analysis, geomorphology, and sequence stratigraphy in eastern North Carolina's Little Contentnea Creek Watershed of the Neuse River Basin: methods for constructing reconnaissance-level geologic maps of a relict Plio-Pleistocene terrane

Kathleen M. Farrell, *North Carolina Geological Survey*
H.E. Mew, Jr., *NCDENR, Division of Water Quality, Groundwater Section*
Amy J. Keyworth, *NCDENR, Division of Water Quality, Groundwater Section*
Timothy W. Clark, *North Carolina Geological Survey*

Introduction

The Atlantic Coastal Plain of eastern North Carolina (Fig. 1) is an area where relict Plio-Pleistocene topography reflects a series of highstand (HS) and falling stage systems tracts (FSSTs) (after Plint and Nummedal, 2000). This landscape is characterized by a series of progressively younger paleoshorelines and intervening terraces that step down in elevation and age towards the coast and into drainages (Fig. 2a). Each highstand shoreline was abandoned during the subsequent forced regression, or fall in relative sea level. Remnants of the transgressive systems tracts (TSST) occur in the subsurface.

This paper provides a logical method for predicting the map distribution of stratigraphic units in the context of a falling stage systems tract (FSST) model (after Nummedal and Plint, 200). The ultimate goal is to deduce the scale and types of permeability associated with geomorphic elements of the proposed conceptual model. The proposed model is based on: 1) landscape analysis at the river basin scale (10^3 km^2), the watershed scale (10^2 km^2), and the site specific scale (10^0 km^2); 2) a stratigraphic analysis at a field scale (10^0 km^2) site called the Lizzie Research Station (Lizzie) (Fig. 2), and 3) a regional stratigraphic model for southeast Virginia (Johnson and Berquist, 1989; Mixon and others, 1989). This paper begins to integrate geomorphology, field mapping and sequence stratigraphy to support the interdisciplinary development of a multi-scale hydrogeologic framework of the watershed for pollutant transport analysis and modeling.

To understand the geologic controls on groundwater in shallow aquifers at the watershed scale, we apply Brierley's (1996) constructivist approach to this dissected coastal plain landscape. This approach simplifies a stratigraphically complex Plio-Pleistocene terrain through an iterative process that defines the relationship between relict landforms and stratigraphy. A set of rules or assumptions for defining the geomorphic elements of a relict falling stage systems tract (FSST) is proposed. Systematic application of these rules subdivides and redefines the landscape in the context of a geologic conceptual model that explains the relative age, position, and geometry of each landform. Facies and significant bounding surfaces identified at detailed study sites such as Lizzie provide bases for defining unconformity bounded units that are regionally extrapolated using geomorphology.

The proposed rules are a synthesis of our ideas and widely circulating concepts proposed or applied elsewhere (for example: Kraft, 1971; Johnson, 1972; Oaks and Coch, 1973; Johnson and Berquist, 1989; Mixon et al, 1989). This approach is useful because the landscape is flat and low relief, outcrops are rare, subsurface data is costly, widespread dissolution has destroyed carbonate fossils, and oxidation has diagenetically altered primary strata. We consider this paper a useful exercise in integrating field mapping with sequence stratigraphy terminology, in an area lacking high resolution seismic lines. Future subsurface work and higher resolution topographic data (lidar) may confirm, refute, or modify this approach, our landscape interpretations, and our proposed model of landscape evolution.

Previous Work

To simplify mapping, early workers subdivided the Atlantic Coastal Plain into ocean-facing scarps and the marine terraces between them (e.g. Johnson, 1904; Clark and Miller, 1906 and 1912; Stephenson, 1912; Cooke, 1930, 1931, 1932, 1935, 1941; Cooke et al, 1943; Wentworth, 1930; Flint, 1940; Doering, 1960). Shattuck (1901, 1906) established the concept of a terrace formation – in today's terms, an unconformity bounded unit, deposited during a (Pliocene to Pleistocene) marine transgression to a highstand position marked by a wave-cut scarp, and the regression that followed (see Coch and Oaks, 1966; Oaks et al, 1974). Clark and Miller (1906, 1912) are responsible for inferring an emergent-submergent cycle for each highstand in sea level (Oaks et al, 1974); this idea was subsequently

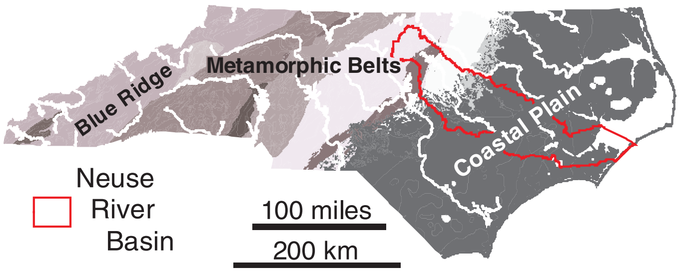


Figure 1. Map of North Carolina shows geologic units for the whole state and the distribution of the Coastal Plain Province (geology from NC state geologic map electronic data), the major rivers, and with the Neuse River Basin outlined in red.

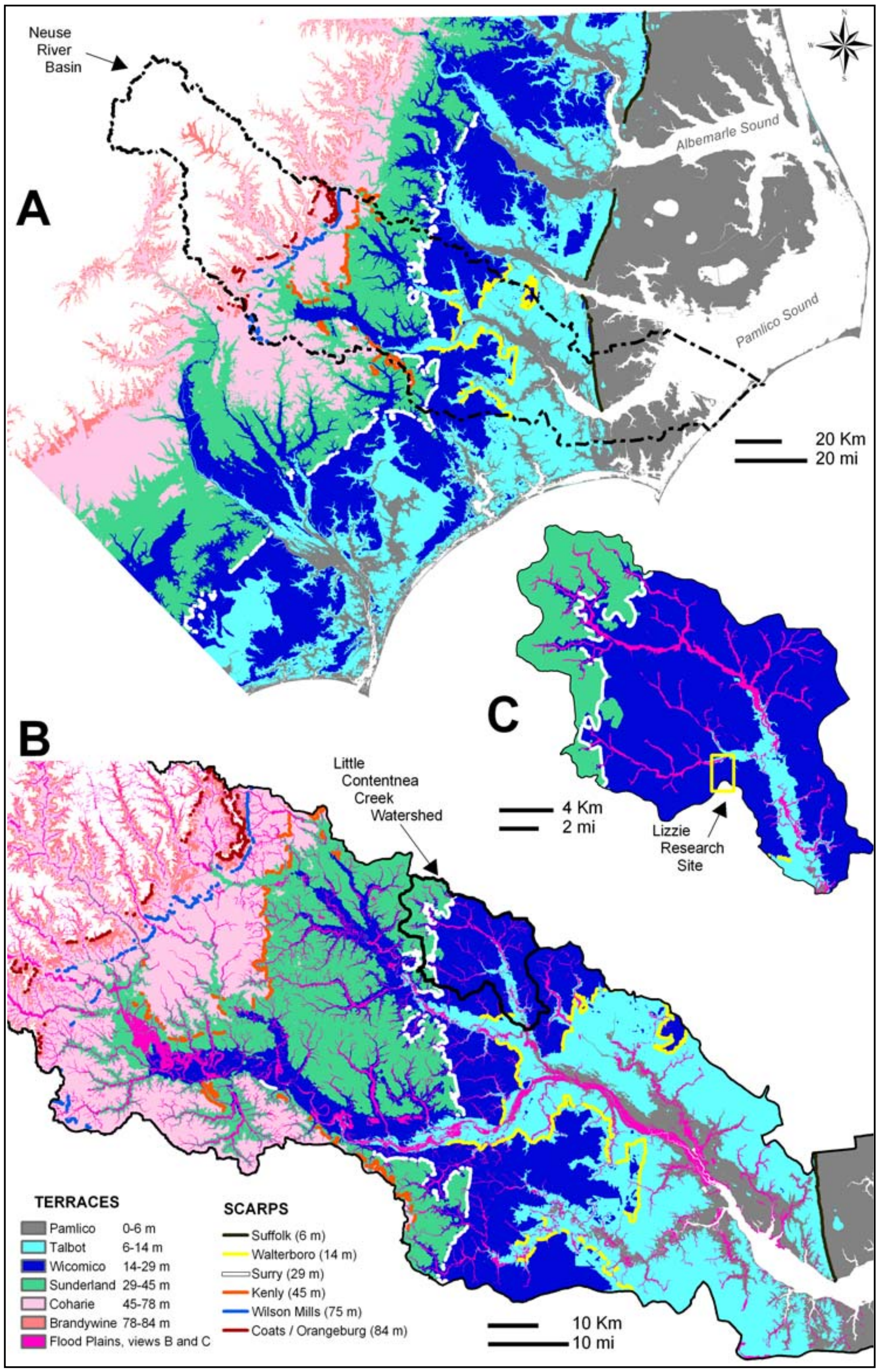


Figure 2. Generalized map of the geomorphology of the Neuse River Basin based on 30 m DEMs; shows location of A) Neuse River Basin, B) Little Contentnea Creek Watershed, and C) Lizzie Research Site.

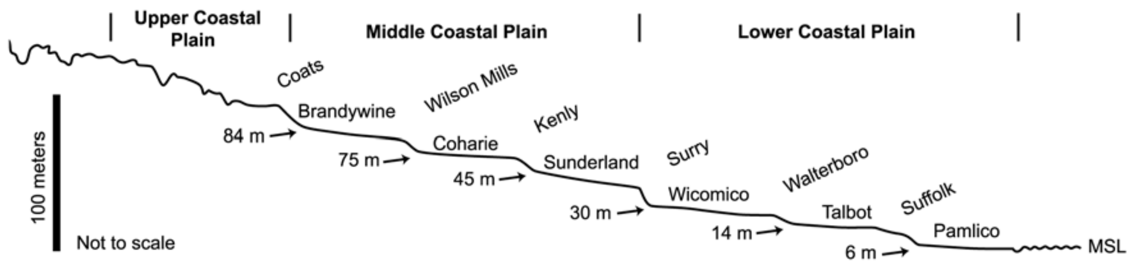


Figure 3. Cross sectional view of Coastal Plain that shows the approximate elevations of scarps and terraces in North Carolina and their nomenclature (after Daniels and others, 1984).

adopted and is retained today in mapping investigations as an unconformity-bounded transgressive-regressive cycle. Oaks and Coch, (1973), Oaks and Dubar (1974), Oaks et al (1974), Daniels and Gamble (1974) and Winker and Howard (1977) provide historical summaries of the terrace formation concept, its nomenclature and application.

In landmark studies in eastern Virginia (Coch and Oaks, 1966; Oaks and Coch, 1973; Oaks et al, 1974), Oaks and Coch (1973) abandoned the terrace formation concept, recognizing that relict landforms (scarps and terraces) were underlain by a complex assemblage of coeval facies. They retained the idea of an unconformity bounded unit associated with marine highstands, but included the possibility of coeval barrier, backbarrier, estuarine and fluvial facies in more landward positions. Their work also expanded the concept of a scarp from a simple wave-cut cliff to a potentially complex paleoshoreline associated with a variety of geologic environments. Later studies, also in Virginia, applied these concepts in other areas (e.g. Johnson, 1972, 1976; Peebles and others, 1985; Mixon et al, 1989; Johnson and Berquist, 1989; Ramsey, 1992). Most importantly, Mixon and others (1989) produced a coastal plain map of (essentially) unconformity bounded, transgressive-regressive units that includes fluvial to estuarine equivalents of marine highstands in drainages. Their map of the Chesapeake Bay area (paleo-Susquehanna River valley) effectively shows that modern drainages are bordered by a series of nested Pleistocene (and Pliocene) paleovalleys that are separated by remnants of older interfluves. Their map also integrates formalized stratigraphic units with regional geomorphic features.

The principles of comprehensive landscape analysis were primarily developed by Fisk (1944, 1947) who used aerial photomosaics to interpret and map Holocene (and older) fluvial landforms on flood plains in the Mississippi Valley. Saucier (e.g. 1969) later refined this mapping. The Texas Bureau of Economic Geology (e.g. Fisher and others, 1972) used Fisk's methods to produce a series of maps of Quaternary deposits that showed not only fluvial, but also backbarrier, marginal marine, and shoreline-related landforms along the Texas coast. Berendsen and Stouthamer (2001) fully integrated subsurface analyses with comprehensive landscape analyses in their atlas of the Rhine-Meuse delta.

Implicit in the aforementioned studies, was the relationship between landforms and sedimentary facies. In accordance with Krumbein and Sloss (1963), a facies has a geometry and internal characteristics that reflect the processes that acted together to form a deposit in a specific sedimentary environment. A facies is defined by a geomorphic form and its bounding surfaces and is a geometrical component of an evolving landscape (Farrell, 2001). These and other investigations of facies and Holocene landforms (e.g. Kraft, 1971) form the geomorphic bases for defining not only coeval depositional systems, but also the concept of a systems tract (see Galloway, 1989a, b; Van Wagoner and others, 1990, Posamentier and Allen, 1999, Nummedal and Plint, 2000).

Even though the terranes are similar, the mapping techniques developed in Virginia and Texas for surficial deposits were not applied in North Carolina, until recently (current research C.W. Hoffman, J.G. Nickerson, N.K. Gay and W. Shroyer at the North Carolina Geological Survey). Several notable studies that integrate geomorphology and stratigraphy (Dubar et al, 1974a, 1974b; Peebles, 1984; Kane, 2000) are the exception. Surficial maps of the entire Coastal Plain based on soils morphology are available (Daniels and Gamble, 1974; Daniels and others, 1984; Mew and others, 2002), but these do not show traditionally defined geologic map units. Unfortunately, the geologic map of North Carolina does not show surficial map units. The current paper develops and demonstrates the principles of comprehensive landscape analysis in an unmapped area, and provides correlations with map units in Virginia.

The study area

The study was conducted in the Neuse River Basin of eastern North Carolina, USA (Fig. 1). The relict landscape in the Coastal Plain sector of this basin is mostly Pliocene through Quaternary in age, consisting of a series of progressively younger paleoshorelines and intervening terraces that step down in elevation and age towards the coast and into drainages (Fig. 2). This was traditionally called 'stairstep topography'. Figure 3 shows approximate elevations of scarps and terraces in North Carolina and their nomenclature (after Daniels and others, 1984). In the Neuse River Basin, most of this relict landscape occurs at elevations less than 91 m (300 ft) above mean sea level (MSL) (Fig. 2B). Older marine terraces occur here as high as 137 m (450 ft), and remnants of even higher fluvial terrace remnants occur at 155.5 m (510 ft) (John G. Nickerson, personal communication). These scarps were defined (by Daniels and others, 1984) based on toe elevations.

Surficial deposits in the Neuse River Basin have not been geologically defined and mapped (North Carolina Geological Survey, 1985), except for unpublished maps in its western part (Nickerson and Gay). The series of scarps mapped for this area (Daniels and others, 1966, Daniels and Kane, 2001) include several (e.g. Coats/Orangeburg, Surry, Suffolk) (Fig. 2) that are known components of more regionally extensive (> 500 km) paleoshorelines (see Winker and Howard, 1977).

The Little Contentnea Creek Watershed (U.S. Department of Agriculture, 1995), covers an area of 470 km^2, and includes landscape features at elevations of about 36 m to 6 m. The watershed (Fig. 2B, 2C) includes segments of the Surry Scarp (toe at 29 m), the Walterboro Scarp (toe at 14 m), the Sunderland and Wicomico terraces, and several, lower, unnamed fluvial to estuarine terraces using terminology from Daniels and others (1984). The current study essentially redefines or further defines these landforms, and places them in the context of a stratigraphically evolving landscape.

Lizzie Site

The Little Contentnea Creek Watershed includes a privately owned, multi-disciplinary research site called the Lizzie Research Station (Fig. 2, where the shallow aquifer system was targeted for a 3D subsurface analysis (Farrell and Mew, 2001, Farrell and Mew, in prep.). The state of North Carolina (Department of Natural Resources-Groundwater Section) established this site in 1993 to investigate ground-water recharge and near surface flow, as part of its federal Clean Water Act, Section 319-funded, Nonpoint Source program. In 1998 the U.S. Environmental Protection Agency selected the Lizzie site to serve as the principal ground water intensive study and calibration site for its Multimedia Integrated Modeling System (MIMS) prototype project in the Neuse River Basin (Spruill and Tesoriero, 2002; Kraemer 2002?). Models will provide estimates of nutrient loads contributed to the stream through the ground water, and serve as an upscaling control for watershed and basin-scale (km^2) regional flow models. Detailed investigations of this site are pending publication elsewhere (Tesoriero and others, Farrell and others).

Methods

The generalized geomorphic map (Fig.2) of the Coastal Plain was prepared from three electronic data sets using Geographical Information System (GIS) software. Digital elevation model grid data (U.S. Geological Survey) was grouped and color coded to conform to the range in elevations assigned to marine terraces by Daniel and others (1984) (Fig. 3). This layer was overlain by a map of the flood plain derived from soils coverages by Mew and others (2002). The scarp layer was provided by Daniels and Kane (2001). These scarps were compiled on 7.5 minute topographic base maps (1:24,000 scale), prior to digitization.

Geomorphic features of the Little Contentnea Creek Watershed were mapped as closed polygons on digital raster graphs of U.S. Geological Survey, 1:24,000 scale, 7.5 minute topographic quadrangles (Farmville, Falkland, Fountain, Hookerton, Ayden, Snowhill, Greenville-SW, Walstonburg). These basemaps had a contour interval of 2 m. Electronic National Wetlands Inventory maps and soils maps for Greene, Pitt, Wilson and Edgecombe Counties helped identify some features. Linework was digitized as arcs on the screen (heads up digitizing) in ArcView^{TM} and converted into ArcInfo^{TM} polygon coverages.

The 3D analysis at Lizzie included 12 wireline cores (7.6 cm in diameter), 15 split spoon cores (10 cm in diameter), and 24 gamma logs. The sampling interval was 1.5 m with recoveries ranging from 0 to 105%. Coreholes were gamma logged through 5 cm diameter PVC tubing. The logging tool had a speed of 15 ft/sec. Data was collected every 0.1 second. Additional stratigraphic information was acquired in wetlands from 7 vibracores (7.6 diameter) acquired with a 2.5 HP vibracorer designed by Smith (1987). Recovery for these was greater than 80%. Facies were defined from recovered intervals and matched to gamma log responses. Structure contour and isopach maps were generated in Spatial Analyst. All elevation data is reported in meters relative to mean sea level (MSL).

Assumptions for comprehensive landscape analysis

This section explains our method (synthesized from many sources) of subdividing a relict Plio-Pleistocene landscape dissected by drainages into a series of progressively younger depositional systems and their landform elements.

A bird's eye view of the generalized geomorphology of the NC Coastal Plain (Fig. 2A) reveals a number of characteristic map patterns at the regional scale. A string of barrier islands forms the Outer Banks and separates the Atlantic Ocean from backbarrier sounds (Albemarle and Pamlico Sounds). Several major rivers (from north to south: the Chowan, Roanoke, Tar and Neuse) discharge into these sounds. All of these rivers, including the Cape Fear

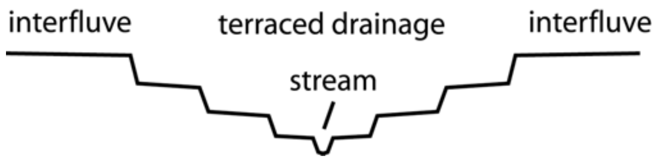


Figure 4. Sketch that shows stairstep topography from the top of an interfluve to the bottom of a drainage.

which discharges directly into the Atlantic, are funnel-shaped estuaries near their mouths. The head of the estuary is the bayhead and its delta. Landward of the bayhead and its delta, the rivers tend to be incised conduits into their floodplains and older terraces. A discrete point can be identified where the river changes its planform from pipe-shaped conduit to funnel-shaped estuary. Elevation patterns (Fig. 2) support the concept that terraces step down in elevation along drainages (Fig. 4) as well as step down to the coast (Fig. 3). Map patterns (Fig. 5) suggest a series of downstepping, paleo-coastlines with associated nested embayed paleovalleys.

In a basin to landward direction, the first task is to identify the marine (ocean facing) wave-cut scarps. Highstands potentially include four coeval shorelines at the same elevation (Fig. 6a): 1) an oceanside, coast-parallel marine shoreline; 2) a backbarrier shoreline on the leeward side of a barrier; 3) a backbarrier shoreline on the headland side of a backbarrier sound, lagoon, tidal flat or salt marsh; and 4) a wave-cut scarp that extends upstream along the borders of estuaries or rivers in drainages. The goal is to identify the elevation of the relative highstand that best defines all of these coeval shorelines. Thus several "scarps" in a variety of landscape positions can be generated at the same highstand; and, the geomorphic slope (and local toe elevation) on each of these shorelines can vary between landforms (Fig. 7). Choose the best fit elevation that explains most of the geomorphic variation associated with a highstand shoreline.

For each highstand, relative elevation and landform

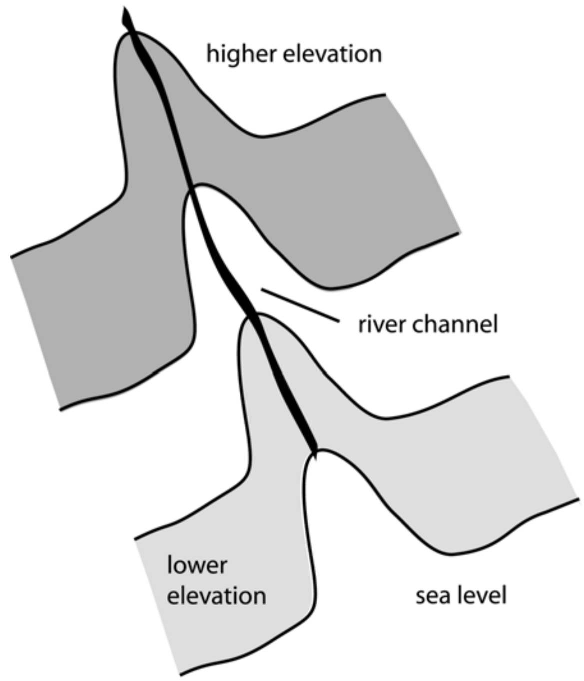


Figure 5. Sketch that summarizes generic map patterns of elevation on the North Carolina Coastal Plain.

geometries help identify barriers, backbarrier areas, estuaries, deltas, headlands, etc. Estuaries and backbarrier environs (Fig. 6b) may include relict channels, tidal bars, flats or deltas, salt marshes, other wetlands, and lagoons. Salt marshes and other wetlands form platforms at about the same elevation as a highstand. These platforms may extend great distances upstream along drainages. Tidal shoals occur seaward of highstand shorelines and may be attached to it (Fig. 6c). Barrier related features (e.g. dunes, washover flats, supratidal flats) are higher than the highstand shoreline. Floors of relict channels and inlets are at lower elevations. Constructional features (e.g. tidal flats, bars and deltas) may be the same elevation as the highstand or lower

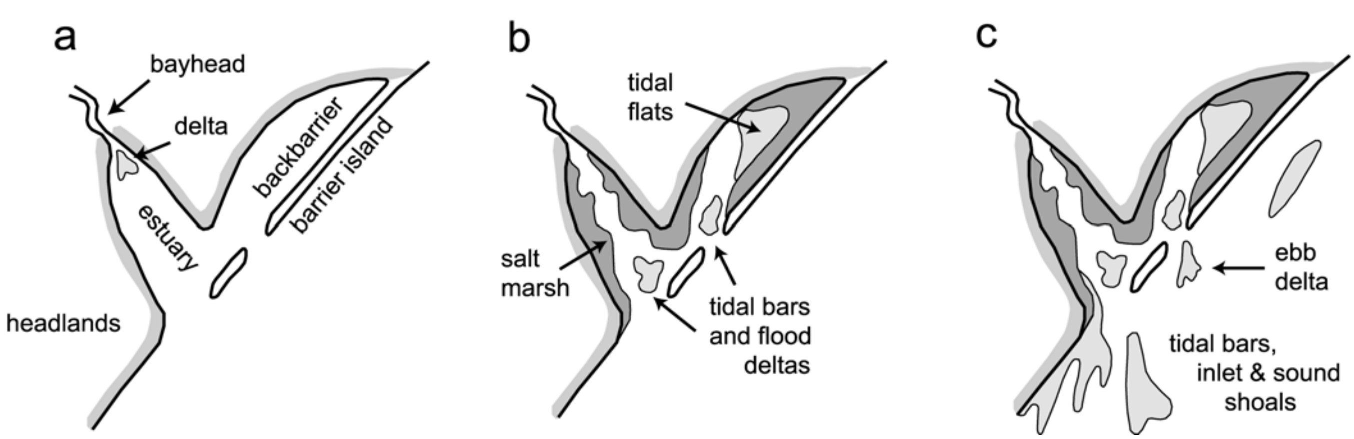


Figure 6. Identification of marine highstand positions (map view).

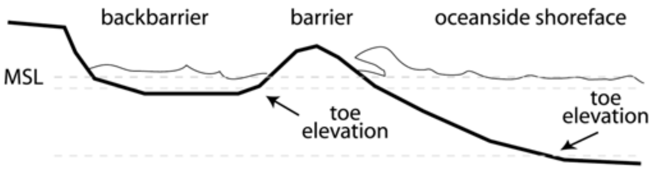


Figure 7. Variations in toe elevation at a marine highstand (cross sectional view).

A map of a highstand position along a drainage shows the configuration of the highstand estuary and bayhead (Fig. 6c). The bayhead is located where a funnel-shaped estuary abruptly constricts to form a fluvial channel network. The bayhead delta is seaward of this constriction. Both salt water and freshwater wetland flats may border the estuary and the river channel. Landward of the constriction at the bayhead, fluvial terraces mantled by wetland flats rise in elevation upstream along the drainage.

At highstands, sediment fills in accommodation space in estuaries, backbarrier areas, and the contiguous fluvial system. The shoreline may prograde seaward at a highstand (normal regression), prior to the subsequent fall in relative sea level, building a series of beach ridges and intervening swales. At any point in time, the available accommodation lies between the depositional surface (sediment water interface) and relative sea level (mean high water). A terrace at the highstand elevation can be generated in the valley bottom as far upstream as tidal influences extend (potentially tens of kilometers). But these terraces are difficult to separate from fluvial wetland terraces that are aggrading during riverine floods. When relative sea level falls after the highstand, the landforms that were contemporaneous with the highstand are abandoned, becoming relict features. The 'marine terrace' in front of the abandoned paleoshoreline marks either relict highstand bottom topography, or forms during the sea level fall.

Beach ridges can also accrete seaward during a fall in relative sea level. In this case, the elevation of successive beach ridges should decrease in elevation towards the coast. Transgressive deposits are likely buried by highstand and falling stage deposits.

Assumptions for stratigraphic model

The stratigraphic model developed for southeast Virginia (e.g. Berquist and Johnson, 1989; Mixon and others, 1989) from a comprehensive geomorphic analysis and targeted subsurface studies applies in North Carolina. The model includes a series of unconformity bounded transgressive-regressive cyclic units and their relationship to regional landscape features and elevation. Each transgressive-regressive cycle includes both paleovalley and interfluve deposits. The model was built assuming that: 1) the field data support development of regional relative sea level curves, 2) the shape of relative sea level curves is controlled primarily by glacial eustasy, recognizing that local variation in sediment supply and subsidence affects landforms and differential facies thicknesses; 3) glacial eustasy affected large map extents; 4) successive highstand deposits stepped down to the coast; 5) packages of unconformity bounded sequences are associated with sea level events; and 6) the occurrence of strata related to sea level events should be confirmed via subsurface analysis at key localities.

Results of Geomorphic Analysis

This section provides the results of the landscape analysis for Little Contentnea Creek watershed, and, in some cases, redefines landforms using new elevation criteria. Where utilized, formal terrace and scarp names (see Fig. 2) are borrowed from Daniels et al (1984).

The Surry Scarp is the most prominent paleoshoreline in the watershed. It is defined here as a highstand shoreline at about 31 m (possibly as high as 35 m), even though its toe elevation here is 29 m, similar to elevations reported elsewhere (Flint, 1940; Johnson and others, 1987; Daniels and others, 1984). It has the four shoreline types outlined in the previous section. Landforms here are grouped into several categories relative to this highstand position (Fig. 8).

The oldest feature in the watershed is an extensively dissected plain at 32-36 m (the Sunderland plain): this predates the Surry shoreline. The dune ridges at 32-36+ m, either slightly predate the highstand shoreline or are contemporaneous with it. Features contemporaneous with the 31 m highstand are the shoreline sands (30-32 m), ebb-tidal deltas (27-30 m), intertidal bars and shoals (at 30+m), and estuary flats (at 30 m). A paleoestuary that distally joins the Contentnea Creek drainage, joins the Surry coast in the watershed.

The "marine plain" at 20-31 m (part of Wicomico plain), is divisible into two parts. The higher western part of the plain (at ~25-31 m) formed at the Surry highstand and during the subsequent fall in relative sea level. It is erosionally notched at ~26 m (~85 ft), with a discontinuous low step that faces the coast and local drainages. East of this notch is a lower and flatter plain (at ~20-25 m), that has subtle evidence of very low (cm), coastwise ridges and swales in soils maps and in lidar data (analysis pending). The Lizzie site occurs below this notch.

Other features that postdate the Surry highstand are scarps at 20 m (~65 ft), 16 m (~50 ft), 12 m (~40 ft), 10 m (~30 ft) and 7 m (~22 ft) that separate plains of fluvial to estuarine origin in drainages. The flats at 16-20 m and 12-16 m are estuarine terraces with highstand shorelines at 20 m and 16 m respectively. Fluvial terraces with relict scroll bars occur at 10-12 m and 7-10 m. At the lower end of Little Contentnea Creek, the fluvial terraces appear to step

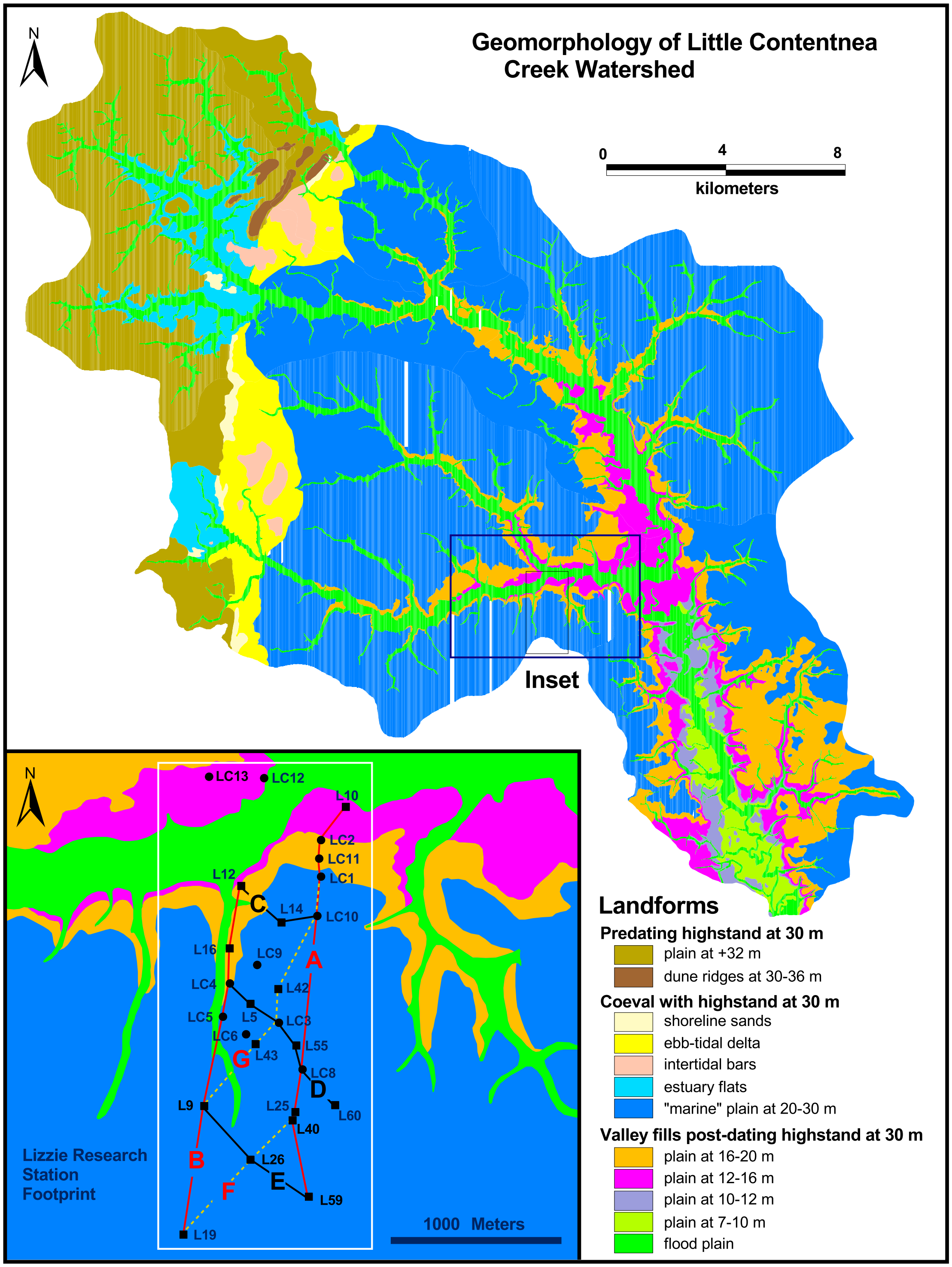
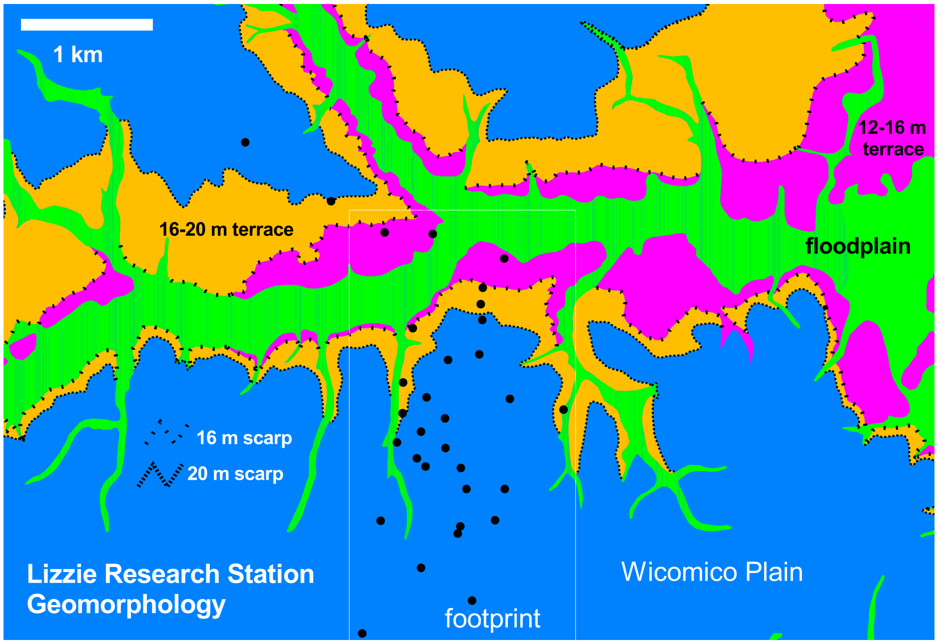


Figure 8. Interpreted geomorphology of Little Contentnea Creek Watershed. Shows location of inset maps (Fig. 9) and the Lizzie site footprint.

A



B

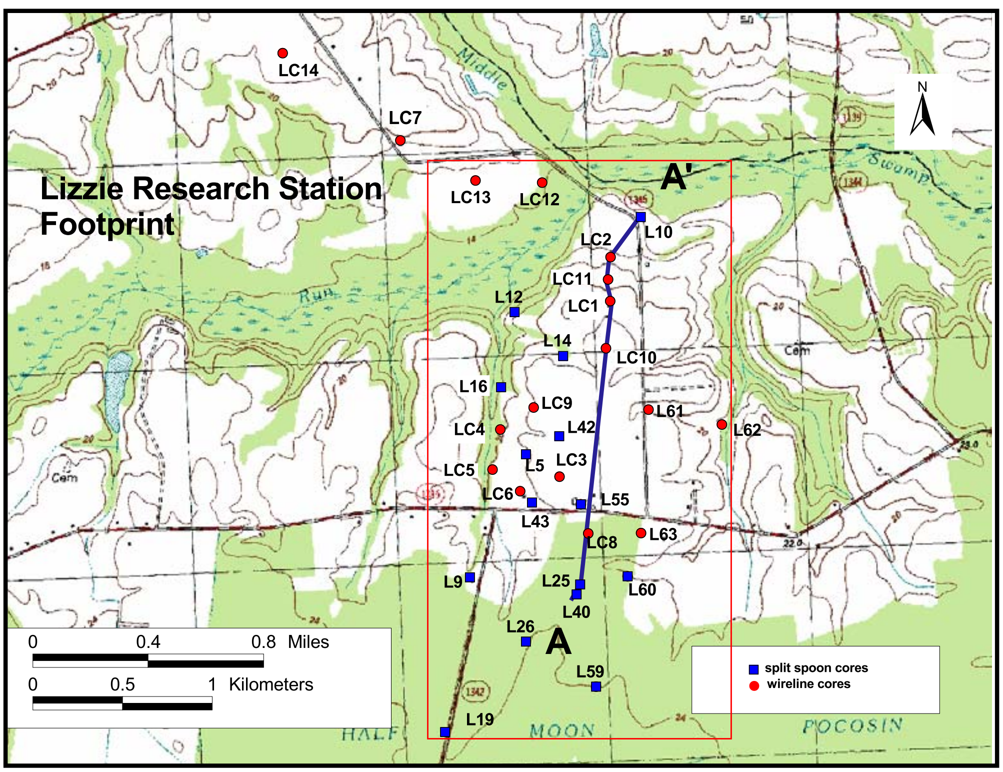


Figure 9. A. Geomorphology in the Lizzie site area. B. Digital raster graphic that shows core locations, and site of cross section utilized in Spruill and others, this volume.

down every 2 m. The modern floodplain postdates all of these features. The active Holocene drainage is expanding incrementally by headward erosion into older terraces. The younger terraces are less dissected than the older higher terraces.

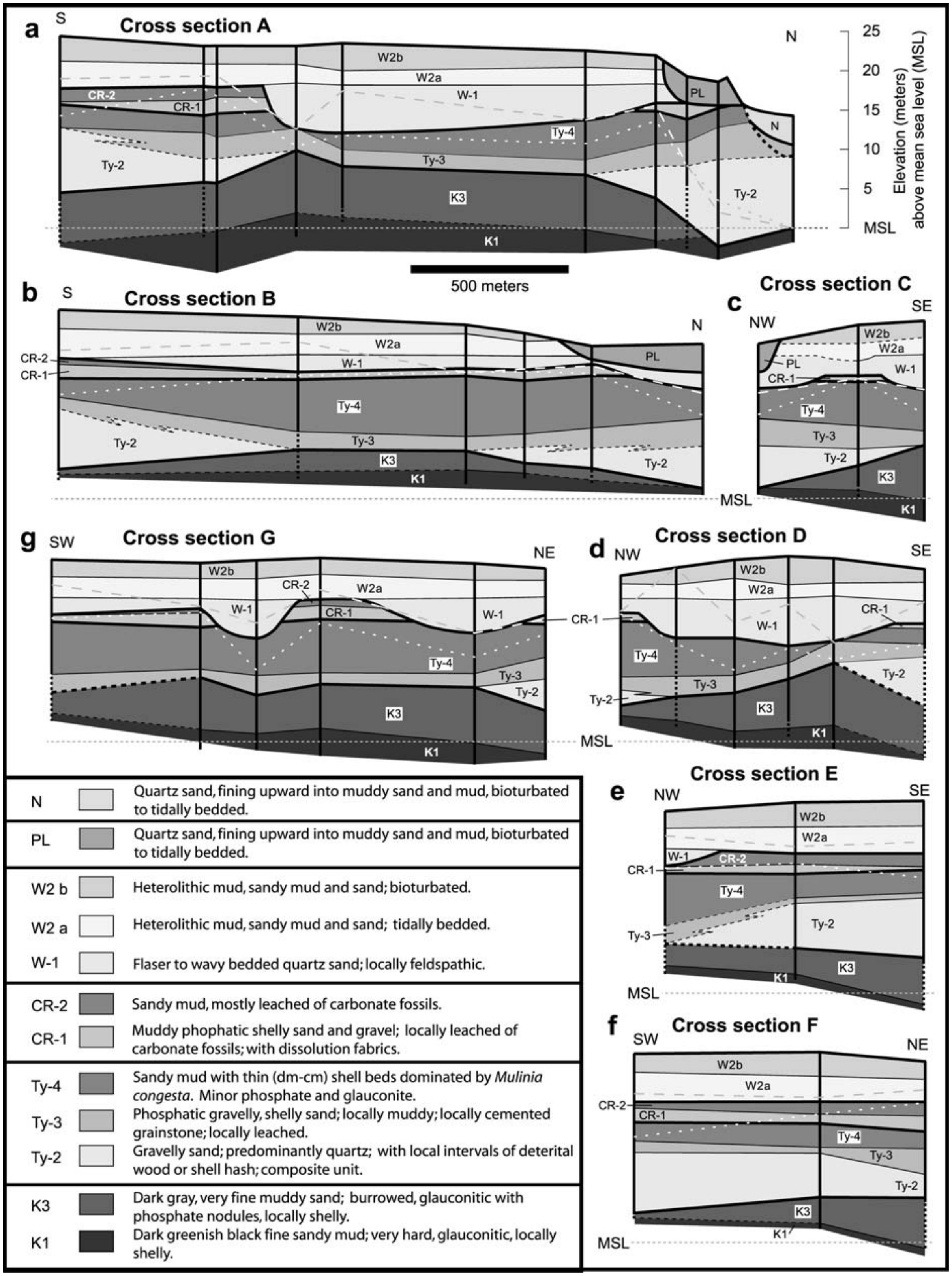


Figure 10. Geologic cross sections at the Lizzie site. Locations for the cross section are shown in Figure 8 (inset). The white dotted line (above MSL line) demarcates the depth above which carbonate fossils are dissolved. The dashed line separates reduced strata (below) from oxidized sediment (above).

Results of 3D Analysis at Lizzie

This section summarizes the conceptual model developed from the 3D analysis at the Lizzie site. Lizzie is strategically located geomorphically (Fig. 9) because it straddles the boundary between between an interfluve plain (locally at 20-24 m) and a drainage (Sandy Run) with two sets of lower terraces separated by the 20 m and 16 m scarps. These step down to the modern floodplain at 12 m. The floodplain has a main stream channel (20 m in width) with flanking wetland flats that are dissected by anastomozed channels during periods of low water. Figure 8 (inset footprint) shows the locations of the geologic cross sections in Figure 10. Figure 9B shows the approx. location of the cross section profile used by Spruill and others (this volume) to post geochemical and hydrologic data.

At Lizzie, a Cretaceous marine unit of Campanian or older age (Lucy Edwards, personal communication), functions as basement for the shallow ground water (Figs. 10, 11A). This unit resembles classic Peedee Formation, a marine shelf unit (K3) of dark gray, glauconitic, fine to very fine muddy sand, with poorly defined bedding and indistinct mottling (see Swift and Heron, 1969; Swift et al., 1969). K3 is underlain by a glauconitic, marine, greenish-black sandy mud (K1). The current study targets the post-Cretaceous section: the Pliocene-age Yorktown Formation and several post-Yorktown units that lack fossils.

The Yorktown (Clark and Miller, 1906) consists of shelly sands and clays exposed along the York River in Virginia. The formation is mostly Pliocene (see Ramsey, 1992 and Krantz, 1991) and includes deposits from three transgressions. Johnson (1972) identified six facies in the Yorktown. Blackwelder and Ward formally divided it into four members – the Sunken Meadow, Rushmere, Morgarts Beach and Morehouse members, which, in some cases, match Johnson's facies. Blackwelder and Ward (1979) revised the Yorktown to include the Duplin and Macks Formations of North Carolina because of lateral continuity between the three units. The Yorktown is associated with a highstand shoreline at the Coats/Orangeburg Scarp (Fig. 1) (See Colquhoun, 1974). At Lizzie, the Yorktown includes at least one and possibly two unconformity bounded units. These are informally designated here as the Ty-unit and the CR-unit.

The Ty-unit (Fig. 10, 11A) includes three facies - a gravelly sand (Ty-2), a phosphatic gravelly shelly sand (Ty-3), and sandy clayey silt with beds of *Mulinia congesta* (Ty-4). Ty-2 is a paleovalley fill that was transgressed and overlain by Ty-3 and Ty-4, a succession of basal lags and marine shoals that are overlain by offshore marine muds. Ty-3 and Ty-4 are respectively the Rushmere and Morgarts Beach Members (Lauck W. Ward, personal communication). These two units are conformable with each other and are part of the second Yorktown transgression, which took place between 4.0 and 3.2 Ma (Krantz, 1991) (see Fig. 12). The Morgarts Beach clayey silt (Ty-4) is an areally extensive, blanket-shaped confining unit (as thick as 7 m) that separates the unconfined surficial aquifer from the confined Yorktown aquifer facies (Ty-2 and Ty-3).

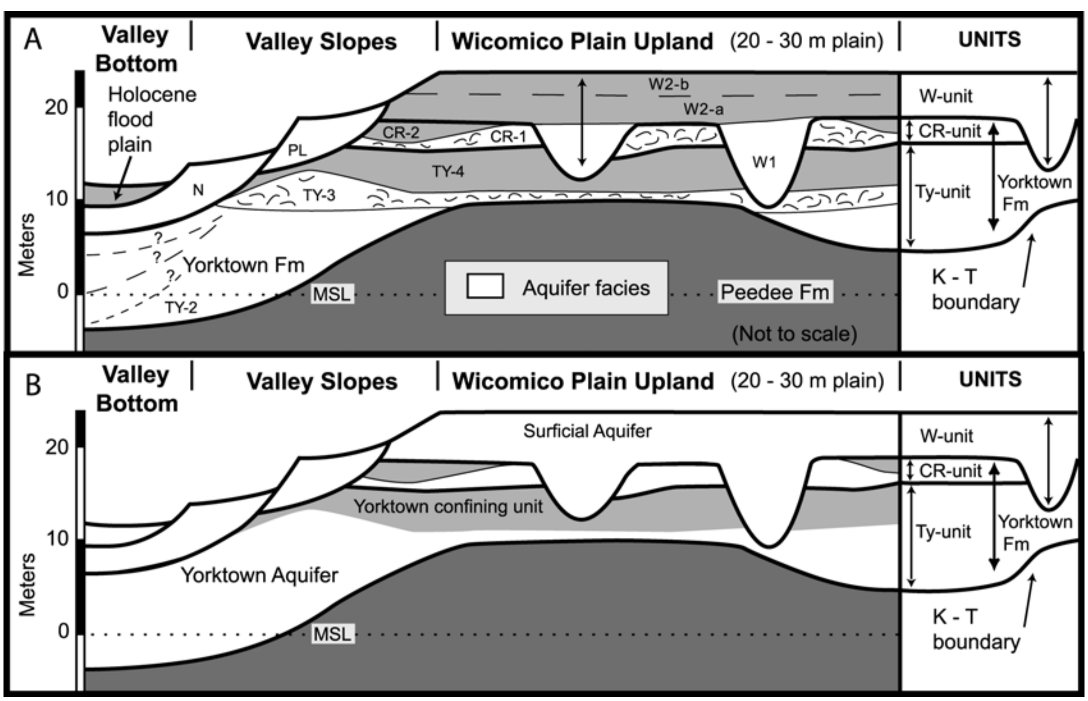


Figure 11. Sketch that shows the a) stratigraphic and b) hydrologeologic framework at the Lizzie site.

Geologic Unit	Age	Surficial Geomorphology	Facies	Facies Summary	Facies Geometry	Origin	Hydrogeologic characteristics
Floodplain	Holocene	< 12 m terrace	FP	Quartz sand, upward fining to mud and detrital plant debris.	shoestring-shaped valley fill	fluvial channel and flood plain	Shallow Aquifer
N-unit	middle? Pleistocene	12-16 m terrace	N	Quartz sand, fining upward into muddy sand and mud, bioturbated to tidally bedded.	shoestring-shaped valley fill	estuarine to fluvial valley fill	
PL-unit	early-mid? Pleistocene?	16-20 m terrace	PL	Quartz sand, fining upward into muddy sand and mud, bioturbated to tidally bedded.	shoestring-shaped valley fill	estuarine to fluvial valley fill	
W-unit	early Pleistocene 1.6 - 0.7 Ma (Krantz, 1991)	20-30 m terrace	W-2	Heterolithic - mud, sandy mud and sand; bioturbated to tidally bedded.	irregular sheet with shoestring sands	tidal flat/ indistributary bay/salt marsh.	
			W-1	Flaser to wavy bedded quartz sand; locally feldspathic.	lens to ovoid-shaped inlet/ valley fills	tidal inlet/valley fill	
Yorktown Fm: Morehouse Mbr. Equivalent	Pliocene 3.0 – 3.2 Ma (Krantz, 1991)	none at study site	CR-2	Sandy mud, mostly leached of carbonate fossils	irregular sheet	marine shelf/ open embayment	Yorktown confining unit
			CR-1	Muddy phosphatic shelly sand and gravel, locally leached of carbonate fossils; with dissolution fabrics.	irregular sheet	shallow marine lags, inlet fill and shoals	
Yorktown Fm: Morgarts Beach Member	Pliocene 4.0 - 3.2 Ma (Krantz, 1991)	none at study site	Ty-4	Sandy mud with thin (dm-cm) shell beds dominated by *Mulinia congesta*. Minor phosphate and glauconite.	irregular sheet	marine shelf/ open embayment	
Yorktown Fm: Rushmere Member			Ty-3	Phosphatic, gravelly shelly sand; locally muddy; locally cemented grainstone; locally leached.	very thin sheet with local mounds and valley infills	lags, marine shoals, inlet fill	Yorktown aquifer
? new unnamed member	Pliocene?	none at study site	Ty-2	Gravelly sand, predominantly quartz; with local intervals of detrital wood or shell hash.	shoestring-shaped valley fill	multi-origin, multi-age? paleovalley fill	
"Peedee" Formation	Cretaceous (Santonian)	none	K	Dark gray very fine to fine muddy sand; burrowed, glauconitic with phosphate nodules, locally shelly.	irregular sheet	marine shelf/open embayment	Cretaceous confining unit

Figure 12. Summary diagram that shows facies units and generalized hydrogeologic characteristics at Lizzie.

Regionally Mappable Unconformity-Bounded Unit	Approximate elevation of highstand shoreline in NC	Morphologic Expression in Little Contentnea Creek Watershed	Equivalent unit at Lizzie	Relative Age
Tabb Formation includes 3 members	**~ 9 m (30 ft)** Suffolk paleoshoreline	fluvial terraces at 7-10 m with relict meander belts.	Not Present at surface	Late (?) Pleistocene
?	?	fluvial terraces at 10-12 m with relict meander belts.	Likely buried under modern flood plain	Late middle? Or Late? Pleistocene
Shirley Formation	**~ 16 m (50 ft)** Unnamed paleoshoreline	fluvial-estuarine flats at 12-16 m	N-Unit	Late Middle Pleistocene (Johnson and Berquist, 1989 Mixon and others, 1989)
Chuckatuck Formation	**~ 20 m (65 ft)** Unnamed paleoshoreline	fluvial-estuarine flats at 16-20 m	PL-Unit	Middle Pleistocene (Johnson and Berquist, 1989 Mixon and others, 1989)
Charles City Formation	**~ 26 m (85 ft)** Unnamed paleoshoreline	dissected flats at 20-26 m; part of Wicomico plain (Daniels and others, 1984).	W-Unit	Early Pleistocene (Johnson and Berquist, 1989 Mixon and others, 1989)
Windsor Formation	**~ 30 m (100 ft)** Surry paleoshoreline	dissected flats at 26-30 m; part of Wicomico plain (Daniels and others, 1984).	Not Present	Early Pleistocene (Johnson and Berquist, 1989 Mixon and others, 1989)
Moorings Unit	**~ 35 m (115 ft)** Surry paleoshoreline	coast-parallel dune ridges at 30-36 m; part of Sunderland plain (Daniels and others, 1984)	Not Present	Late Pliocene or Early Pleistocene (Johnson and Berquist, 1989 Mixon and others, 1989)
Bacons Castle Formation Barhamsville Member	**~ 52 m* (170 ft)** Kenly paleoshoreline	highly dissected flats at +32 m; part of Sunderland plain of Daniels and others (1984).	Not Present	Late Pliocene (Johnson and Berquist 1989; Mixon and others, 1989) (1.8-2.05 ma, Krantz, 1991)
Yorktown Formation - Morehouse Member?/ (Chowan River Formation?)	**~ 75 m** (246 ft)** Wilson Mills paleoshoreline	None	CR-Unit	Late Pliocene (3.0-3.2 ma?; Krantz, 1991)
Yorktown Formation Morgarts Beach Member Rushmere Member	**~ 84 m** (275 ft)** Coats/Orangeburg paleoshoreline	None	Ty-4 Ty-3	Pliocene 4.0-3.2 ma Krantz, 1991
Yorktown Formation (?) Unnamed Member	**~ 84 m** (275 ft)** Coats/Orangeburg paleoshoreline	None	Ty-2	Pliocene (?)

* highstand estimate from Ramsey (1987, 1988)
** toe elevation from Daniels and others (1984); (toe elevations may be lower than actual highstand position).

Figure 13. Regionally correlated unconformity bounded units: from the Virginia map (Mixon and others, 1989) to Little Contentnea Creek Watershed.

The Ty-unit shoals upward into the CR-unit (Fig. 11A) and is truncated by it. The CR-Unit includes two facies, a muddy phosphate-rich leached shell bed (CR-1) and an overlying clayey silt (CR-2). These facies are similar in lithologic and faunal succession to the Rushmere (Ty-3) – Morgarts Beach (Ty-4) interval below it (Lauck W. Ward, personal communication) but are higher in the section, younger in age, and more extensively leached for carbonate. The succession represents transgressive lags and shallow marine shoals and inlet fill that are overlain by offshore (?) marine muds. Preliminary results indicate a fossil assemblage that is at least very late Yorktown in age, suggesting a possible correlation with the third Yorktown transgression (Morehouse Member), approximately 3.0 – 3.2 million years B.P. (after Krantz, 1991) (Fig. 12). Alternatively, the CR-unit may correlate with the Chowan River Formation, a late Pliocene marine unit that unconformably overlies the Yorktown Formation (Blackwelder, 1981). Hydrologically, the CR-unit functions as a discontinuous confining layer in the surficial aquifer.

The CR-unit is unconformably overlain by the W-unit, which forms the surficial deposit of the 20-24 m plain (Fig. 11A). Typically, the W-unit is tidally bedded but lacks carbonate fossils. It has two major facies. W1 is a lower coarse clastic facies of flaser bedded sand that infills paleovalleys or inlets that cut into the Yorktown. W1 functions as an unconfined aquifer. It is overlain by W2a, a sheet-shaped, heterogeneous unit that includes sharp-based, upward-fining sands flanked by heterolithic strata that grade out into lenticularly bedded mud. Surficially (0-10 ft depths), W2b is extensively bioturbated with remnant tidal bedding. W2 formed as tidal flat or indistributary bay-like deposits (W2a) that evolved upward into salt marsh (W2b).

Geomorphic position suggests that the uppermost W-unit correlates with the Charles City Formation of Virginia, considered early Pleistocene in age (Berquist and Johnson, 1989; Mixon and others, 1989) (Fig. 13). Parts of the W-unit may correlate with the slightly older Windsor Formation, a unit that outcrops surficially at elevations of about 24-31 m in the watershed. The Windsor is also early Pleistocene in age (1.6 to 0.7 Ma) (Krantz, 1991). The W1 and W2 facies have the same respective geomorphic and stratigraphic position as the Waccamaw and James City Formations of eastern North Carolina (see Blackwelder, 1981) but contain no fossils to confirm these correlations.

Along the Sandy Run drainage, the Wicomico plain interfluve and the three units (the Ty-, CR- and W-) that underlie it are truncated and overlain by two younger units, the P-unit and the N-unit that conform to two lower sets of terraces (Figs. 10, 11A). Both are (respectively) upward fining, sandy estuarine deposits associated with highstand scarps at 20 m and 16 m. The P-unit correlates with the Chuckatuck Formation of Virginia, which is middle Pleistocene (see Johnson and Berquist, 1989, Mixon and others, 1989), in Virginia (Fig. 13). The N-Unit correlates with the Shirley Formation which is late middle Pleistocene in age (Johnson and others, 1987). Holocene deposits less than 3 m thick overlie Pleistocene terrace deposits at Lizzie. These consist of a thin basal fluvial gravelly sand that fines upward into peaty floodplain sands and muds.

Paleogeographic Reconstruction of the Watershed

This section summarizes the geomorphic evolution of Little Contentnea Creek Watershed (Fig.14). The upland flats higher than 32+ m (Sunderland plain) are late Pliocene in age and pre-date the formation of the Surry paleoshoreline (Fig. 14a). The sand ridges (32-36 m) at the top of the scarp are early Pleistocene highstand (HS) barrier islands that predate the scarp or are contemporaneous with it. A highstand at 31 m or higher in early Pleistocene time notched the scarp's toe (29 m), but also formed the associated shoreline shoals, tidal deltas, and estuaries. A large paleoestuary, the ancestral Contentnea Creek (floor at ~30 m), that was connected to the Contentnea Creek drainage joins the paleo-coast here (Fig. 14a). In the early Pleistocene, relative sea level abruptly fell, stranding relict topography along the Surry paleoshoreline and generating the western higher part of the Wicomico plain (31-26 m). During the relative fall, a stillstand or slight rise in sea level notched a low scarp at 26 m. Successive middle Pleistocene highstands (with intervening lowstands) notched the scarps at 20 m (Fig. 14b) and 16 m (Fig. 14c). The fluvial terraces at 12 m and lower (Fig.14d) are probably late-middle or late Pleistocene in age, and associated with the transgressive-regressive cycle that generated the Suffolk paleoshoreline.

Regional extrapolation of stratigraphic units

Figure 13 correlates the theoretical distribution of geologic units and landforms in the Little Contentnea Creek Watershed with analogous deposits and landforms in Virginia. The late Pliocene Bacons Castle Formation outcrops west of the Surry paleoshoreline at elevations +32 m (Fig. 14d). This is a very muddy unit with a lower channel, inlet and valley fill facies and an upper heterogeneous, tidally bedded, fine-grained facies called the Barhamsville Member (Ramsey, 1992). The sand ridges at the crest of the scarp are underlain by the Moorings Unit, a barrier/backbarrier assemblage of facies that is very late Pliocene or early Pleistocene in age (Fig. 14d). Both of these units are exposed in the Martin Marietta Quarry at Fountain (Stop 1, this trip), but further work is needed to differentiate them. Snyder and Katrosh (1979) identified early Pleistocene backbarrier foram assemblages in muds at the Fountain quarry.

East of the Surry paleoshoreline, the Wicomico plain is underlain by two early Pleistocene units. The Windsor Formation outcrops between elevations 31 and 26 m. A low relief scarp at 26 m separates it from the next younger formation, the Charles City Formation which occurs at

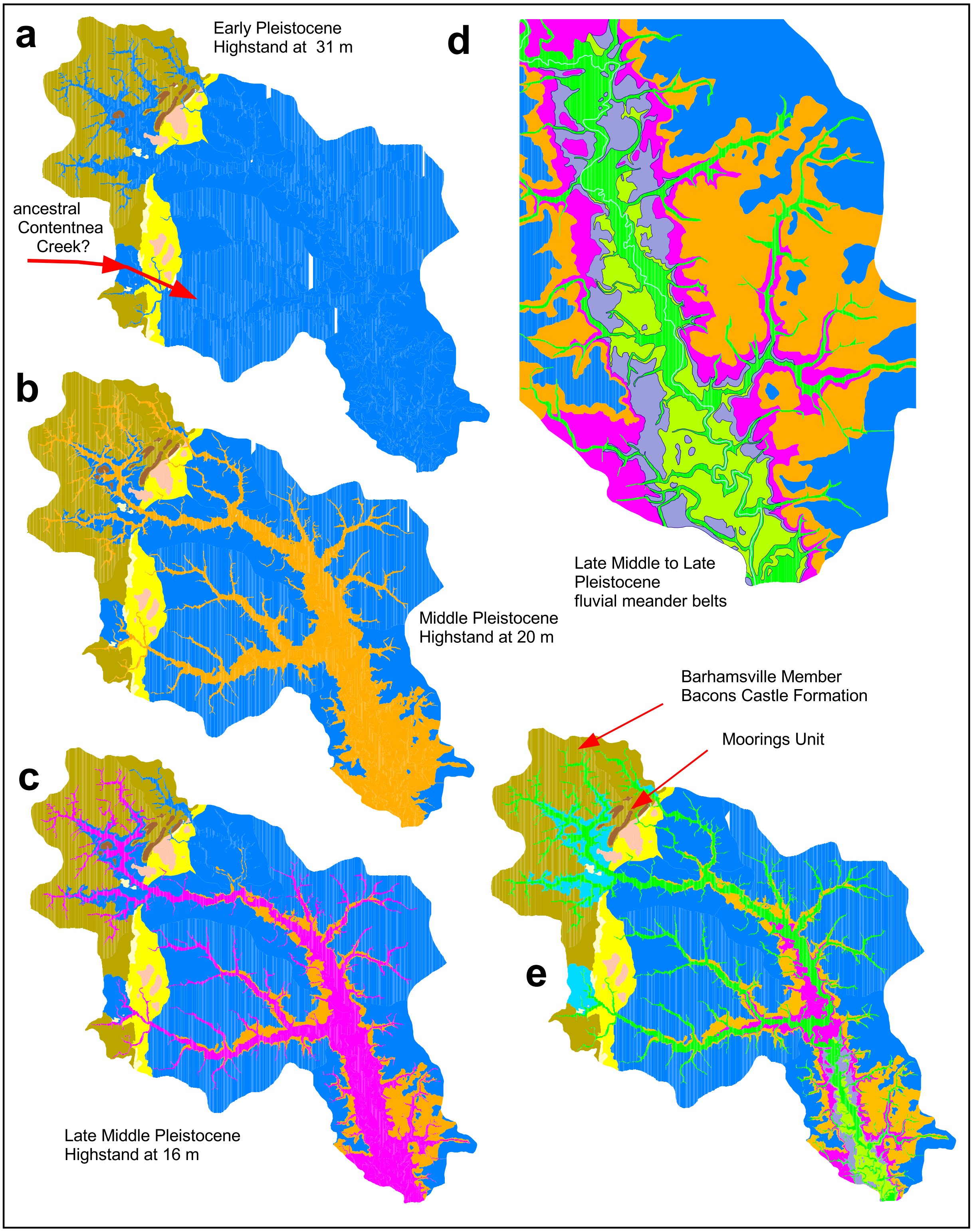


Figure 14. Paleogeographic reconstruction of the Little Contentnea Creek Watershed.

elevations of about 26-20 m. Lizzie sits on Charles City Formation deposits, according to the proposed conceptual model.

Along the margin of the Contentnea paleovalley, the three unconformity-bounded units that underlie the Wicomico Plain are truncated and overlain by at least two younger unconformity bounded units – the PL-unit and the N-unit. These correlate with the Middle Pleistocene Chuckatuck and Late-Middle Pleistocene Shirley Formations. The lower fluvial terraces below the Shirley Formation likely correlate with three sequences associated with the Late Pleistocene Tabb Formation, or an older unit. We reiterate that proposed map extents need to be confirmed with subsurface analysis.

Summary: Shallow aquifers and confining units

Figure 11B summarizes the relationship between stratigraphic facies and hydrogeologic units at Lizzie. Sand-rich aquifer facies are shown in white; muddy units and confining beds are shown in gray. Other papers in this guidebook fully discuss hydrologic, geochemical and age-dating aspects of these units. Mew and others (2002) provide methods on integrating hydrologic characteristics with landscape units. The integration of Mew's landscape units (Fig. 15) with the geomorphic (Fig. 9) and stratigraphic principles presented here will provide a very powerful predictive tool for hydrogeologic characterization studies.

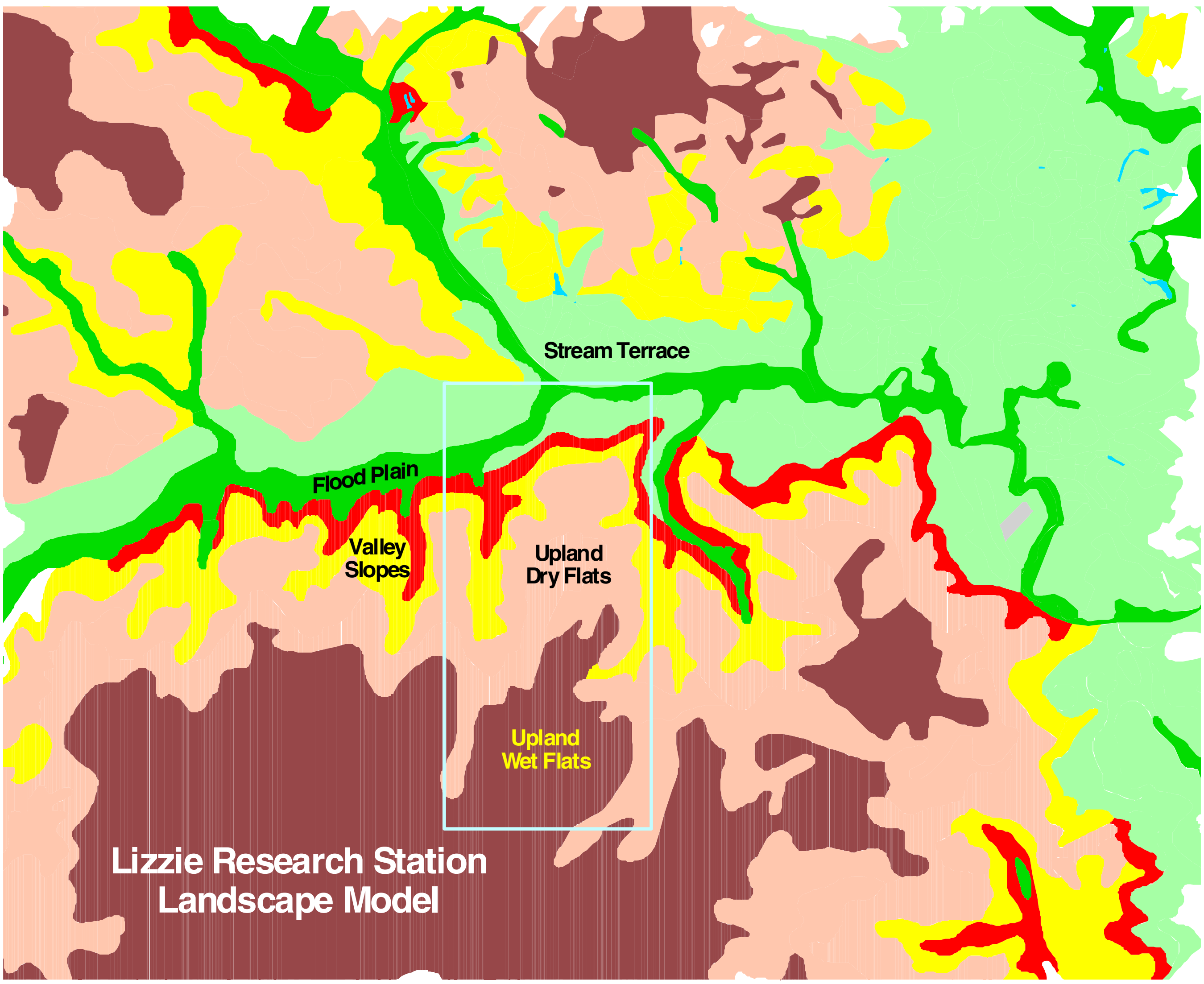


Figure 15. Landscape units from Mew and others 2002.

In summary, the hydrogeologic conceptual model at Lizzie (Fig. 11) is generalized as follows. Beneath the Wicomico plain interfluve, the Yorktown confining bed is an irregular sheet-shape (dominantly Ty-4, parts of the CR-unit). It separates confined Yorktown aquifer facies from the overlying unconfined surficial aquifer. The Yorktown confined aquifer includes a discontinuous thin sheet of shell hash (Ty-3) with local thickenings of sandy shoal deposits (Ty-2). Locally, this shell sheet truncates and overlies Yorktown inlet fill and paleovalley deposits (Ty-2) that also are aquifers. The unconfined surficial aquifer consists of the W-unit, which has lower coarser-grained paleovalley or inlet fill deposits (W1) and an upper muddier sheet (W2).

Because of erosive downcutting during Pleistocene falls in eustatic sea level, the Yorktown, CR-unit and W-Units are eroded along the Sandy Run drainage. The result is that the regionally significant Yorktown aquifer (Ty-4) was truncated and removed by erosive processes, and that it does not occur in the area of the drainage (paleovalley complex). In the area of the drainage, Pleistocene sandy terrace deposits are inset as nested paleovalley deposits. Thus the Yorktown aquifer facies (Ty-2 and Ty-3) that were confined beneath the Wicomico interfluve, are unconfined along the Sandy Run drainage, where they are directly connected to surficial aquifers in Pleistocene terrace deposits (N and PL units).

The proposed conceptual model, developed from the site-specific subsurface characterization Lizzie, allow us to generalize somewhat about regional geologic conditions. Interfluve deposits are different from nested paleovalley deposits along drainages. Interfluve deposits are characterized by sheetlike muddy units that truncate and overlie sandy inlet and paleovalley deposits. Thick unconfined sandy aquifers are concentrated as nested paleovalley complexes along drainage margins.

References

Berendsen, H.J.A. and Stouthamer, E, 2001, Paleogeographic development of the Rhine-Neuse delta, the Netherlands: Koninklijke Van Gocum, Assen, the Netherlands; 3 maps, 1 CD rom, 268 pp.

Blackwelder, B.W., 1981, Stratigraphy of upper Pliocene and lower Pleistocene marine and estuarine deposits of Northeastern North Carolina and southeastern Virginia. U.S. Geological Survey Bulletin 1502-B, 19 p.

Blackwelder, B.W., and Ward, L.W., 1979, Stratigraphic revision of Pliocene deposits of North Carolina dn South Carolina, Geologic notes, v. 23, no. 1, p.33-49.

Brierley, J.G., 1996, Channel morphology and element assemblages: a constructivist approach to facies modeling. In: Carling, P.A., Dawson, M.R., (Eds). Advances in Fluvial Dynamics and Stratigraphy, Wiley, Chichester, NY, p. 263-298.

Clark, W.B. and Miller, B.L., 1906, Geology of the Virginia Coastal Plain. In: The clay deposits of the Virginia Coastal Plain, Virginia Geological Survey, Bulletin 2, p. 11-24.

Clark, W.B., Miller, B.L. and Stephenson, L.W. 1912, Physiography and Geology of the Coastal Plain Region. In: Clark, W.B., Miller, B.L., Stephenson, L.W., Johnson, B.L., and Parker, H.N., 1912, The Coastal Plain of North Carolina, North Carolina Geological and Economic Survey, Volume III, Part 1, 372 pages.

Coch, N.K., and Oaks, R.Q., 1966, "Terrace Formation" concept in Atlantic Coastal Plain stratigraphy. Abstract, Geological Society of America, Northeastern Section, Program, 1st Annual Meeting, p. 17-18.

Colquhoun, D.J., 1974, Cyclic surficial stratigraphic units of the Middle and Lower Coastal Plains, central South Carolina. In: Post-Miocene stratigraphy, central and southern Atlantic Coastal Plain, R.Q. Oaks, Jr. and J.R. Dubar, Eds., Utah State University Press, Logan, Utah.

Cooke, C.W., 1930, Pleistocene seashores, Journal, Washington Academy of Science, v. 20, p. 389-392.

Cooke, C.W., 1931, Seven coastal terraces in the southeastern states, Washington Academy of Science, Journal, (or Journal of the Washington Academy of Science) v. 21, p. 503-513.

Cooke, C.W., 1932, Tentative correlationof American glacial chronology with the marine time scale. Journal, Washington Academy of Science, v. 22, p. 310-312.

Cooke, C.W., 1935, Tentative ages of Pleistocene shorelines, Journal , Washington Academy of Science, v. 25, p. 331-333.

Cooke, C.W., 1941, Two shorelines or seven? American Journal of Science, v.11, p. 171-192.

Daniels and others, 1966

Cooke, C.W., Gardner, Julia and Woodring, W.P., 1943, Correlation of the Cenozoic formation of the Atlantic and Gulf Coastal Plain and the Caribbean region. Geological Society of America, Bulletin, v. 54, p. 1713-1723.

Daniels, R.B. and E.E. Gamble, 1974, Surficial deposits of the Neuse-Cape Fear Divide above the Surry Scarp, North Carolina, In: R.Q. Oaks, Jr., and J.R. Dubar, Eds. Post-Miocene Stratigraphy Central and Southern Atlantic Coastal Plain, Utah State University Press, Logan, Utah, 275 pp. P. 88-101.

Daniels, R.B., and Kane, E.O., 2001, Coastal Plain Scarps of the Neuse River Basin, North Carolina, as delineated by R.B. Daniesls: a new GIS coverage. Ground Water Circular No. 18, NC-DENR, Raleigh, NC.

Daniels, R.B., Kleiss, H.J., Buol, S.W., Byrd, H.J., and Phillips, J.A., 1984, Soil systems in North Carolina, Bulletin 467, North Carolina Agricultural Research Service, North Carolina State University, Raleigh, NC.

Doering, J.A., 1960, Quaternary Surface Formations of southern part of Atlantic Coastal Plain. Journal of Geology, v. 68, p. 182-202.

Dubar, J.R., H.S. Johnson, Jr., Bruce Thom, and W.O. Hatchell, 1974A, Neogene stratigraphy and morphology, south flank of the Cape Fear Arch, North and South Carolina. In: R.Q. Oaks, Jr., and J.R. Dubar, Eds., Post-Miocene Stratigraphy Central and Southern Atlantic Coastal Plain, Utah State University Press, Logan, Utah, 275 pp. p. 139-173.

Dubar, J.R., J. R. Solliday,and J.F. Howard, 1974B, Stratigraphy and morphology of Neogene deposits, Neuse River Estuary, North Carolina. , In: R.Q. Oaks, Jr., and J.R. Dubar, Eds. Post-Miocene Stratigraphy Central and Southern Atlantic Coastal Plain, Utah State University Press, Logan, Utah, 275 pp. p. 102-122.

Farrell, K.M., 2001, Geomorphology, facies architecture and high-resolution non-marine sequence stratigraphy in avulsion deposits, Cumberland Marshes, Saskatchewan: Sedimentary Geology, 139, p. 93-150.

Farrell, K.M. and H.E. Mew, Jr. 2001. A geomorphic and stratigraphic conceptual model for evolving valleys and interfluves on the Coastal Plain: Little Contentnea Creek Watershed of the Neuse River Basin, North Carolina, USA. in Fluvial Sedimentology 2001: 7th International Conference on Fluvial Sedimentology, Program and Abstracts. Open-File Report 60, Conservation and Survey Division, Institute of Agriculture and Natural Resources, University of Nebraska-Lincoln.

Fisher, W.L., McGowan, J.H., Brown, L.F., Jr., and Groat, C.G., 1972, Galveston-Houston Area: Environmental Geologic Atlas of the Texas Coastal Zone, Bureau of Economic Geology, Austin, TX; 91 pages, 22 figures, 7 tables, 9 mps, reprinted 2000.

Fisk, H.N., 1944, Geological investigation of the alluvial valley of the Lower Mississippi River Mississippi River Commission. Waterways Experiment Station, Vicksburg, MS.

Fisk, H.N., 1947, Fine grained alluvial deposits and their effect on Mississippi River activity: War Department, Corps of Engineers, Waterways Experiment Station, Vicksburg, MS. 2 volumes.

Flint, R.F., 1940, Pleistocene features of the Atlantic coastal plain. American Journal of Science, v. 238, p. 757-787.

Galloway, W.E.,1989a, Genetic stratigraphic sequences in basin analysis, I. Architecture and genesis of flooding-surface bounded depositional units: AAPG Bulletin 73, p 125-142.

Galloway, W.E.,1989b, Genetic stratigraphic sequences in basin analysis, I. Application to northwest Gulf of Mexico Cenozoic Basin: AAPG Bulletin 73, p. 143-154.

Johnson, B.L. 1904, Pleistocene terracing in the N. Carolina Coastal Plain. Science, v. 26, p. 640-642.

Johnson, G.H., 1972, Geology of the Yorktown, Poquoson West, and Poquoson East Quadrangles, Virginia. Virginia Division of Mineral Resources, Report of Investigations 30, 57 pp.

Johnson, G. H., 1976, Geology of the Mulberry Island, Newport News, and Hampton Quadrangles,

Virginia. Virginia Division of Mineral Resources, Report of Investigations 41.

Johnson, G.H., and Berquist, C.R., Jr., 1989,Geology and Mineral Resources of the Brandon and Norge Quadrangles, Virginia. Virginia Division of Mineral Resources Publication 87, Department of Mines, Minerals, and Energy, Division of Mineral Resources, Charlottesville, Virginia.

Johnson, G.H., Ward, L.W., and Peebles, P.C., 1987, Stratigraphy and paleontology of Pliocene and Pleistocene deposits of southeastern Virginia: in Whittecar, G.R., editor, Geological Excursions in Virginia and North Carolina, Southeastern Section, Geological Society of America, Guidebook, Old Dominion University, Norfolk, VA, p. 189-218.

Kane, E.O., 2001, Sediments and geomorphology of a portion of the updip Coastal Plain of North Carolina, Thesis, North Carolina State University, 133pp.

Kraemer, S. 2002. Investigation of multi-media, multi-scale modeling of hydrology and nitrogen loadings, Contentnea Creek Basin, North Carolina. U.S. Environmental Protection Agency Research Brief. Athens, GA.

Kraft, J.C., 1971, Sedimentary facies patterns and geological history of a Holocene marine transgression: Geological Society of America Bulletin, v. 82, p. 2131-2158.

Krantz, D.E., 1991, A chronology of Pliocene sea-level fluctuations: the U.S. Middle Atlantic Coastal Plain record, Quaternary Science Reviews, v. 10, p. 163-174.

Mew, H.E., Jr., D.K. Hirth, D.V. Lewis, R.B. Daniels, and A.J. Keyworth, 2002, Methodology for compiling groundwater recharge maps in the Piedmont and Coastal Plain provinces of North Carolina. Ground Water Bulletin No. 25. N.C. Dept. of Environment and Natural Resources, Div. of Water Quality, Groundwater Section. Raleigh, NC.

Mew, H.E. Jr. and K.M. Farrell. 2002. Part I. Geology and ground water at the Lizzie Research Station, Greene County, North Carolina. Ground Water Bulletin Number 25, N.C. Dept. of Environment and Natural Resources, Division of Water Quality, Groundwater Section, Raleigh, NC.

Mixon, R.B., Berquist, C.R., Jr., Newell, W.L., Johnson, G.H., Powars, D.S., Schindler, J.S., and Rader, E.K., 1989, Geologic map and generalized cross sections of the coastal plain and adjacent parts of the Piedmont, Virginia: U.S. Geological Survey Miscellaneous Investigations Series Map I-2033.

North Carolina Geological Survey, 1985, Geologic Map of North Carolina, North Carolina Geological Survey, 1:500,000 color.

Oaks, R.Q., Jr. and N.K Coch, 1973, Post Miocene stratigraphy and morphology, southeastern

Virginia. Bulletin 82, Virginia Division of Mineral Resources, Charlottesville VA.

Oaks, R.Q., Jr. and J.R. Dubar, 1974, Introduction. In: R.Q. Oaks, Jr., and J.R. Dubar, Eds. Post-Miocene Stratigraphy Central and Southern Atlantic Coastal Plain, Utah State University Press, Logan, Utah, 275 pp. p. 2-8.

Oaks, R.Q., Jr., N.K. Coch, J.E. Sanders, and R.F. Flint, 1974. Post-Miocene shorelines and sea levels, southeastern Virginia. In: R.Q. Oaks, Jr., and J.R. Dubar, Eds. Post-Miocene Stratigraphy Central and Southern Atlantic Coastal Plain, Utah State University Press, Logan, Utah, 275 pp. P. 53-87.

Peebles, P.C., 1984, Late Cenozoic landforms, stratigraphy and history of sea level oscillations of southeastern Virginia and northeastern North Caolina: PhD disssertaion, College of William and Mary, 227 pp.

Peebles, P.C., Johnson, G.H., and Berquist, C.R., Jr., 1985, The middle and late Pleistocene stratigraphy of the outer coastal plain, southeastern Virginia: Virginia Minerals, v. 30, p. 13-22.

Plint, A.G., and Nummedal, Dag, 2000, The falling stage systems tract; recognition and importance in sequence stratigraphic analysis. In Hund, D. and Gawthorpe, R.L. (editors), Sedimetnary responses to forced regressions, Geological Society Specail Publications, 172, p. 1-17, Geological Society of London, London, United Kingdom.

Posamentier, H.W., and Allen, G.P., 1999, Siliciclastic Sequence Stratigraphy – Concepts and Applications: SEPM (Society for Sedimentary Geology, Concepts in Sedimentoogy and Paleontology No. 7, Tulsa, OK, USA. 210pp.

Ramsey, K.W. , 1992, Coastal response to late Pliocene climate change: middle Atlantic Coastal Plain, Virginia and Delaware. In: C.H. Fletcher, III and J.F. Wehmiller, Eds., Quaternary Coasts of the United States: Marine and Lacustrine Systems, Special Pub. 48, Society for Sedimentary Geology, Tulsa, OK.

Saucier, R.T., 1969, Geological Investigation of the Mississippi River Area, Artonish to Donaldsonville, LA. US Army Corps of Engineers, Waterways Experiment Station, Technical Report S-69-4, Vicksburg, MS.

Shattuck, G.B., 1901, The Pleistocene problem of the North Atlantic Coastal Plain. Johns Hopkins University Circular v. 20, no. 152, p. 67-75. (reprinted in American Geologist, v. 28, p. 87-107).

Shattuck, G.B., 1906, The Pliocene and Pleistocene deposits of Maryland, Maryland Geological Survey, Pliocene and Pleistocene, p. 21-137.

Snyder, S.W., and Katrosh, M.R., 1979, An exposure of marginal marine Pleistocene sediments, Pitt County, North Carolina: Southeastern Geology, v. 20, p. 247-259.

Spruill, T.B. and A.J. Tesoriero. 2002. Part II. Geohydrologic foundations for multimedia exposure assessment: Observations of atmospheric-hydrospheric tracers and nutrient loads within hierarchical drainages of the Neuse River Basin; Summary of Hydrologic and Water-Quality Data, 1999-2002. U.S. Geological Survey Open File Report 03-XXX, Raleigh, NC.

Stephenson, L.W. 1912. The quaternary formations. in W.B Clark, B.L. Miller, and L.W. Stephenson. 1912, Part I: The physiography and geology of the Coastal Plain of North Carolina. North Carolina Geological and Economic Survey, vol. III, The Coastal Plain of North Carolina, Raleigh, NC, pp. 266-290.

Stephenson, L.W., and B.L. Johnson. 1912, The water resources of the Coastal Plain of North Carolina, in Clark, W.B., and others, 1912, The Coastal Plain of North Carolina: North Carolina Geological and Economic Survey, v. III, pt. II, p. 333–483.

Swift, D.J.P. and Heron, S.D., Jr., 1969, Stratigraphy of the Carolina Cretaceous. Southeastern Geology, v. 10, p. 201-246.

Swift, D.J.P., Heron, S.D., Jr., and Dill, C.E., Jr., 1969, The Carolina Cretaceous – Petrographic reconnaissance of a graded shelf. Journal of Sedimentary Petrology, v. 39, p. 18-33.

United States Department of Agriculture, Natural Resources Conservation Service. 1995, North Carolina cooperative hydrologic unit river basin study. Raleigh, NC, 16 pp. + unit maps.

Van Wagoner, J.C., Mitchum, R.M., Campion, K.M., Rahmanian, V.D., 1990, Siliciclastic Sequence Stratigraphy in Well Logs, Cores, and Outcrops. Am. Assoc. Pet. Geol., Methods in Exploration 7, Tulsa, OK.

Ward, L.W., and Blackwelder, B.W., 1980, Stratigraphic revision of Upper Miocene and Lower Pliocene beds of the Chesapeake Group, Middle Atlantic Coastal Plain. U.S. Geological Survey Bulletin 1482D, 61pp and 5 plates.

Winker, C.D. and J.D. Howard, 1977, Correlation of tectonically deformed shorelines on the southern Atlantic coastal plain. Geology, v. 5, p. 123-127.

Wentworth, C.K., 1930, Sand and gravel resources of the coastal plain of Virginia.Virginia Geological Survey, Bulletin 32, 146 p.

Hydrogeology of a Small Coastal Plain Catchment in the Little Contentnea Creek Watershed

Timothy B. Spruill, *U.S. Geological Survey*
Anthony J. Tesoriero, *U.S. Geological Survey*
Douglas. G. Smith, *U.S. Geological Survey*
Kathleen M. Farrell, *North Carolina Geological Survey*
H.E. Mew, Jr., *North Carolina Division of Water Quality*

Introduction

Studies have been conducted over the last 10 years (1993-2003) at the Lizzie Research Station (Figure 1) and in the Little Contentnea Creek watershed to determine the geologic and hydrologic characteristics of a shallow aquifer, uppermost confined aquifer and their relation to streams discharging in the area. These cooperative studies have been conducted by the North Carolina Division of Water Quality-Groundwater Section, the U.S. Geological Survey, the North Carolina Geological Survey, and the U.S. Environmental Protection Agency. This paper describes the basic hydrogeology of the Lizzie Research Station, which is considered representative of the hydrology of the Little Contentnea Watershed.

Lithology and geomorphic setting

Geologically, the Lizzie site lies in the Coastal Plain province, a landscape characterized by a series of progressively younger paleoshorelines and intervening terraces that step down in elevation and age towards the coast and drainages. The relic landscape is mostly Pliocene through Quaternary age, with modern drainages bordered by a series of nested Plio-Pleistocene paleovalleys that are separated by remnants of older interfluves. The Lizzie site straddles the boundary between the Wicomico plain interfluve (20-30 m terrace lying east of the Surry Scarp paleoshoreline, [Daniels and Kane, 2001]) and the 12 m Sandy Run floodplain, with two sets of lower terraces separated by the 20 m and 16 m scarps. Landforms characterizing the Plum Tree Branch catchment (Figure 1) include the poorly-drained wet upland flat headwaters, known locally as Half Moon Pocosin, and the generally well- to moderately well-drained dry upland flat and valley side slopes comprising the Plum Tree Branch upland valley (see Fig 15, p. 14). The Branch drains into Sandy Run, an alluvial paleovalley with riverine landforms along the valley bottoms.

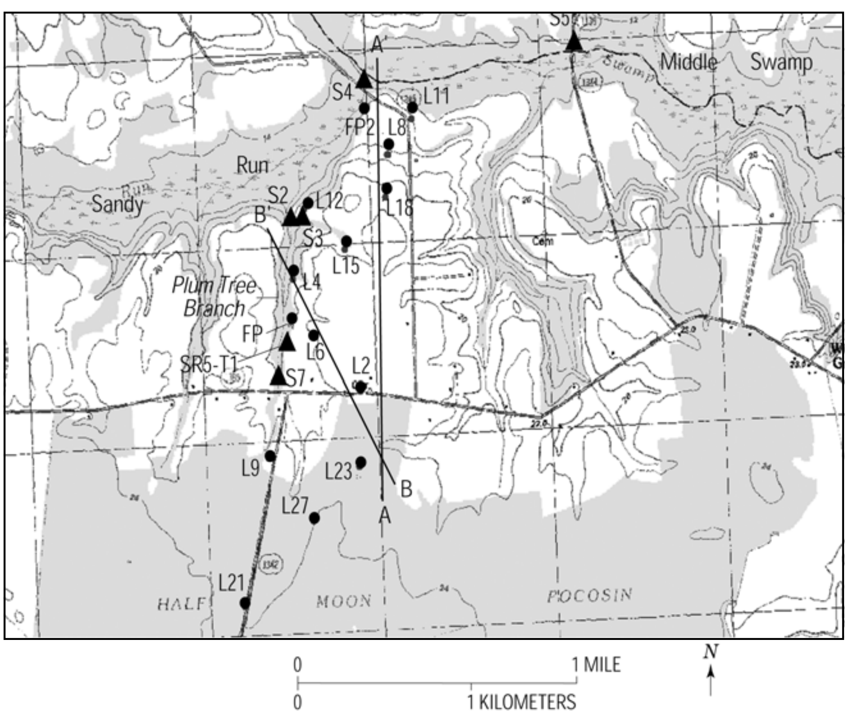


Figure 1. Ground and surface water sampling sites and transect locations.

At Lizzie, a late Cretaceous marine shelf deposit resembling the Peedee Formation functions as basement (-2 m to 3 m) for the shallow ground water system of near-surface aquifers and confining beds. Overlying the Cretaceous section is the Pliocene-age Yorktown Formation and several poorly exposed Pliocene to Pleistocene units. Stephenson and Johnson (1912) prepared the first detailed hydrogeologic maps of ground water resources in the North Carolina Coastal Plain, associating the surficial aquifer with Pleistocene terrace deposits, and equated the first confining layer and underlying confined aquifer with the Yorktown Formation. More recently the surficial aquifer was generalized to include post-Yorktown deposits of Quaternary age (Winner and Coble, 1996).

Lithologically, the Yorktown aquifer is composed of gravelly sands and a phosphatic gravelly, shelly sand, overlain by a sandy clayey silt with beds of *Mulinia congesta* that functions as the 1-7 m thick Yorktown confining bed. The tidally bedded surficial deposits of the Wicomico plain form the upland surficial or terrace aquifer at the Lizzie site. These deposits include two units: a lower fine-medium grained flaser bedded sand that infills paleovalleys and other channel-like features that cut into the Yorktown and an upper sheet shaped wavy to lenticularly bedded mud. Overlying these units is a sheet-shaped, heterogeneous, extensively bioturbated, 1-3 m thick, surficial layer that formed as tidal flat or indistributary bay-like deposits that evolved upward into salt marsh deposits.

Within the Sandy Run paleovalley, several periods of erosion had truncated the surficial and Yorktown formations, with the Yorktown confining layer completely eroded below the 16 m scarp. Subsequent Middle Pleistocene fluvial to estuarine deposition, associated with later sea level advances, overlie fine to coarse sands within the valley. Modern floodplain deposits rich in detrital plant debris form a riparian zone along Sandy Run and lower portions of Plum Tree Branch. Hydrologically, the paleovalley substrate serves as the potential discharge area for the Yorktown confined aquifer and functions as an unconfined alluvial valley aquifer.

Hydraulic properties of the Surficial and Yorktown Aquifers

The Little Contentnea Creek drainage basin area encompasses a large part of Greene County but also includes areas in Pitt and Wilson Counties. Geology in the area is composed primarily of sedimentary rock and unconsolidated sediment layers. The near surface sediments are comprised of unconsolidated sands, silts, and clays. Sedimentary layers in the area frequently consist of a mixture of sand, clay and silt particles. The area has been affected by multiple sea level transgression and regression events. As a result, the properties of near surface sediment layers can vary significantly across the area.

In general, the hydrogeology of the area consists of an unconfined surficial aquifer that is underlain by several deeper confined aquifers, with the first confined aquifer over much of the area either the Yorktown or the Peedee Aquifers. In an unconfined aquifer system, precipitation seeps down into the soil eventually reaching the saturated zone. The top of the saturated zone is referred to as the water table. Water that percolates down into the saturated zone is collected and stored in the pore spaces of sediments, forming an unconfined aquifer. Water stored in an unconfined aquifer is generally free to move upward through the process of evapotranspiration. A less permeable layer, referred to as a confining layer, forms the lower boundary of an unconfined aquifer and limits the downward migration of water. The thickness of the surficial aquifer and underlying confining layers varies considerably. The saturated thickness of the unconfined aquifer at most sites was generally less than 6 meters and the lower boundary of the surficial aquifer was generally less than 8 meters below land surface.

Five aquifer tests in three different geomorphic settings were conducted during Water Year 2003 (October 2002 to September 2003) to characterize hydraulic properties of the surficial aquifer and to determine if differences were evident between varied geomorphic settings. Aquifer tests were conducted to reveal water-bearing properties of the aquifer, primarily hydraulic conductivity (k) and transmissivity (T). Hydraulic properties of the Surficial and Yorktown aquifer and confining units are shown in Table 1. Based on the available data (5 aquifer tests conducted in 3 settings) that were collected during this study, there does not appear to be a consistent relationship between hydraulic properties of the surficial aquifer and landscape setting. The highest transmissivity value (mean=37.8 m^2/day) was found on a hillside setting near Scuffleton, N.C. The lowest transmissivity value (4.7 m^2/day) was found in a flood plain area near Ballards Crossroads, N.C. The highest (4.5 meters/day) and lowest (1.2 meters/day) hydraulic conductivity values were found in a flood plain setting. The one generalization about hydraulic properties of the surficial aquifer that can be made is that hydraulic conductivity in the Little Contentnea Creek drainage appears to be less than 5 meters/day. This is somewhat less than the average hydraulic conductivity for the surficial Aquifer in the entire North Carolina Coastal Plain, estimated by Winner and Coble (1997) to be about 9 meters/day. More information will be necessary before reliable generalizations about landscape settings can be derived.

Geologic Unit	Age	Surficial Geomorphology	Facies	Facies Summary	Facies Geometry	Origin	Hydrogeologic characteristics	Hydrogeologic Unit
Floodplain	Holocene	< 12 m terrace	FP	Quartz sand, upward fining to mud and detrital plant debris.	shoestring-shaped valley fill	fluvial channel and flood plain	Shallow Aquifer-	
N-unit	middle? Pleistocene	12-16 m terrace	N	Quartz sand, fining upward into muddy sand and mud, bioturbated to tidally bedded.	shoestring-shaped valley fill	estuarine to fluvial valley fill	Hydraulic Conductivity (k) ranges from 1-5 m /day. (Winner and Coble, 1996 reported average of 9 m/day)	
PL-unit	early-mid? Pleistocene?	16-20 m terrace	PL	Quartz sand, fining upward into muddy sand and mud, bioturbated to tidally bedded.	shoestring-shaped valley fill	estuarine to fluvial valley fill		Surficial Aquifer
W-unit	early Pleistocene 1.6 - 0.7 Ma (Krantz, 1991)	20-30 m terrace	W-2	Heterolithic - mud, sandy mud and sand; bioturbated to tidally bedded.	irregular sheet with shoestring sands	tidal flat/ indistributary bay/salt marsh.	Transmissivity ranges from 4.7-37.8 m^2/day;Gradient=0.9 cm/day	
			W-1	Flaser to wavy bedded quartz sand; locally feldspathic.	lens to ovoid-shaped inlet/ valley fills	tidal inlet/valley fill	Saturated thickness ranges from 3-10 meters.	
Yorktown Fm: Morehouse Mbr. Equivalent	Pliocene 3.0 – 3.2 Ma (Krantz, 1991)	none at study site	CR-2	Sandy mud, mostly leached of carbonate fossils	irregular sheet	marine shelf/ open embayment	Thickness 3-21 meters. Average at Lizzie: 6 meters.	Yorktown Confining Unit
			CR-1	Muddy phosphatic shelly sand and gravel, locally leached of carbonate fossils; with dissolution fabrics.	irregular sheet	shallow marine lags, inlet fill and shoals		
Morgarts Beach Member	Pliocene 4.0 - 3.2 Ma (Krantz, 1991)	none at study site	Ty-4	Sandy mud with thin (dm-cm) shell beds dominated by *Mulinia congesta* . Minor phosphate and glauconite.	irregular sheet	marine shelf/ open embayment		
Rushmere Member			Ty-3	Phosphatic, gravelly shelly sand; locally muddy; locally cemented grainstone; locally leached.	very thin sheet with local mounds and valley infills	lags, marine shoals, inlet fill	Avg k = 6.7 m/day (Winner and Coble, 1996) Tests at Lizzie: k=7.6 m/day	Yorktown Aquifer
? new unnamed member	Pliocene?	none at study site	Ty-2	Gravelly sand, predominantly quartz; with local intervals of detrital wood or shell hash.	shoestring-shaped valley fill	multi-origin, multi age? paleovalley fill		
"Peedee" Formation	Cretaceous (Santonian)	none	K	Dark gray very fine to fine muddy sand; burrowed, glauconitic with phosphate nodules, locally shelly.	irregular sheet	marine shelf/open embayment		Cretaceous confining unit

Table 1. Summary of Hydrogeologic Framework at the Lizzie Site. For explanation, see Farrell and others, this guidebook.

Ground-water Flow Paths

Head measurements in both the surficial and Yorktown aquifers were taken periodically at the Lizzie site to determine horizontal and vertical flow directions. Head values for December 13, 2000 are shown for the surficial and Yorktown Aquifers in Figures 2 and 3.

Flow directions in the surficial aquifer indicate that much of the ground water underlying the upland flats and valley slopes discharges to Plum Tree Branch (Figure 2, top). Some direct discharge to Sandy Run also occurs along the northern portion of the site. Flow in Yorktown aquifer moves almost directly to the north (Figure 2, bottom).

Head differentials between the surficial and Yorktown aquifers along the south-north cross-section A-A' (Figure 3) are several meters in the upland areas, but decrease toless than 10 cm along the paleovalley slope as the stream terrace is approached. It is hypothesized that beneath this paleovalley stream terrace the confining layer has been eroded or leached and no longer acts as a barrier to flow. As a result, Yorktown aquifer sediments have been overlain by fluvial to estuarine deposits, creating a 14-15 m thick unconfined alluvial aquifer, as indicated by the head measurements shown (Figure 3).

In contrast, the first order Plum Tree Branch stream does not breach the Yorktown confining layer, but flows above it (Figure 3, B-B'). Along the SE-NW cross-section B-B', large downward gradients exist between the surficial and Yorktown aquifers as the stream is approached, indicating ground water from the Yorktown does not discharge to Plum Tree Branch.

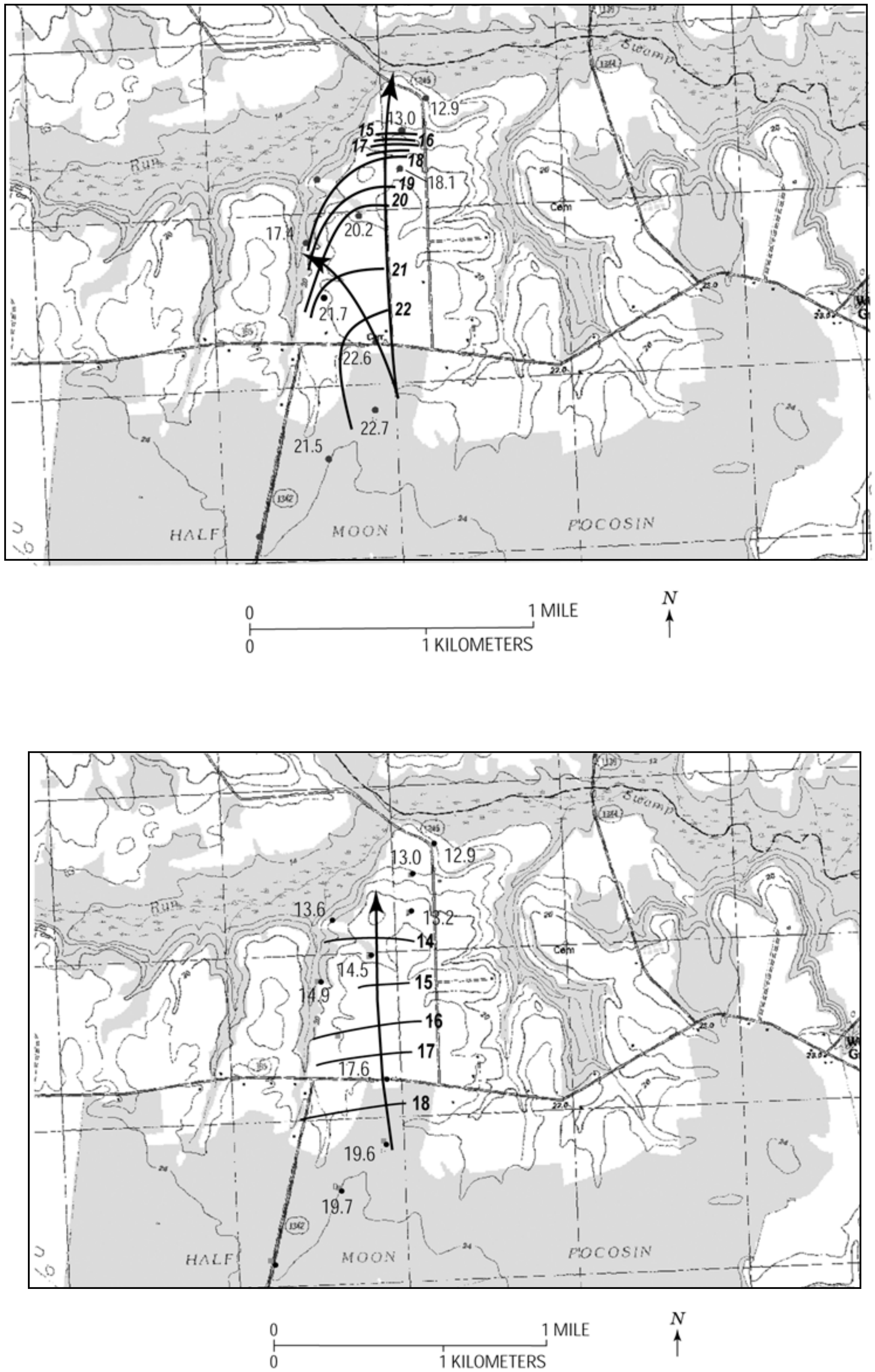
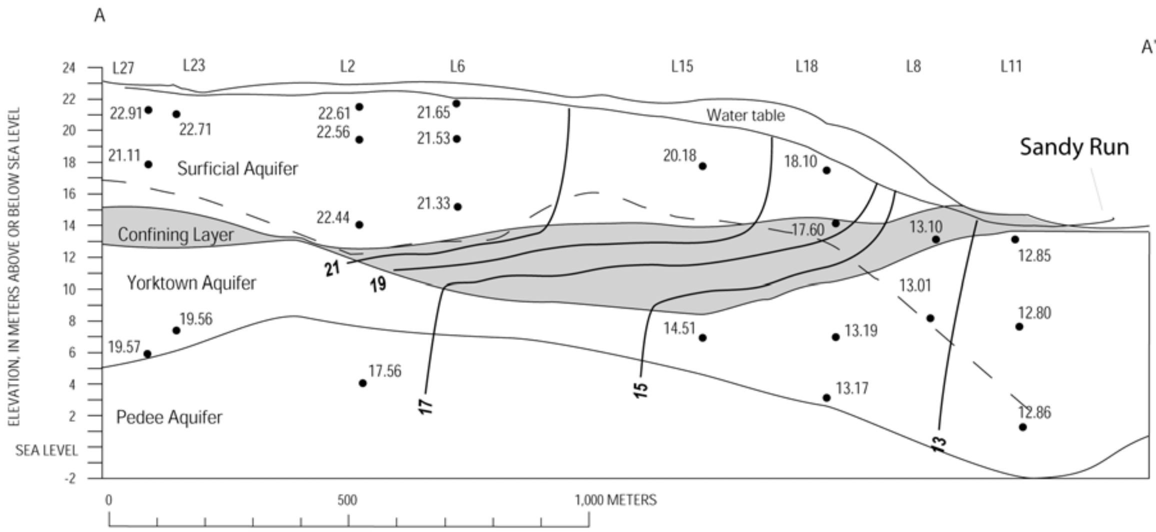


Figure 2. Piezometric head values and contours (in meters above mean sea level) and flow directions for the surficial (top) and confined aquifers (bottom). Measurements were taken on December 13, 2000.



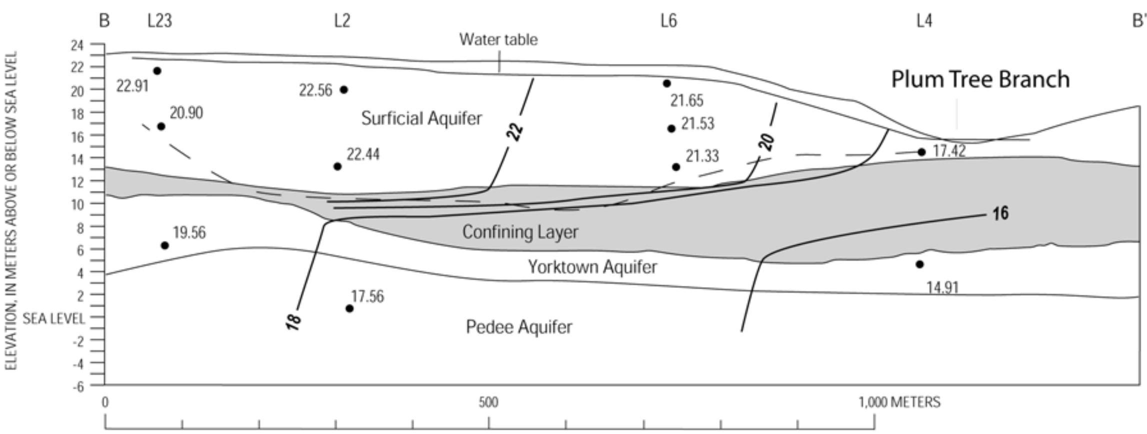


Figure 3. Piezometric head values (in meters above mean sea level) and contours along cross section A-A' in figure 1 (top) and B-B' in figure 1 (bottom). Area above dashed line indicates where calcareous sediments have been dissolved.

Ground-water/Surface Relationships

Hydrogeology, which encompasses both understanding of surface-water and ground-water hydrology is best understood by utilizing chemical as well as physical techniques. By comparing major ion chemistry of the major aquifers and streams it is often possible to discern the origin of surface waters in the region. Ground water from the confined aquifers (primarily Yorktown) is a Ca^{2+}-HCO_3^- type water (Figure 4). In contrast, water from the unconfined aquifers (primarily surficial aquifer) has a more varied mix of cations, while anion chemistry is dominated by Cl^- and NO_3^-. Water from the unconfined portion of the Yorktown has similar anion and cation chemistry as the surficial aquifer and not the Yorktown, providing further evidence that this portion of the Yorktown is receiving water from the surficial aquifer. Shallow ground water in both the surficial aquifer and the unconfined Yorktown have low pH and alkalinity values suggesting that these areas are rapidly recharged and have been extensively leached of their soluble minerals.

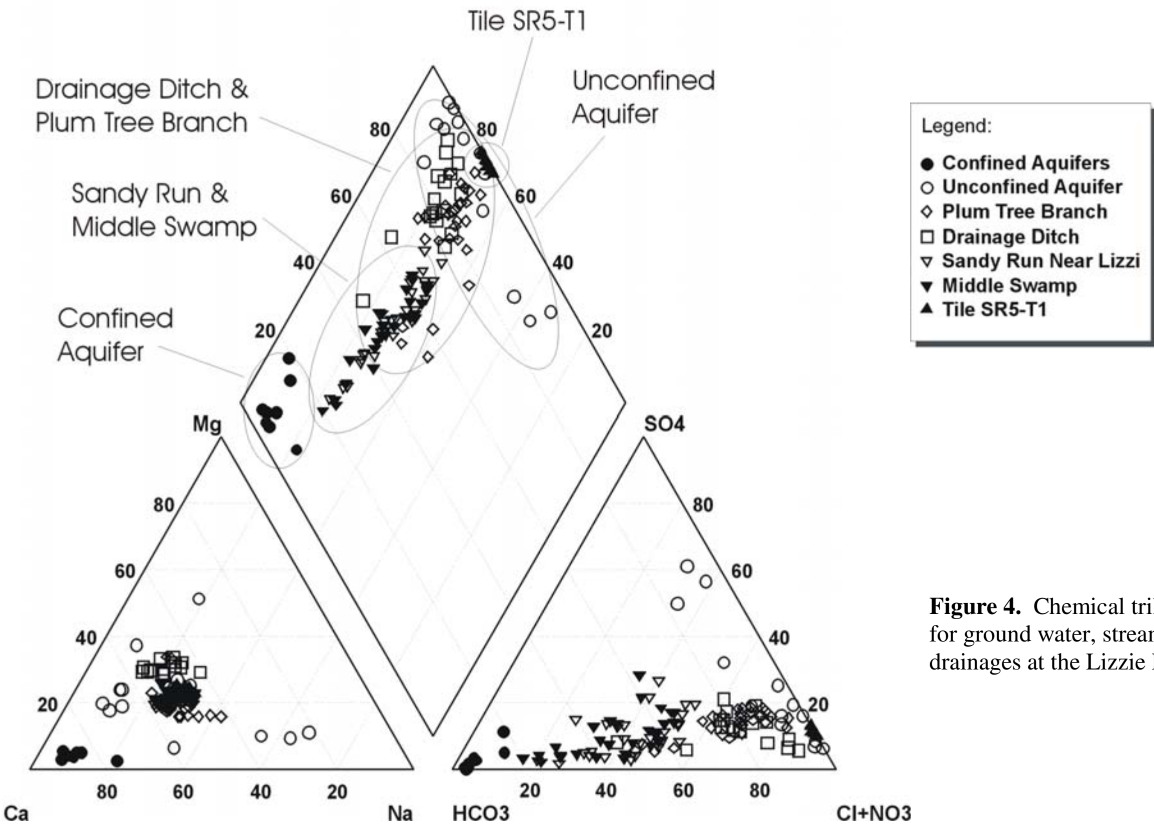


Figure 4. Chemical trilinear diagrams for ground water, streams, and artificial drainages at the Lizzie Research Station.

Figure 4. Chemical trilinear diagrams for ground water, streams, and artificial drainages at the Lizzie Research Station.

The cation chemistry of Plum Tree Branch, Sandy Run and Middle Swamp are similar and are bounded by the range in cation chemistry found in the unconfined aquifer. In contrast, the anion chemistry of all of these streams appears to trend from a Cl-NO_3^--dominated water similar to the unconfined aquifer, to a HCO_3^--dominated water similar to that of the confined aquifers (Figure 4). However, because a similar trend towards confined aquifer water for cations was not observed, the hypothesis that a higher proportion of water from confined aquifers were the cause of the observed trend toward a HCO_3^- type water is rejected. A more likely explanation for the change in water type as a function of discharge is an increase in alkalinity derived from biologically-mediated reactions.

Inferences about the residence times of surface water in the watershed can be made by comparing SiO_2 concentrations in surface water to the relationship between SiO_2 and ground water residence time (see Ground-water Chemistry, this volume). Concentrations of SiO_2 increase as a function of ground water age, with shallowest parts of the surficial aquifer having the lowest levels and the highest levels found in the confined portions of the Yorktown. Concentrations of SiO_2 in Plum Tree Branch do not change much seasonally and are always in the range indicated by the surficial aquifer (Figure 5). This suggests that water in Plum Tree Branch is largely derived from the surficial aquifer. Little or no contribution from the Yorktown is expected since this stream does not breach the confining unit separating the surficial aquifer from the Yorktown. Overland flow and other fast pathways having low SiO_2 concentrations due to low contact time with sediments are not indicated as major sources in Plum Tree Branch during the flow conditions sampled in this study (storm events were not targeted). In contrast to Plum Tree Branch, Middle Swamp and Sandy Run occasionally incise through the confining unit and into the Yorktown so some Yorktown discharge into these streams is more likely. However, SiO_2 concentrations in Middle Swamp, Sandy Run and Plum Tree Branch are not intermediate between unconfined and confined aquifers. In fact, SiO_2 concentrations are much lower than that found in the unconfined aquifers, suggesting a large portion of flow in these streams have short residence times (e.g., < 1 year) that are likely derived from overland flow and interflow. The finding of the dominance of young water in the stream channel for this study appears to agree with previous findings by Michel (1992) who reported that the Neuse River even at Fort Barnwell, N.C., many tens of miles downstream, is dominated by young water (~1 year).

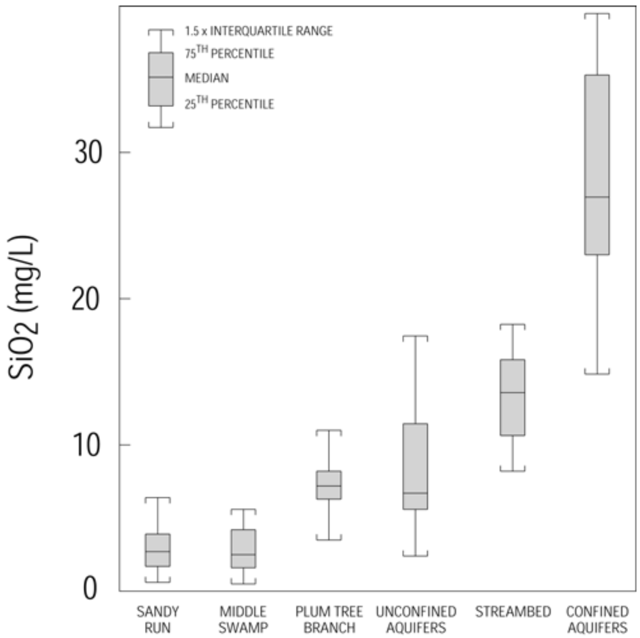


Figure 5. **Concentrations of SiO_2 in ground and surface water.**

Summary

The combined use of chemical, hydrologic, and geomorphic information has been used to examine ground water transport and its interactions with surface water in a coastal plain setting in the Little Contentnea Creek Watershed. Hydrogeologic data collected from 5 sites throughout the Little Contentnea Creek Basin indicate that hydraulic conductivity of the surficial aquifer is generally less than 5 meters/day, somewhat lower than hydraulic conductivity (~9 meters/day) reported for the surficial aquifer in the Coastal Plain Horizontal from earlier work. Based on the available data (5 aquifer tests conducted in 3 settings) that were collected during this study, there does not appear to be a consistent relationship between hydraulic properties of the surficial aquifer and landscape setting. Based on piezometric measurements made in wells installed on the Lizzie Research Station, horizontal flow is induced by the presence of a confining unit at a shallow depth. It is hypothesized that this confining unit is cut out or leach along drainages, thus hydrologically connecting the surficial and Yorktown aquifers. Age-dating, chemical, and piezometric data all point to horizontal flow from the surficial aquifer as the dominant source of ground water to streamflow. Available chemical data suggests that relatively young water dominates in larger streams, which may indicate ground water discharging from short flow-paths from alluvial deposits, interflow, or surface runoff. In the vicinity of the Lizzie Research Station little water appears to be derived from the confined portions of the Yorktown aquifer.

References

Daniels, R.B. and Evan O. Kane, 2001, Coastal plain scarps of the Neuse River Basin, North Carolina as delineated by R. B. Daniels: Ground Water Circular Number 18, N.C. Dept of Environment and Natural Resources, Raleigh.

Mew, H. E., Jr., D.K. Hirth, D. V. Lewis, R. B. Daniels, and A. J. Keyworth, 2002, Methodology for compiling Groundwater Recharge Maps in the Piedmont and Coastal Plain Provinces of NC, Groundwater Bulletin Number 25. Groundwater Section, Division of Water Qulaity, NC Department of Environment and Natural Resources, Raleigh, NC.

Michel, R.L., 1992, Residence times in river basins as determined by analysis of long-term tritium records: J. of Hydrology, v. 130, p. 367-378.

Stephenson, L.W., and B.L. Johnson. 1912, The water resources of the Coastal Plain of North Carolina, in: Clark, W.B., and others, editors, The Coastal Plain of North Carolina: North Carolina Geological and Economic Survey, v. III, pt. II, p. 333–483.

Winner, M.D., Jr., and Coble, R.W., 1996, Hydrogeologic framework of the North Carolina Coastal Plain, in Regional Aquifer-System Analysis—Northern Atlantic Coastal Plain: U.S. Geological Survey Professional Paper 1404–I, 106 p. +14 pls.

Using Ground Water Chemistry and Age-Dating to Evaluate Nitrogen Fate and Transport in a Coastal Plain Environment

Timothy B. Spruill, *U.S. Geological Survey*
Anthony J. Tesoriero, *U.S. Geological Survey*
S.L. Harden, *U.S. Geological Survey*

Introduction

Within North Carolina's Neuse River basin (Figures 1, 2 in Farrell & others, this volume), nonpoint-source nutrient loads have been identified as a major component of increased estuarine nutrient loading. In particular, confined animal feeding operations appear to have a substantial effect on N and P loading to streams [*Burkholder,* 2000]. The specific objectives of this paper are to (1) link chemical, hydrologic, and geologic data to obtain a mechanistic understanding of the fate and transport of nitrate in ground water in a coastal lain environment, and (2) estimate historical ground-water nitrate levels and fate by combining age-dating and chemical analyses of ground water.

Ground-water flow paths delineated by mapping the piezometric surface coupled with ground-water residence times using age-dating methods allow for a rigorous understanding of flow in an aquifer system. Chlorofluorocarbons (CFCs) have been successfully used to track changes in contaminants over time (e.g., Böhlke and Denver, 1995; Tesoriero et al., 2000). Wells were installed and sampled for chloro-fluorocarbon, tritium, major ions and nutrients at the Lizzie Site (Figure 1) since 1999. Age-dating techniques and geochemical changes that take place along two flow paths will be discussed in this paper.

Age Dating Ground Water at Lizzie

Chlorofluorocarbons and tritium concentrations in ground water were measured to estimate the age since the time of recharge. Three distinct flow regimes are present at the site and can be characterized by the overlying landscape settings (see Fig. 15 in Farrell & others, this volume): poorly drained upland wet flats (pocosins), well drained upland dry flats, and broad riverine alluvial valleys (Mew & others, 2002). These landscape features are typically found in the middle coastal plain environment and have been

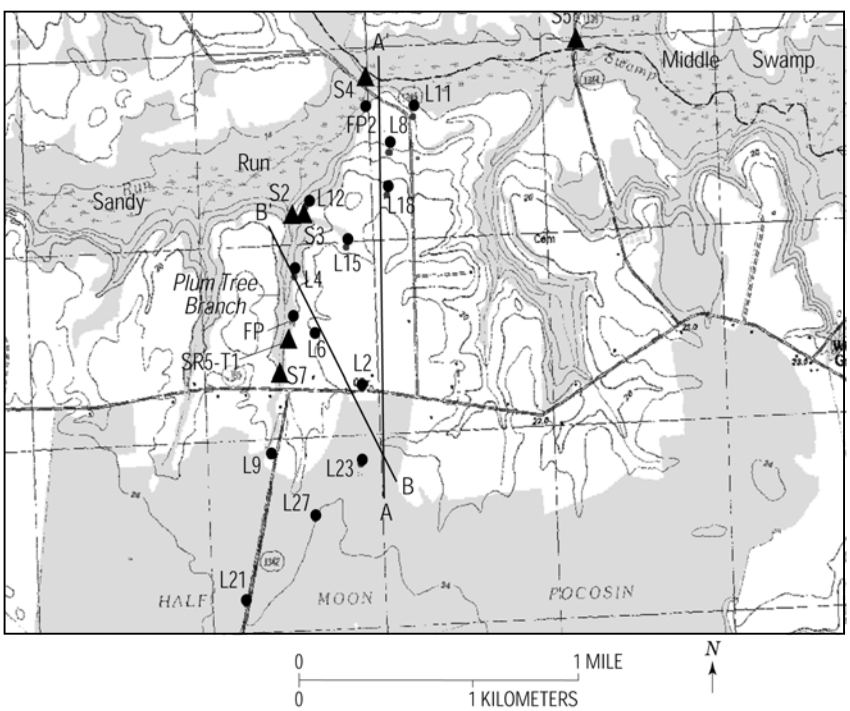


Figure 1. Ground and surface water sampling sites and transect locations.

mapped across the entire North Carolina Coastal Plain (Haven, 2003).Examples of flow regimes along two transects (A-A' and B-B') present at Lizzie are presented in Figure 2.

Not surprisingly, the poorly drained upland wet flats to the south have a recharge age profile indicative of slow percolation rates. Recharge age contours are tightly spaced with old water (<1955) found at the base of the shallow aquifer (Figure 2). In contrast, along the intermediate part of the flow system, moderately well-drained soils are present and faster recharge is indicated by the spreading of the recharge age contours. Ground water at the base of the surficial aquifer at this portion of the flow system is approximately 30 years old. Piezometric head values

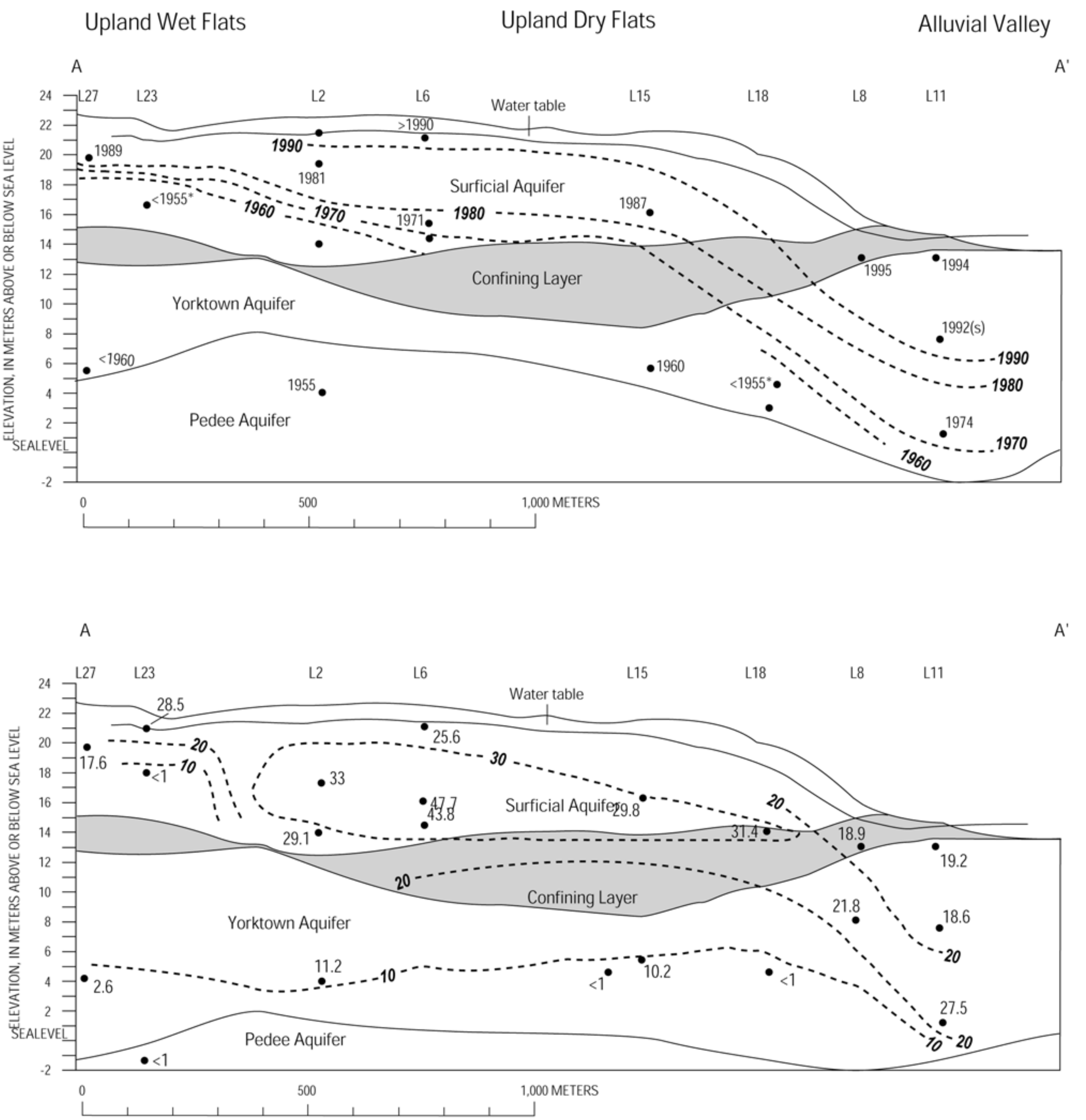


Figure 2. Recharge dates and contours using chlorofluorocarbon concentrations along transect A-A' (top). Bottom: Tritium concentrations and contours (in pCi/L) in ground water along transect A-A" (see Figure 1 for transect location).

indicate that as Sandy Run is approached, incision of the surficial aquifer increases and the vertical component of ground water flow increases (Figure 3). In the alluvial valley, recharge date contours penetrate through the confining unit (fig. 2) suggesting that this unit has been leached or eroded and is more permeable than in upland areas. Young CFC ground water ages in the portion of the Yorktown aquifer that is adjacent to Sandy Run suggest that ground water flows from the surficial aquifer through the confining unit into the Yorktown prior to discharging to the stream. In upgradient samples collected from the Yorktown, CFC ground water ages suggest recharge occurred prior to

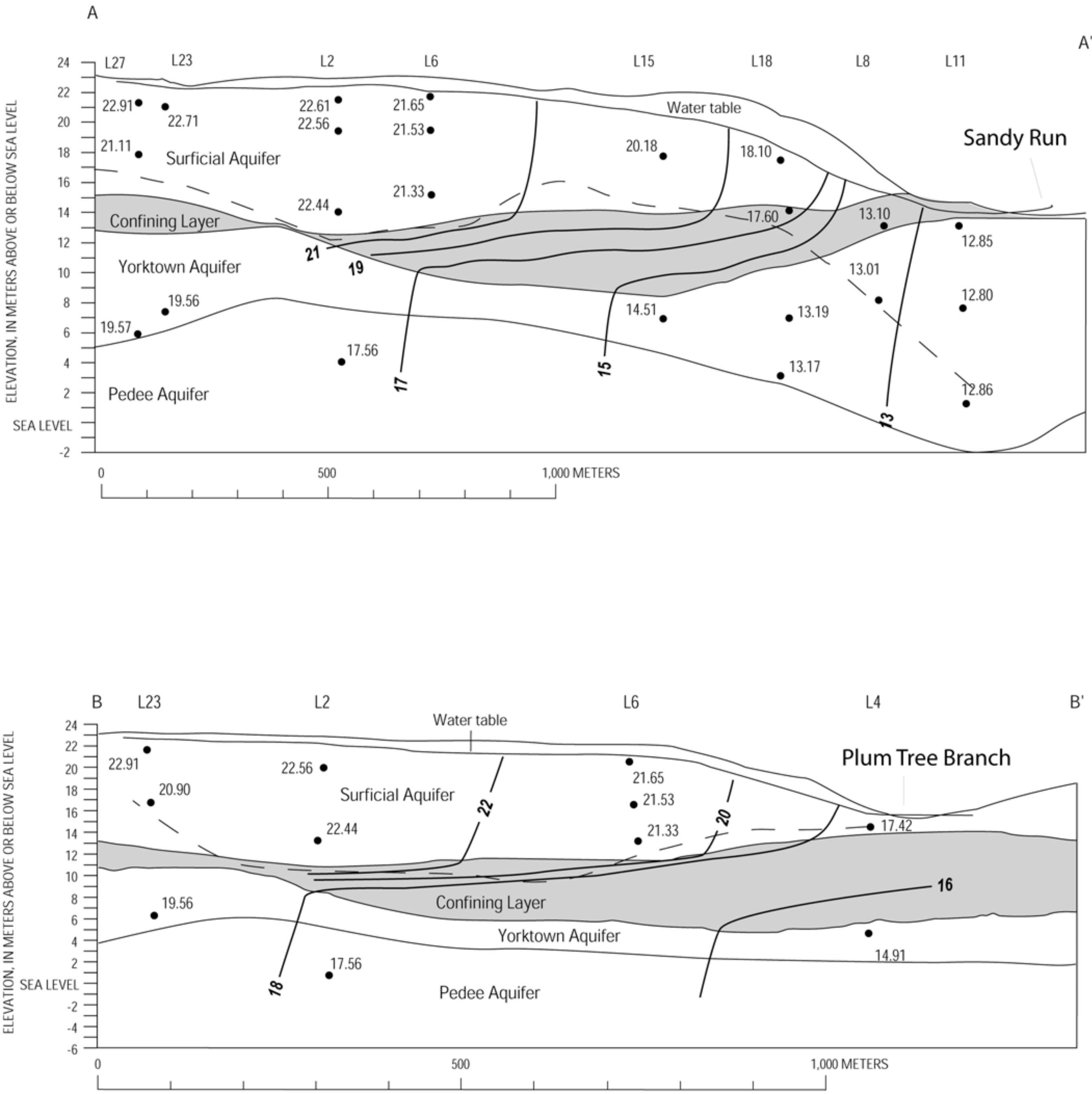


Figure 3. Piezometric head values (in meters above mean sea level) and contours along transects A-A' (top) and B-B' (bottom) for December 2000. See Figure 1 for locations of transects. Area above dashed line indicates area where calcareous sediments have been dissolved.

1960. Therefore, upwelling of upgradient Yorktown water into Sandy Run is not indicated by these recharge estimates since recharge age contours may be expected to narrow if old and new water are mixed in this zone. Rather, it appears that water from the surficial aquifer has migrated into the Yorktown aquifer.

Tritium concentrations in the atmosphere are derived from atmospheric testing of nuclear weapons. As such, tritium is a particularly helpful marker of whether recharge occurred before or after the onset of atmospheric testing (approximately 1953). The intensity of atmospheric testing has varied since its inception. Non-detectable levels of tritium for CFC-based ages that are prior to 1953 provide a definitive verification that these samples recharged prior to 1953 since atmospheric testing did not occur until after this date. Tritium levels as a measure of the accuracy of CFC ages becomes less quantitative with more recent ages because a single tritium level may represent recharge from widely different time periods. Further, mixing of water from different ages can have a dramatic affect on tritium levels because of the non-uniform tritium profile caused by the bomb testing peaks.

No tritium was detected in samples with CFC-based recharge ages prior to 1953. While tritium peak levels were not found, when tritium concentrations were plotted in cross section (Figure 2) higher concentrations of tritium were observed at the base of the surficial aquifer (except beneath the pocosin) which corresponds to CFC-based ages that are consistent with bomb peak periods. Beneath the pocosin, tritium was not detected at the base of the surficial aquifer consistent with a slow rate of recharge that is expected in this part of the aquifer.

Geochemical tracers have also been used to determine the relative amounts of stream water derived from differing flow paths. Flow paths in a catchment range from short overland flow paths on the order of hours to long ground water flow paths on the order of years. Silica has often been used as a chemical tracer because these pathways often have distinctly different silica concentrations, with concentrations increasing as a function of residence time. The relationship between silica concentrations and residence time is typically modeled in these studies (e.g., Scanlon et al., 2001). The availability of silica and age-dating information provides an opportunity to determine the relationship between silica concentrations and residence time. Silica concentrations in the unconfined aquifers in this study area increase linearly as residence times increase (r^2=0.95, Figure 4). As a result silica concentrations in the unconfined aquifer (primarily surficial aquifer) may be used as a first approximation of the residence time for samples where direct estimates (e.g., CFCs, tritium) of residence times are not available. In the confined aquifers (primarily Yorktown aquifer) there is also a relationship between silica concentrations and residence time, however the slope indicates a faster rate of silica dissolution (Figure 4). The relationship between silica and residence time is being used to distinguish between the various sources of surface water (e.g., overland flow, shallow ground water).

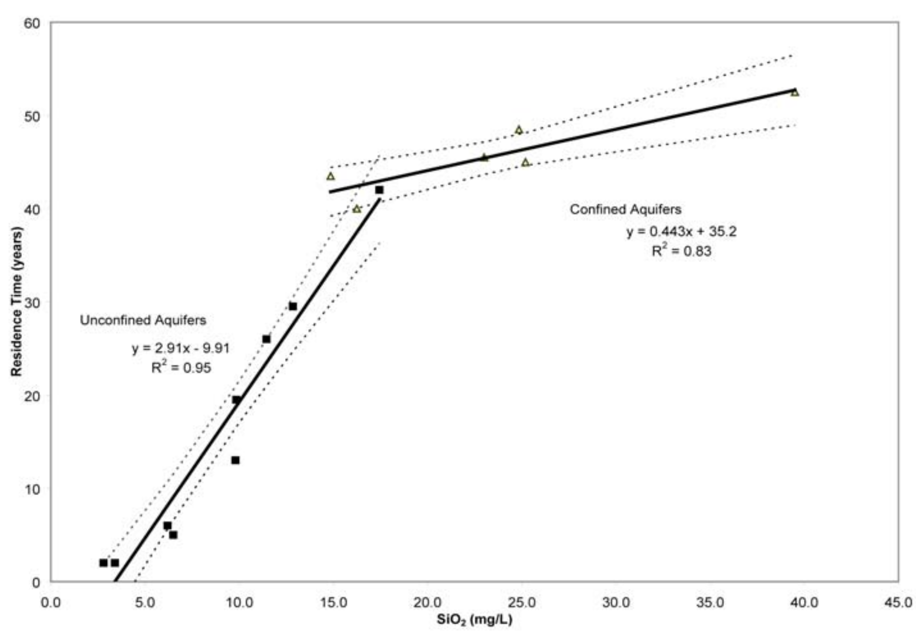


Figure 4. Ground water residence time interpreted from chlorofluorocarbon concentrations plotted against SiO_2 concentrations. Dashed lines indicate 95% confidence intervals.

Fate and Transport of Nitrogen in the Surficial and Yorktown Aquifers

Shallow ground water beneath the site often has concentrations of nitrate exceeding the drinking water standard (i.e., 10 mg/L as N). Nitrate concentrations decrease quickly with depth, with levels below 1 mg/L less than 5 m below the water table (Figure 5). Two processes may be responsible for the sharp decrease in nitrate with depth: 1) nitrate contaminated water from agricultural activity may not have reached this point in the flow system (i.e., the age of deep, low nitrate ground water pre-dates the intensive fertilizer application) and/or 2) nitrate is denitrified as it moves deeper in the aquifer system. Coupling age-dating and water chemistry data can discern betwee these two processes.

The concentrations of redox-active constituents in ground water can be used to delineate the aquifer based on the dominant terminal electron accepting process (TEAP). Redox reactions occur in sequence, with the more thermodynamically favorable reactions occurring first. With respect to nitrate, denitrifying bacteria are facultative anaerobes and as a result will prefer to use oxygen as an electron acceptor if it is present. Consequently, nitrate is not likely to be denitrified in portions of the aquifer containing oxygen. Conversely, if high levels of dissolved iron are present, iron-reducing conditions are indicated and nitrate is not stable. Dominant terminal electron acceptors were delineated along flow paths through both the surficial and Yorktown aquifers to determine the portions of these aquifers where transformations of nitrate and other redox-active contaminants may occur. Dominant TEAPs were determined using the classification system of Chapelle et al. (1995). Oxygen-reducing conditions were indicated when concentrations of dissolved oxygen exceeded 0.5 mg/L. Nitrate-reducing conditions were considered dominant when dissolved oxygen levels were below 0.5 mg/L and nitrate concentrations were above 0.5 mg/L. Iron-reducing conditions were considered dominant when both dissolved oxygen and nitrate levels were below 0.5 mg/L and iron concentrations exceeded 0.5 mg/L. When seasonal variations in TEAPs occurred, the TEAP that was dominant for most of the year was selected.

Dominant TEAPs along a south to north transect across the site indicate that only in the uppermost portions of the shallow aquifer (e.g., <5 m below the water table) is nitrate expected to be stable (Figure 5). Shallow hydraulic gradients induce largely horizontal flow (Figure 3), limiting the transport of dissolved oxygen into deeper portions of the aquifer. Furthermore, the high organic carbon content in this aquifer favors high rates of oxygen consumption due to microbial respiration. As a result, the consumption of oxygen by microbial respiration quickly exceeds the supply, with ground water becoming anaerobic at relatively shallow depths. In deeper portions of the surficial aquifer and most of the Yorktown aquifer, iron-reducing conditions are present: nitrate is not stable in this environment. Only at the northern terminus of the flow path where the surficial aquifer does not exist, are oxygen-reducing conditions found in the Yorktown aquifer. Flow paths are apparently not impeded by the confining unit in this area. Lithologic cores taken from this portion of the confining unit have been noticeably leached of carbonate cements, increasing the hydraulic conductivity of this unit in this area.

Selected ground water samples were analyzed for dissolved nitrogen and argon gas to estimate the amount of nitrogen derived from atmospheric sources. Nitrogen and argon are incorporated in ground water during recharge by air-water equilibration processes. Air bubbles can also be transported to the saturated zone resulting in concentrations of N_2 and Ar in excess of equilibrium (Heaton, 1982). Nitrogen gas that is derived from atmospheric sources (both

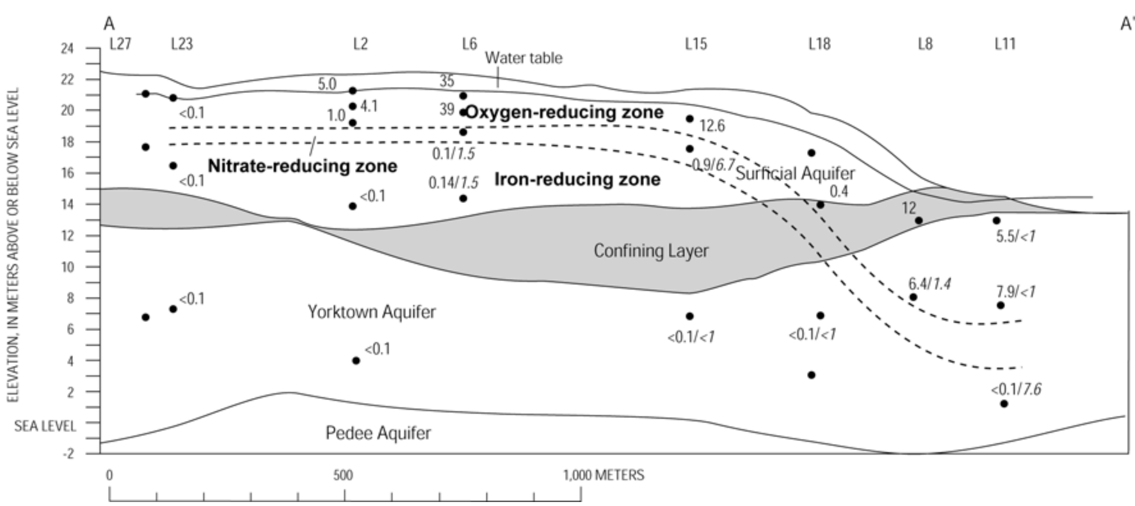


Figure 5. Delineation of terminal electron accepting processes along transect A-A'. Nitrate (normal type) and excess N_2 (italics) concentrations in milligrams per liter are also shown.

air-water equilibrium and excess air) can be estimated using N_2/Ar ratios for samples from aerobic portions of the aquifer where denitrification is not expected (Dunkle et al., 1993). The amount of nitrogen gas that exceeds the amount expected from atmospheric sources is termed "excess N_2" and is assumed to be from denitrification.

The combined use of age-dating techniques and the concentrations of nitrate, excess N_2 and other redox–active constituents provides insight into fate and history of nitrate contamination in these aquifers (Figure 6). Three regimes regarding the history of nitrate contamination are apparent. Ground water samples that are less than 10 years old tend to be oxic and have elevated nitrate concentrations reflecting both the stability of nitrate in this region and a recharge time period of high nitrogen application. Ground water samples that are greater than 10 but less than 30 years old have low nitrate and dissolved oxygen concentrations indicating that nitrate is not stable, while the increased excess N_2 values indicate that these waters did at one time contain elevated nitrate concentrations. Samples over 30 years also have low nitrate and dissolved oxygen and high levels of iron suggesting that nitrate is also not stable in this environment. However, these samples have little or no excess N_2 indicating that these samples did not contain elevated nitrate at an earlier point along their flow paths.

A more detailed assessment of nitrogen transport is needed across the riparian zone because sharp chemical gradients are often observed in these environments. High dissolved-oxygen concentrations indicate that aerobic conditions occur upgradient of the riparian zone with high concentrations of nitrate beneath the spray field (Figure 7). As ground water enters the riparian zone, dissolved-oxygen and nitrate concentrations are very low and iron and methane concentrations increase, indicating that conditions are sufficiently reducing to assure that any nitrate passing through this zone will likely be reduced prior to discharging to Plum Tree Branch. Dilution of aerobic, nitrate-laden shallow ground water, with a large fraction of deeper anaerobic water can yield similar riparian zone concentrations of redox-active constituents to those found near Plum Tree Branch. However, silica concentrations remain essentially constant along the transect, suggesting that mixing with deeper high-silica water is not occurring to a significant degree. Dentrification and dissimilatory nitrate reduction to ammonium (DNRA) are possible pathways for nitrate reduction. Increases in ammonium levels occurring in the riparian zone are very small relative to upgradient nitrate concentrations indicating that DNRA may be responsible for only a small fraction of nitrate reduction. As such, denitrification is the likely nitrate-removal mechanism in the riparian zone. Unfortunately, dissolved-gas samples collected in the riparian zone and in the streambed contained too much methane and CO_2 to obtain a meaningful estimate of excess N_2.

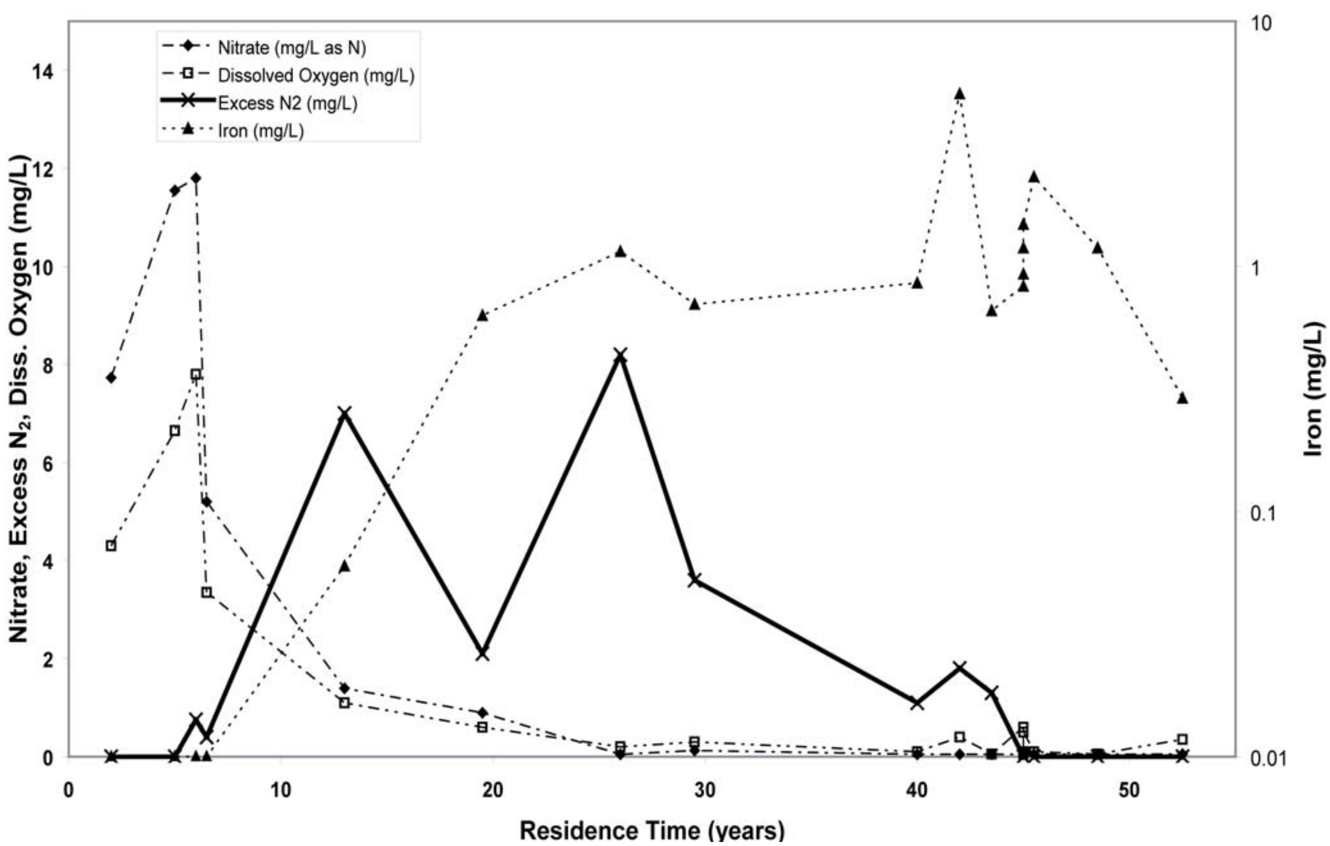
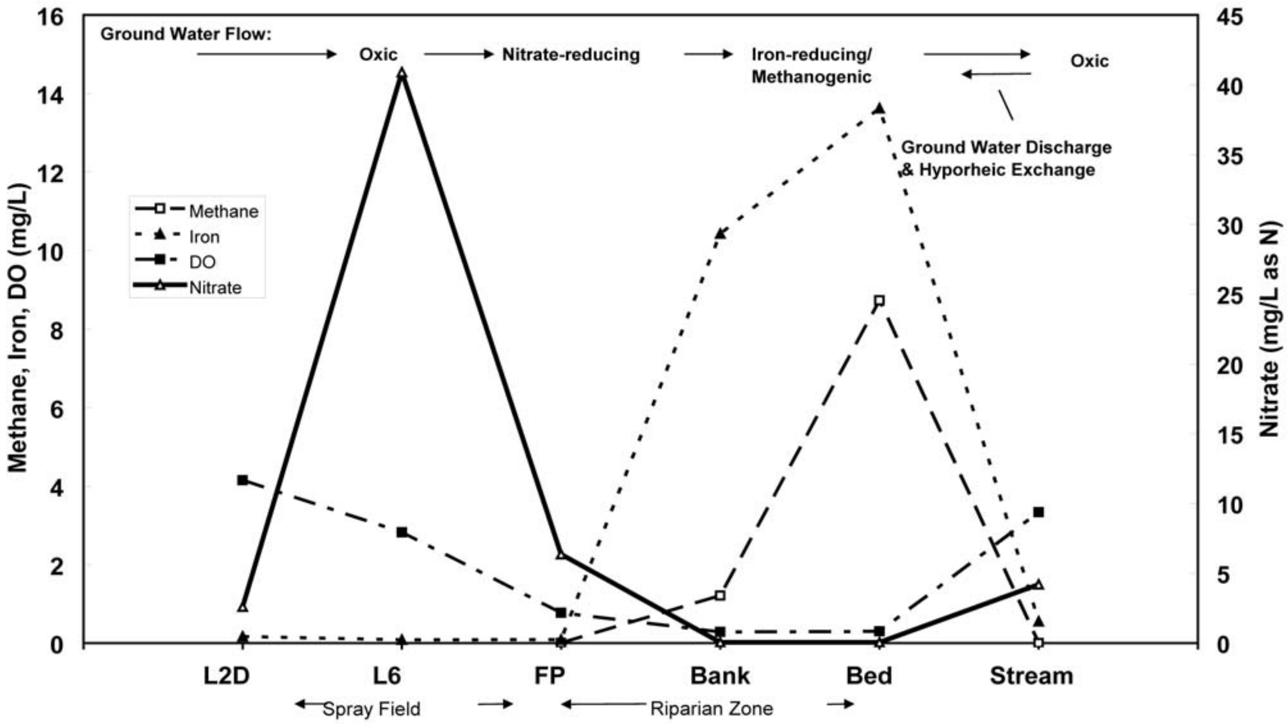


Figure 6. Redox-active species as a function of ground water residence time.



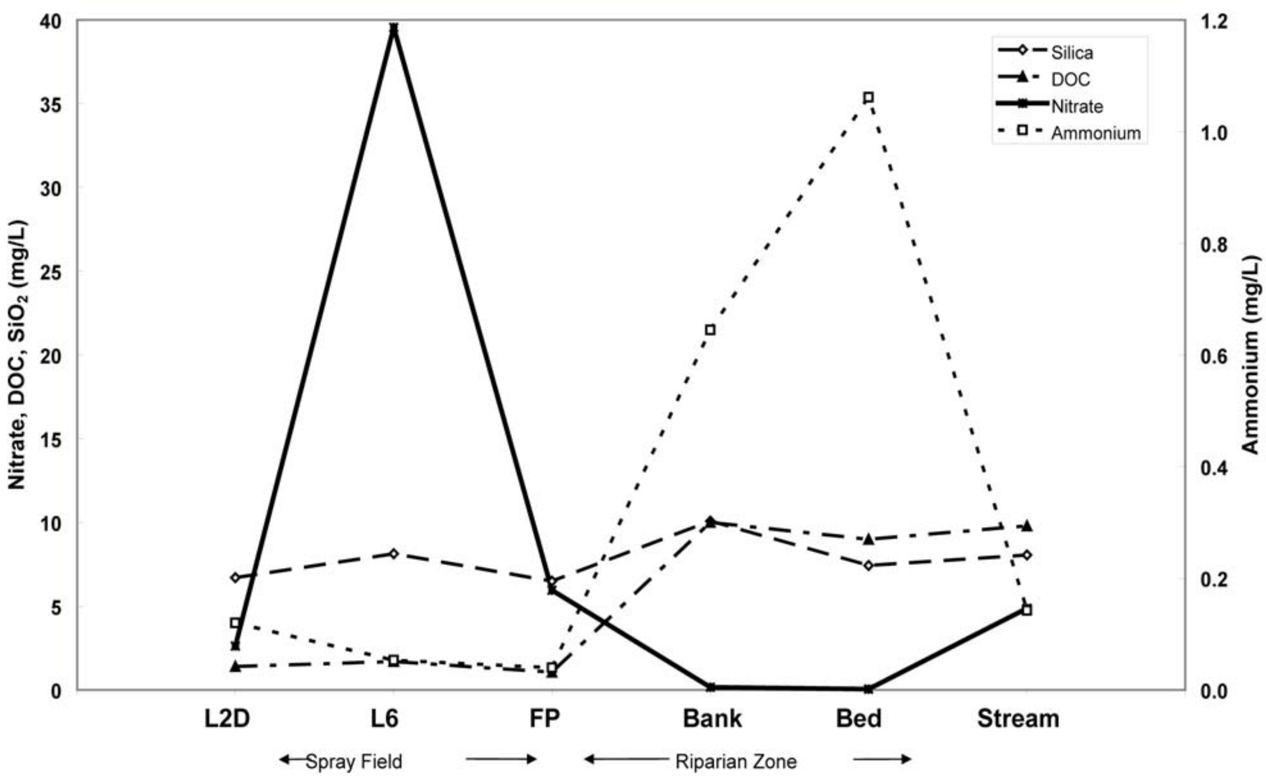


Figure 7. Top: Selected redox-active constituents along transect from L2 to Plum Tree Branch near FP site (see Figure 1). Bottom: Nitrate, ammonium, dissolved organic carbon (DOC) and SiO_2 along the same transect.

Summary

The combined use of chemical, hydrologic, and geomorphic information has been used to examine the transport of contaminants in ground water and their pathways to surface water in a coastal plain setting in the Southeastern United States. Horizontal flow is induced by the presence of a confining unit at a shallow depth. This confining unit is cut out along drainages, thus connecting the surficial aquifer to the Yorktown aquifer. Age-dating, chemical, and piezometric data all point to horizontal flow from the surficial aquifer as the dominant source of ground water to streamflow.

With regard to contaminant transport, the upper few meters of saturated thickness of the surficial aquifer is the only region where nitrate is stable. Denitrification in deeper parts of the aquifer and in the riparian zones is indicated by a characterization of redox conditions in the aquifer and by the presence of excess levels of N_2. Direct ground water discharge of nitrate to surface water during baseflow conditions is unlikely to be significant due to the strongly reducing conditions that exist in the riparian zones of these streams.

References

Böhlke, J. K., and Denver, J.M., 1995, Combined use of groundwater dating, chemical, and isotopic analyses to resolve the history and fate of nitrate contamination in two agricultural watersheds, Atlantic coastal plain, Maryland: Water Resources Research, v. 31, no. 9, p. 2319-2339.

Chapelle, F.H., P.B. McMahon, N.M. Dubrovsky, R.F. Fujii, E.T. Oaksford, and D.A. Vroblesky, 1995, Deducing the distribution of terminal electron-accepting processes in hydrologically diverse groundwater systems: Water Resources Research, v. 31, p. 359-371.

Dunkle, S.A., L.N. Plummer, E. Busenberg, P.J. Phillips, J.M. Denver, P.A. Hamilton, R.L. Michel, and T.B. Coplen, 1993, Chlorofluorocarbons (CCl_3F and CCl_2F_2) as dating tools and hydrologic tracers in shallow groundwater of the Delmarva Peninsula, Atlantic Coastal Plain, United States: Water Resources Research, v. 29, p. 3837-3860.

Glasgow, H.B. and J.M. Burkholder, 2000, Water quality trends and management implications from a five year study of a eutrophic estuary: Ecological Applications, v. 10, p. 1024-1046.

Haven, W.T., 2003**,** Introduction to the North Carolina Ground Water Recharge Map: Ground Water Circular Number 19, N.C. Department of Environment and Natural Resources, Division of Water Quality, Groundwater Section.

Heaton, T.H.E. and J.C. Vogel, 1981, “Excess air” in groundwater: J. of Hydrol., v. 50, p. 201-216.

Mew, H. E., Jr., D.K. Hirth, D. V. Lewis, R. B. Daniels, and A. J. Keyworth, 2002, Methodology for compiling Groundwater Recharge Maps in the Piedmont and Coastal Plain Provinces of NC, Groundwater Bulletin Number 25. Groundwater Section, Division of Water Qulaity, NC Department of Environment and Natural Resources, Raleigh, NC.

Scanlon, T.M., J.P. Raffensberger and G.M. Hornberger, 2001, Modeling transport of dissolved silica in a forested headwater catchment: implications for defining the hydrochemical response of observed flow pathways: Water Resources Research*,* v. 37, p. 1071-1082.

Tesoriero, A.J., H. Liebscher, and S.E. Cox**,** 2000, The mechanism and rate of denitrification in an agricultural watershed: Electron and mass balance along ground water flow paths: Water Resources Research, v. 36, no. 6, p. 1545-1559.

Carolina Geological Society
Annual Field Trip
November 14-16, 2003

Modeling to Evolve Understanding of the Shallow Ground Water Flow System Beneath the Lizzie Research Station, North Carolina

S.R. Kraemer, *US Environmental Protection Agency*
Timothy B. Spruill, *U.S. Geological Survey*
Anthony J. Tesoriero, *U.S. Geological Survey*
H.E. Mew, Jr., *North Carolina Division of Water Quality*
Kathleen M. Farrell, *North Carolina Geological Survey*

Introduction

Analytical solutions of subsurface geohydrology are useful tools for building understanding of aquifer flow systems. The step-wise approach, in starting with a clear problem statement, and progressing from simple conceptualizations to sufficient complexity as understanding evolves, has been shown to be a good modeling practice. Examples of the approach can be found in the area of capture zone delineation [Kraemer et al.,2003] and groundwater-lake interactions [Hunt et al., 2003]. Analytic element models are well suited for a step-wise approach because of their physical intuitiveness (each element represents a geohydrologic feature) and grid/mesh independence. The real challenge is the question of sufficient conceptual complexity, and how do we objectively measure the approach to this point? While this subject draws upon the art of good modeling practice, a possible practical approach is to evolve the conceptual model just beyond the sufficient complexity in order to answer the problem at hand. That is, additional complexity does not improve the explanatory value of the model given the observations. Granted, this exercise may require more complexity than the currently available analytic element solutions. If that is the case, then analytic element solutions can be used to pre-condition finite difference grids or finite element meshes for more complex simulations. This paper will demonstrate the step-wise approach applied to the understanding of a multi-aquifer system.

It is important to note the distinction between modeling for conceptual understanding, and simulation modeling for prediction. The goal of predictive modeling usually involves the search for a unique parameter set that best calibrates the model to the observed data, given a conceptual model. The goal of modeling for understanding is to establish the conceptual model from competing hypotheses, and capture the essence of the system. For example, is the aquifer best characterized by an equivalent porous medium or by a discrete fracture flow system, or some combination of the two? Or is the aquifer best characterized as stratified or multi-layered? The choice is assisted by comparison of overall model performance to field observations. Once the conceptual model is established, parameter estimation can begin in earnest.

The study area for testing our understanding is located in the shallow middle Coastal Plain aquifer system of the Neuse River basin near the city of Lizzie in Greene County, North Carolina, USA. (Figure 1). The Lizzie Research Station is located on an active and privately owned hog farm and hosts multiple groups investigating the assimilation of sprayed liquid hog waste and associated nutrients on subsurface water quality, nearby surface water quality, and local air emissions [Mew, Spruill, 2000], [USEPA, 2003]. Excess nitrogen drainage is a suspected contributing factor in the occurrence of harmful algal blooms in the Neuse River estuary. The establishment of a quantitative relationship between land use loadings and water quality standards in the rivers and estuary is a part of the load allocation of the state of North Carolina TMDL (total maximum daily load) regulatory program.

The purpose of the modeling effort presented here is to evolve a conceptual model of ground-water flow at the Lizzie site using analytic solutions and field observations. The resulting analytic element parameterization of boundary conditions, aquifer transmissivities, confining layer resistance, and areal recharge distribution will be the foundation for more detailed simulations of water quality, and the potential extrapolation to knowledge of ground-water flow at the watershed scale.

Lizzie conceptual model

The Lizzie site is located on the south side of Sandy Run, which drains to the Middle Swamp catchment (140 km^2). See Figures 1 and 2. The area is bounded by Little Contentnea Creek to the north and east and Contentnea Creek to the west and south. An unnamed tributary of Sandy Run (locally known as Plum Tree Branch) drains the west side of the Lizzie site. The area around the Lizzie site is characterized by broad, somewhat-poorly to well-drained

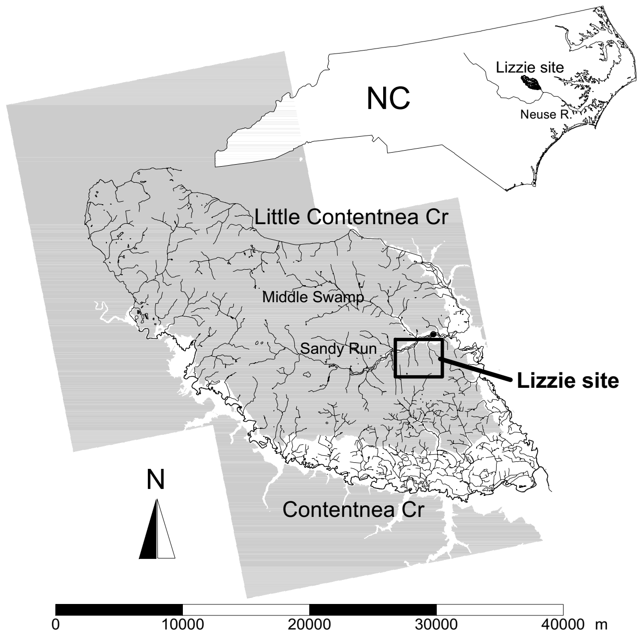


Figure 1. The study region in the middle Coastal Plain of North Carolina. The shaded region approximates the topographic transition between the alluvium and the uplands.

upland flats 22-24 m above mean sea level. The transition from upland flat to the alluvium in the major stream drainages is represented in the land topography by terraces, which occur around elevation 16 m at the Lizzie site. The alluvium consists of mixed sand and clay. The soils at the Lizzie site are sandy loam and loamy sand.

A detailed stratigraphy model of the Lizzie site and the Little Contentnea Creek basin is under development [Farrell and Mew, 2001], [Farrell and Mew, 2003]. The unconfined surficial aquifer is composed of post-Pliocene fine to medium sand and mud deposits extending to a depth of 6-9 m beneath the upland flats. The Yorktown semi-confining layer, 2-6 m thick, separates the surficial aquifer from the Yorktown aquifer. The Yorktown aquifer, <0.5-10 m thick, overlies the Peedee confining unit, and is composed of fine to coarse shelley-sand. Pumping tests report the transmissivity of the Yorktown aquifer ranges from 9.3 to 106.5 m^2/day, and the transmissivity of the Sandy Run alluvium at 232.5 m^2/day [Mew et al., 1999]. A geologic cross section along A-A' (Figure 2) based on drilled cores is shown in Figure 3(a).

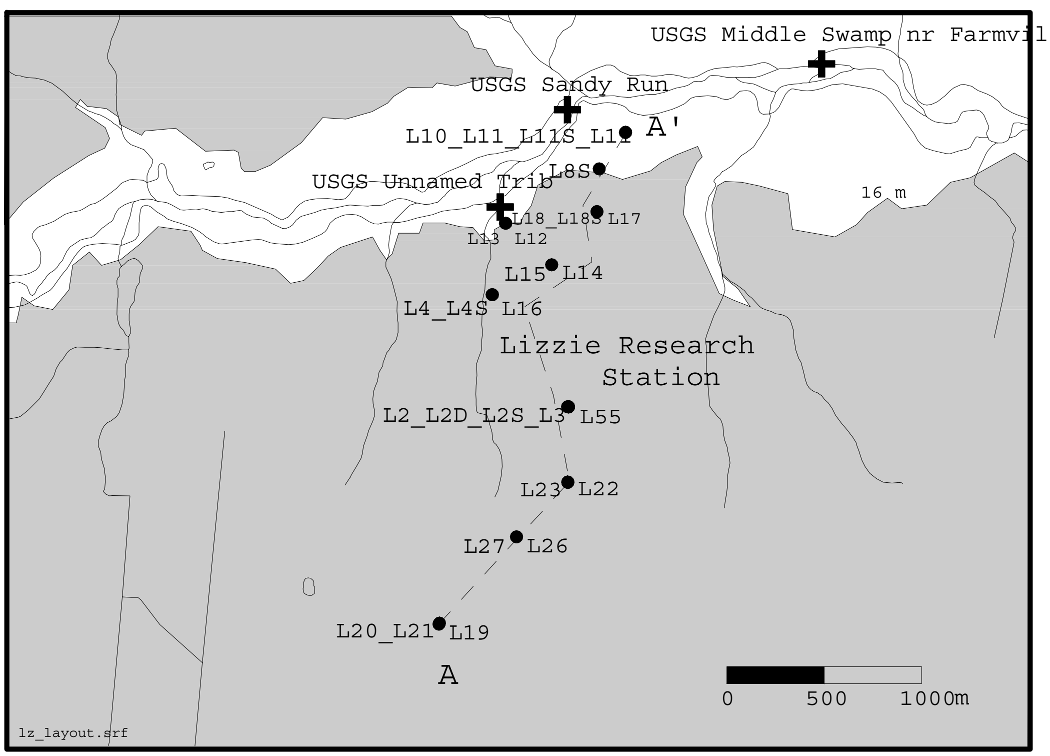


Figure 2. The Lizzie Research site, monitoring well clusters (filled circles), and USGS stream gages (plus symbols). Wells screened in the surficial aquifer are listed to the left of the symbol; wells screened in the Yorktown aquifer are listed to the right. Cross section A-A' is shown as dashed line.

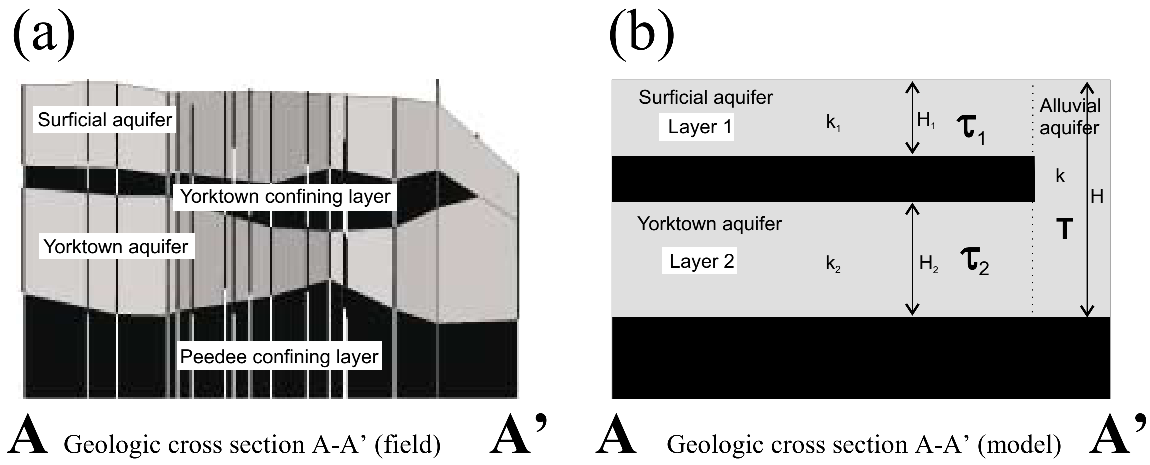


Figure 3. (a) The geologic cross section based on core logs (vertical exaggeration 50x). (b) The model idealization. Each aquifer layer has a constant transmissivity.

The US Geological Survey(USGS) has been monitoring water levels at the Lizzie site and nearby stream flow for the period 1999-2003. The water level observation selected for this study includes 18 wells; 10 wells are screened in the surficial aquifer and are labeled to the left of the points in Figure 2; 8 nested wells are screened in the Yorktown semi-confined aquifer and are labeled to the right of the points in Figure 2. The conceptual model of the Lizzie flow system emerging from the field work challenges explanation [Tesoriero et al., 2003]. Apparently, even though the surficial and Yorktown aquifers are expected to have similar transmissivities (with the Yorktown having slightly greater transmissivity), most of the water in the alluvium deposits of Sandy Run is of water type associated with the surficial aquifer (Figure 4). Also, the streamlines that would fit the piezometric head data and the chlorofluorocarbon (CFC) age dating along cross section A-A' require a significant dip into the alluvium upon leaving the upland terrace. See Figures 5 and 6. How does this aquifer flow system work? We begin the step-wise approach.

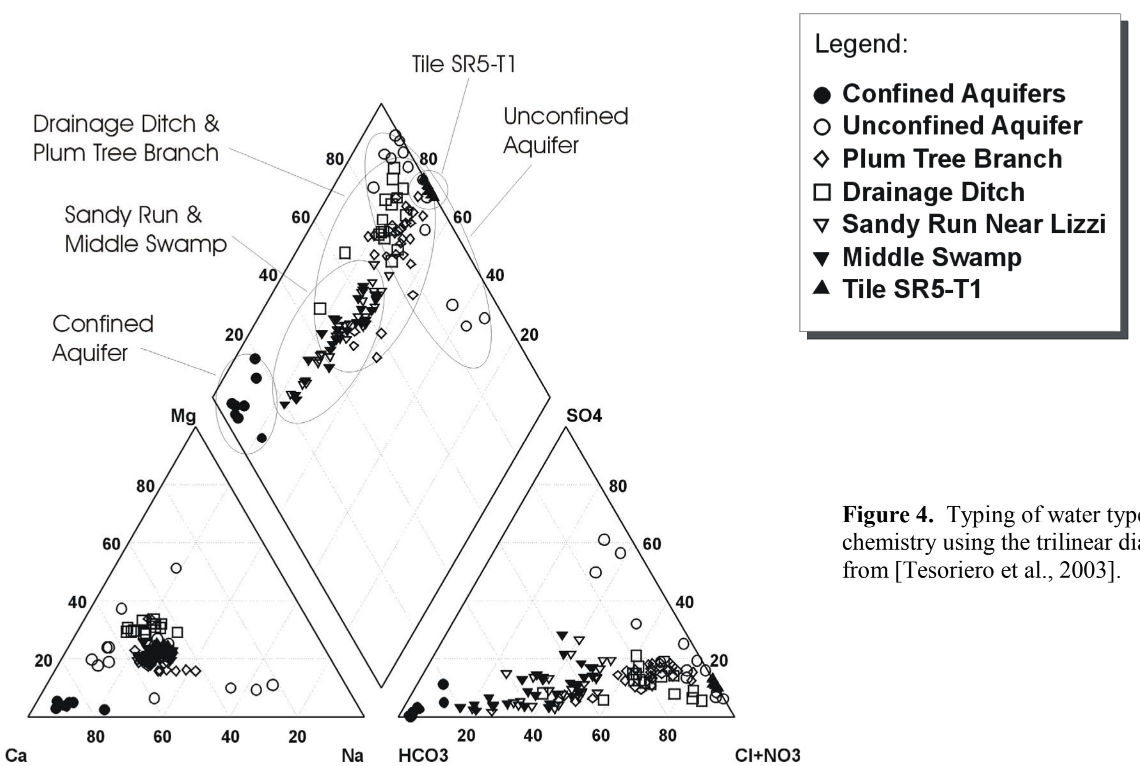


Figure 4. Typing of water types by chemistry using the trilinear diagram, from [Tesoriero et al., 2003].

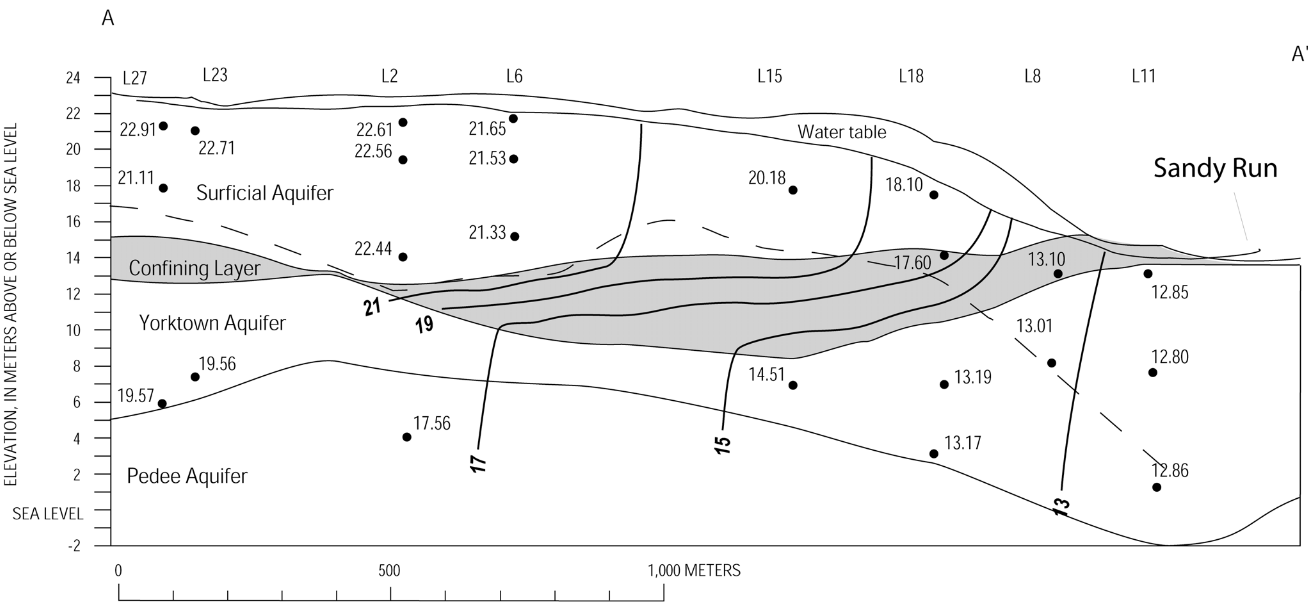


Figure 5. Hydraulic head contours along cross section A-A' , from [Tesoriero et al., 2003].

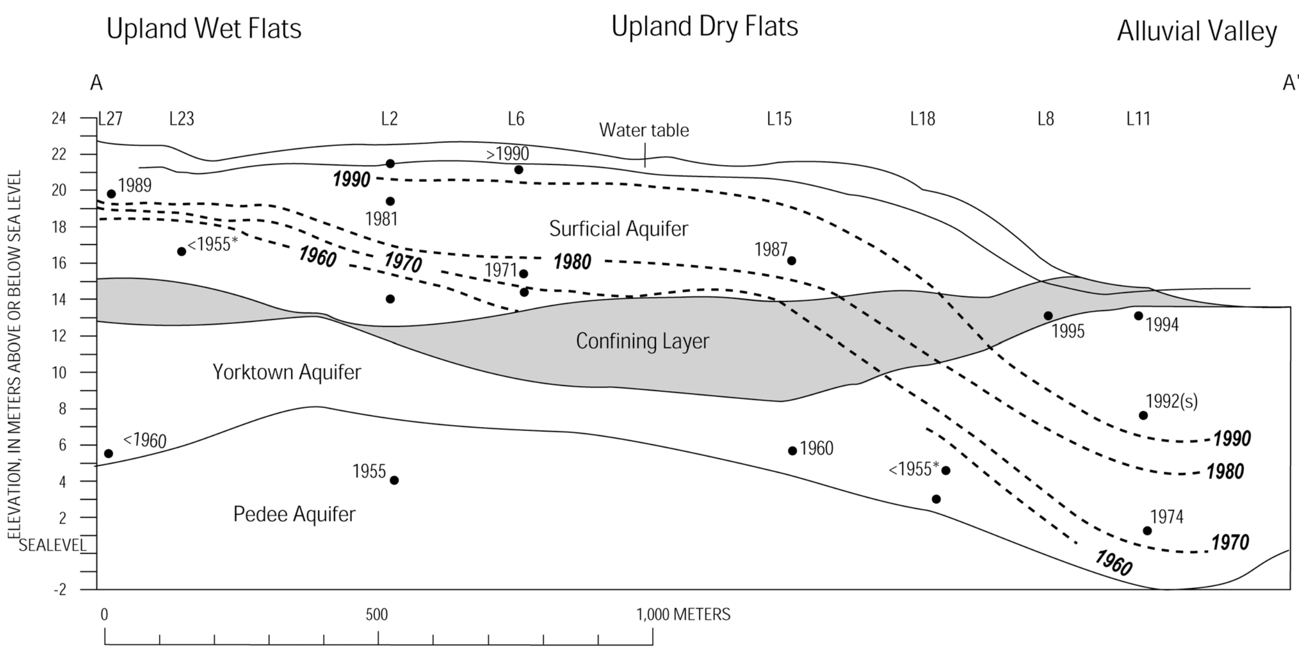


Figure 6. Age of recharge waters (in years) from CFC data along cross section A-A', from [Tesoriero et al., 2003].

Back-of-the-envelope analyses

A simple dimensionless parameter is available for assisting in the justification of steady state analysis [Haitjema,1995], [Townley,1995]. If the dimensionless factor

$$\frac{SL^2}{TP} > 1$$ use a steady-state model with average boundary conditions and recharge rates. If

$$0.1 < \frac{SL^2}{TP} < 1$$ use a transient model with transient boundary conditions and recharge rates. If

$$\frac{SL^2}{TP} < 0.1$$ use a steady-state model with instantaneous boundary conditions and recharge rates, for instance, representing summer and winter conditions where S (-) is the aquifer storativity, L (m) is the average half distance between surface waters, T (m^2/d) is the transmissivity, and P (d) is the period of the rainfall forcing function (365 days for seasonal fluctuations). Pumping tests estimate S=2.2e-4 in the surficial aquifer and S=2.2e-4 to 3.0e-4 in the Yorktown aquifer [Mew et al.,1999]. Transmissivities are reported above. The estimated half distance L=500m. The resulting characteristic parameter SL^2/TP is much less than 0.1 for each of the units, suggesting steady-state analysis is justified at Lizzie, and bounding steady state solutions are reasonable approximations of the hydrologic extremes. The well hydrograph response is clearly dampened based on the rainfall forcing at Lizzie, as is shown in Figure 7. Base flow separation of the USGS daily stream flow data at Middle Swamp gage (2091736) for 2000-2002 (Figure 7) using the PART program [Rutledge, 2002], and using a drainage area of 132 km^2 (51 square miles), yields an estimated recharge rate of N = 0.231 mm/d.

(a)

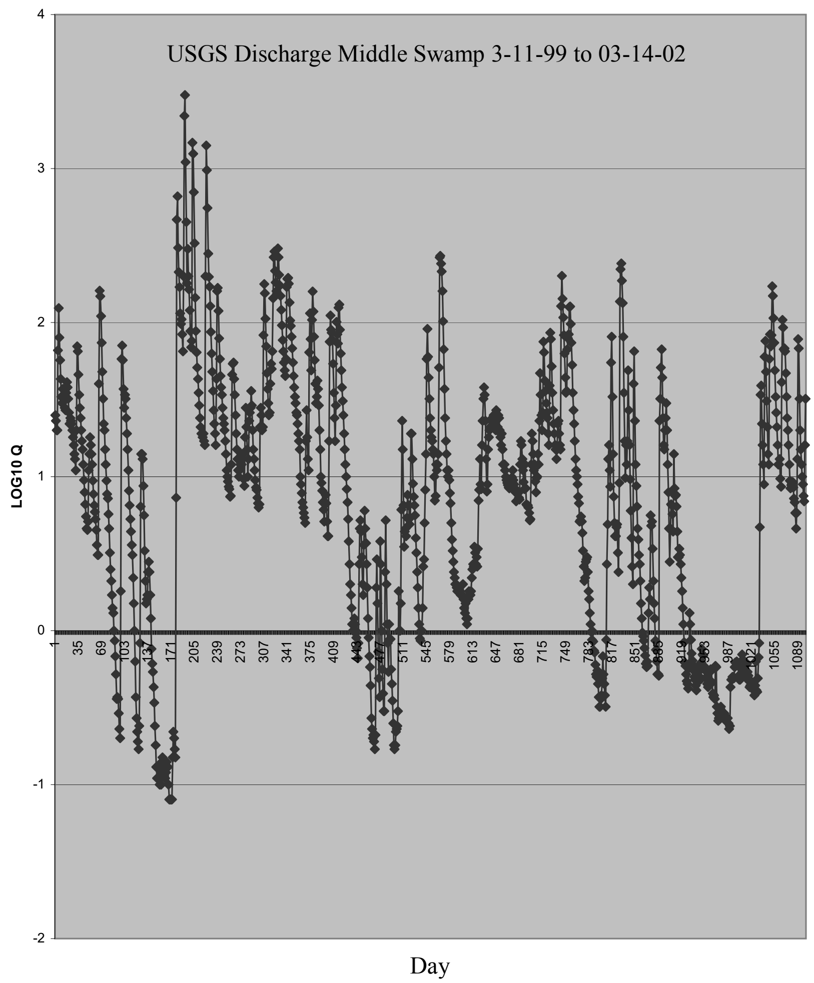


Figure 7. Lizzie hydrographs for period 11 March 1999 to 14 March-2002: (a) log discharge (m^3/d) at USGS gage at Middle Swamp; (b) heads (m above mean sea level) at nested pairs L2/L55 and L18/L17.

(b)

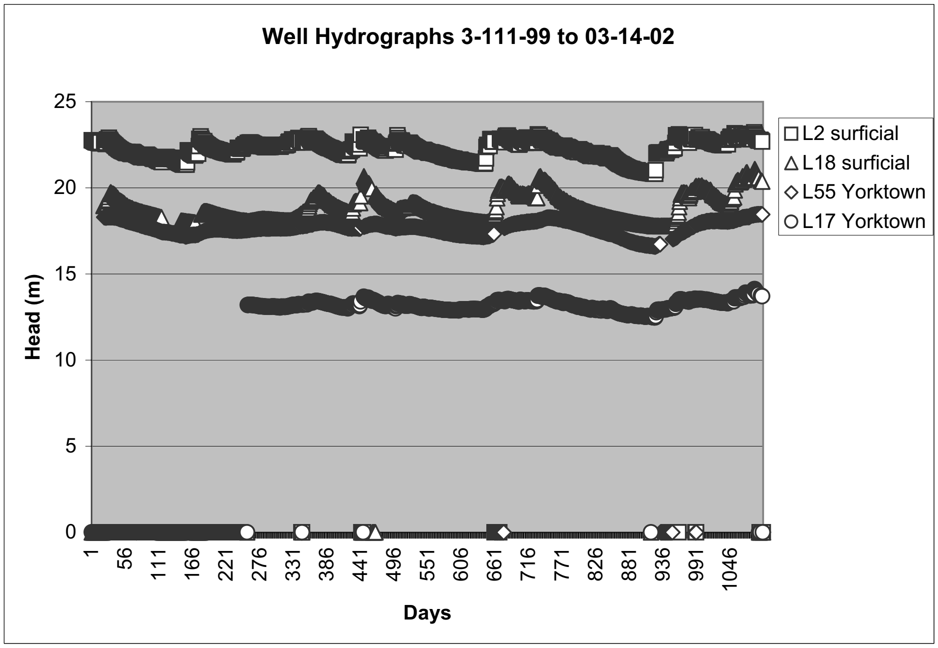


Figure 7. Lizzie hydrographs for period 11 March 1999 to 14 March-2002: (a) log discharge (m^3/d) at USGS gage at Middle Swamp; (b) heads (m above mean sea level) at nested pairs L2/L55 and L18/L17.

Perhaps focused recharge in the alluvium might be responsible for pushing the streamlines down as inferred from the field data. A simple 1D analysis can show the ratio between the alluvium recharge and the uplands recharge needed to have an observed depth of penetration of the dividing streamline between the recharge over the alluvium and the recharge from the uplands z_o. See Figure 8. Given

$$N_1 L_1 = Q_1 + Q_2; \quad N_2 L_1 = Q_2; \quad N_s L_s = Q_s \tag{1}$$

where N_1 is the recharge rate (m/d) from the uplands, N_2 is the leakage rate (m/d) through the Yorktown semi-confining layer, N_s is the recharge rate (m/d) from the alluvium, Q_i are the discharge vectors for the respective zones (flow per unit width) (m^2/d), L_1 (m) is the distance along A-A' between the ground water divide and the alluvium/uplands transition, L_s (m) is the distance from the alluvium/uplands transition to the stream, the dividing streamline depth z_o (m) over the saturated thickness H (m) is estimated from continuity of flow,

$$\frac{z_o}{H} = \frac{Q_1 + Q_2}{Q_1 + Q_2 + Q_s} = \frac{N_1 L_1}{N_1 L_1 + N_s L_s} \tag{2}$$

and therefore,

$$\frac{N_s}{N_1} = \frac{H}{z_o}\left(1 - \frac{z_o}{H}\right)\frac{L_1}{L_s} \tag{3}$$

If $z_o / H \approx 0.5$ at the Lizzie site, as suggested by Figure 6, then

$$\frac{N_s}{N_1} = \frac{L_1}{L_s} \tag{4}$$

Plugging in the following estimates for $L_1 = 3710$ m and $L_s = 525$ m, we get $N_s / N_1 = 7.07$. This implies we would need 7 times the upland recharge over the alluvium to push the streamline down to half the aquifer thickness. This recharge distribution would not be consistent with the distribution estimated by NCDENR as shown in Figure 9, where recharge is expected to be 4.5 times greater in the uplands based on soil types and geomorphology [Mew et al.,2003]. This difference will be examined later in the paper using the analytic element methods.

Another calculation reveals the expected leakage between the surficial and the Yorktown aquifer,

$$N_2 = \frac{\tau_2}{\tau_1 + \tau_2} N_1 \tag{5}$$

where τ_1, τ_2 (m^2/day) are the transmissivities of the surficial aquifer and the Yorktown aquifer, respectively. If we assume the transmissivities are equal, we expect the leakage N_2 to be half of the upland recharge N_1.

The back-of-the-envelope analyses provide insight. In the next section we will advance the conceptual model using analytic element tools.

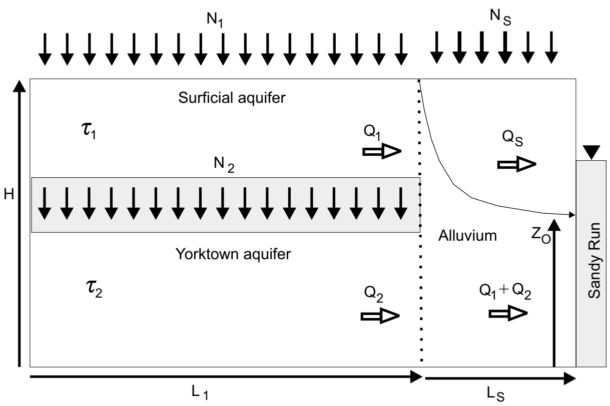


Figure 8. Simple conceptual model of the dividing streamline of recharge waters over the alluvium from recharge over the uplands.

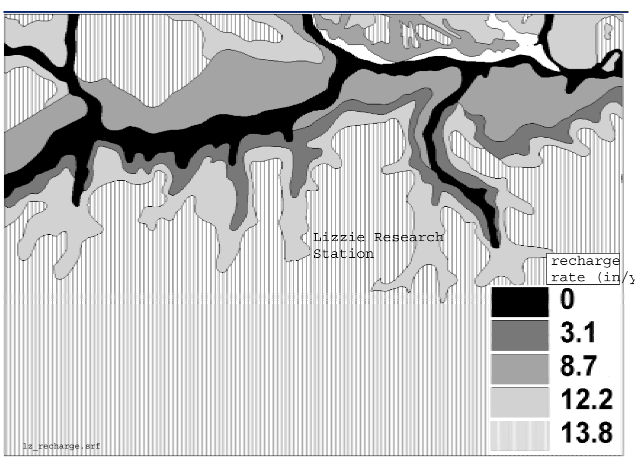


Figure 9. Map of potential recharge for the Lizzie site, from [Mew et al., 2003].

Analytic Element Methods

We will first use the single-layer steady-state analytic element model GFLOW1 [Haitjema, 2003] and calibrate to a single transmissivity, variable recharge conceptual model. The calibration targets, or test points, are the observed average "comprehensive" heads at each of the monitoring well nests, $\phi_c = \dfrac{\tau_1\phi_1 + \tau_2\phi_2}{\tau_1 + \tau_2}$ where ϕ_1 is the piezometric head and τ_1 is the transmissivity in the surficial aquifer, and ϕ_2 is the head and τ_2 the transmissivity in the Yorktown semi-confined aquifer. In the single-aquifer zone associated with the alluvium, the comprehensive head is equal to the average piezometric heads from the surficial and Yorktown elevations at the well. In the two-aquifer zone beneath the uplands, and assuming for now the transmissivities of the surficial and Yorktown aquifers are equal, the comprehensive head is the average of heads ($(\phi_1 + \phi_2)/2$). The conceptual model is shown in cross section in Figure 3b.

The representation within GFLOW1 is intended to capture the influence of regional boundary conditions on the local flow system. The perennial surface water features are assumed in perfect communication (i.e., no resistance to flow) with the aquifer and are represented with line-sinks. The head at the center of the line-sink is fixed to the stream level. Stream levels are approximated from points where topographic contour lines cross the stream channel on 7.5 minute USGS maps and are interpolated in between.

Inhomogeneity polygon elements provide piece-constant areal recharge, which can be superimposed. The recharge to the alluvium and the far field (N_s) is supplied by an inhomogeneity polygon in the form of a circle that encompasses the domain. The recharge to the upland flat area ($N^* = N_1 - N_s$) is represented by an inhomogeneity polygon element superimposed within the recharge circle polygon. The layout of elements is shown in Figure 10.

The GFLOW1 model was manually calibrated by varying the regional transmissivity and the recharge rates. The objective was to minimize the residual error between model predicted and observed comprehensive heads at the Lizzie site, and to have the streamline along cross section A-A' that started at the top of the aquifer at the contact between the uplands and alluvium to dive about half the aquifer thickness. A regional transmissivity of $T = 74.55$ m^2/d gave the smallest residual error. A ratio of $N_s/N_1 = 1.5$ satisfied the diving streamline criteria. Maps of the gridded hydraulic head contours are shown in Figures 10 and 11. The residual errors (model-observed head) are shown besides each well nest in Figure 11. The calibration statistics are graphed in the insert of Figure 11 and summarized in Table 1. Reverse streamlines released from the bounding tributaries define the "catchment" of the Lizzie site, as shown in Figure 11. Forward streamlines released from the top of the surficial aquifer at the alluvium/uplands transition are shown in Figure 12. The depth of aquifer penetration (z_o/H) is indicated alongside the tic marks of the central streamlines. It is interesting that only a slightly greater recharge in the alluvium than the uplands was needed to satisfy the dipping streamline criteria ($N_s/N_1 = 1.5$), when the 1D analysis of the previous section predicted the need for 7 times the recharge.

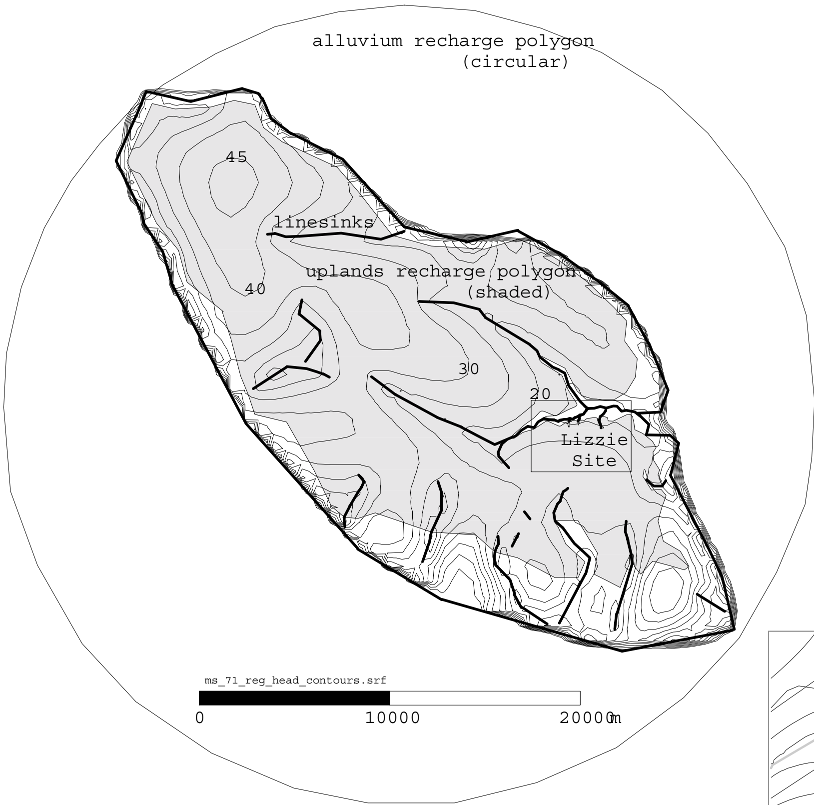


Figure 10. (left) Regional layout of analytic elements and grid of hydraulic head contours (m) from the GFLOW1 model. Far field heads are not shown.

Figure 11. (below) Local layout of analytic elements and grid of hydraulic head contours (m) from the GFLOW1 model. The residual errors (m) are reported beside each monitoring well, and the calibration statistics are mapped in the insert. Reverse streamlines (dashed lines) from the side tributaries define the Lizzie "catchment".

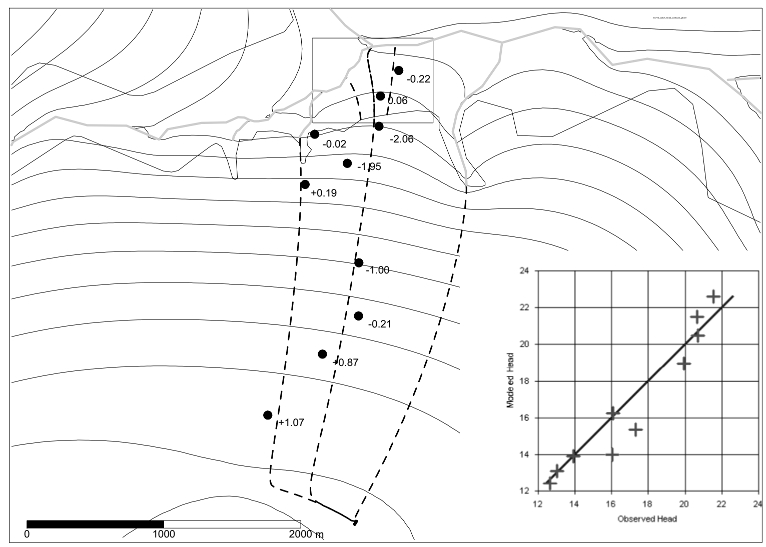
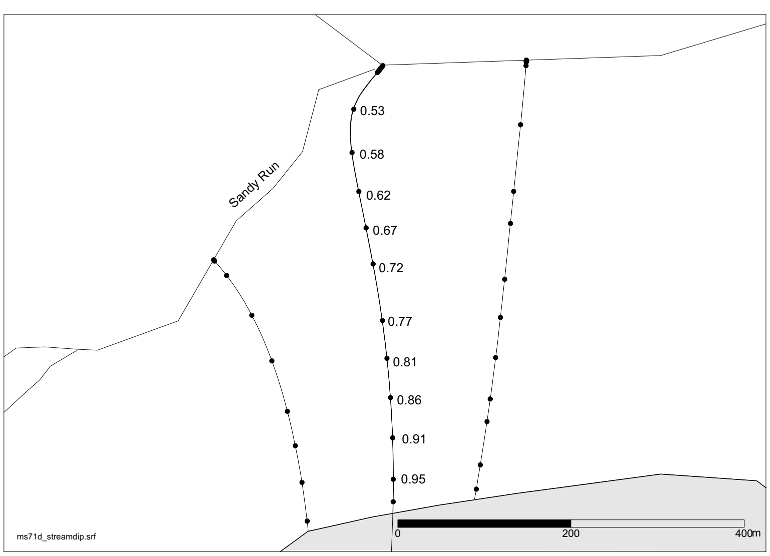


Figure 12. (below) Forward tracelines released at the top of the surficial aquifer from the GFLOW1 model, with tic marks indicating depth of aquifer penetration (reported as ratio z_o/H).



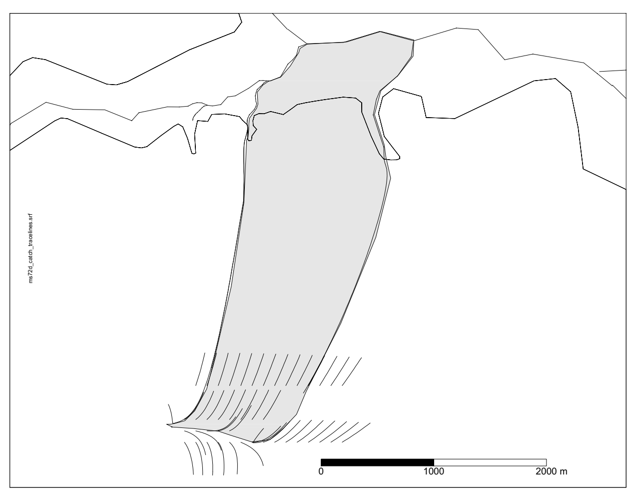


Figure 13. Tim^{ML} traces in the Yorktown (aquifer 2). The traces help to refine the definition of the Yorktown subsurface catchment of the Lizzie site.

Property Name	Symbolic	Result
Transmissivity, single layer (m^2/d)	$T = k * H$	74.6
Recharge ration alluv/uplands (-)	N_s / N_1	1.5
Number of monitoring wells	w	10
Sum Sq Residuals (m^2)	$SSR = \sum_1^w (\phi_{model} - \phi_{obs})^2$	11.0
Root Mean Sq Error (m)	$RMSE = \sqrt{SSR / w}$	1.1

Table 1. Setup and results of the GFLOW1 calibration.

However, inspection of Figure 12 reveals the divergence of streamlines which invalidates the 1D flow assumption. The modest divergence at this location is enough to get deep penetration of streamlines into the Sandy run alluvium.

We solve for two-aquifer flow in the uplands using the analytic element model Tim^{ML} [Bakker, 2003a,b]. The solution accounts for the vertical leakage between the surficial (aquifer 1) and the confined Yorktown (aquifer 2) based on a constant resistance c (days). We estimated the resistance c to be equal to 32,466 days based on the observed head differences and semi-confining layer thickness at nested well pairs. The model was calibrated using PEST [Doherty,2001] by allowing the transmissivities (τ_1, τ_2) to vary, fixing the single layer transmissivity (T_s) and the areal recharge properties (N_s / N_1) from the previous GFLOW1 solution, and minimizing the sum square of the residuals between the observed and simulated comprehensive heads in aquifer 1 and 2. The summary of the parameters and the results of the calibration are shown in Table 2.

We can use the Tim^{ML} model to delineate the subsurface catchment of the Lizzie site by forward traceline mapping, as shown in Figure 13.

Have we captured enough complexity at the Lizzie site to understand the advective flow system? Certainly we have not captured the details of the local scale stratigraphy. We will need to use the USGS finite difference model MODFLOW [Harbaugh, 2000] in order to investigate the influence of variable layer thickness and variable transmissivity.

Property Name	Symbolic	Result
Transmissivity, single layer (m^2/d)	$T = k * H$	74.6
Transmissivity, inclusion layer 1 (m^2/d)	$\tau_1 = k_1 * H_1$	43.2
Transmissivity, inclusion layer 2 (m^2/d)	$\tau_2 = k_2 * H_2$	34.3
Recharge ration alluv/uplands (-)	N_s / N_1	1.5
Resistance (d)	c	32466
Leakage Factor (m)	λ	787.7
Number of monitoring wells	w	18
Sum Sq Residuals (m^2)	$SSR = \sum_1^w (\phi_{model} - \phi_{obs})^2$	58.93
Root Mean Sq Error (m)	$RMSE = \sqrt{SSR / w}$	1.8

Table 2. Setup and results of the Tim^{ML} calibration.

MODFLOW Setup

A challenge for numerical ground-water modeling is to assign the effective spatial and temporal boundary conditions. The finite difference grid of MODFLOW requires accounting for conditions, whether constant head or flux, at active cells on the boundary. Ideally, these boundary cells correspond with real hydrogeologic features, such as rivers or impermeable contacts, but this is often not possible, especially with multi-layer aquifers. A topographic divide is not considered a real hydrogeologic boundary; it is a dynamic boundary that depends on the balance of recharge and discharge from the aquifers. The option to assign an arbitrary or artificial condition to the boundary can be justified if the boundary condition and location chosen can be shown to have no significant influence on the problem to be solved. This often involves placing the boundary far away from the local problem, and therefore stretching the grid and expending computational resources. Local grid refinement is also an option, but that requires a sophisticated modeling framework.

An alternative approach uses regional scale analytic element models to set the boundary and initial conditions for the local scale MODFLOW grid. A strength of the analytic element method is that the regional flow solution is valid in an infinite domain, with effective boundary conditions being met at internal control points associated with real hydrogeologic features. Regional analytic element solutions can pass boundary conditions, either constant head or constant flux, to an embedded MODFLOW grid, as has been demonstrated by Hunt et al. [2003] using the single layer analytic element model GFLOW1.

In addition to passing boundary conditions, the analytic element models can be used to design the MODFLOW grid, as discussed by Haitjema et al. [2001]. A leakage factor (λ) may be computed from the eigenvalues of the system matrix, which is a function of the aquifer and leaky layer properties only. The leakage factor (λ) is a characteristic length ---it has been shown that influences on the flow field (such as from pumping wells) become negligible about 4-5 times λ away from the area of interest. Also, MODFLOW cell sizes need to be about 0.1 times the characteristic length in order to properly represent leakage through the semi-confining layer. The leakage factor for the semi-confining layer in the Tim^{ML} model is $\lambda = 787.7$ m. We can use these requirements to build a 2-layer MODFLOW grid for the Lizzie site.

Imagine we superimpose four hypothetical pumping wells at the Lizzie site in our Tim^{ML} model, two in the surficial aquifer, and two in the Yorktown aquifer, each pumping 100,000 gallons per day, to provide a local disturbance to the flow field. As shown in Figure 14a,b, the influence of the wells on the hydraulic head contours in each aquifer diminishes after about 4-5 times the characteristic length away from the near field.

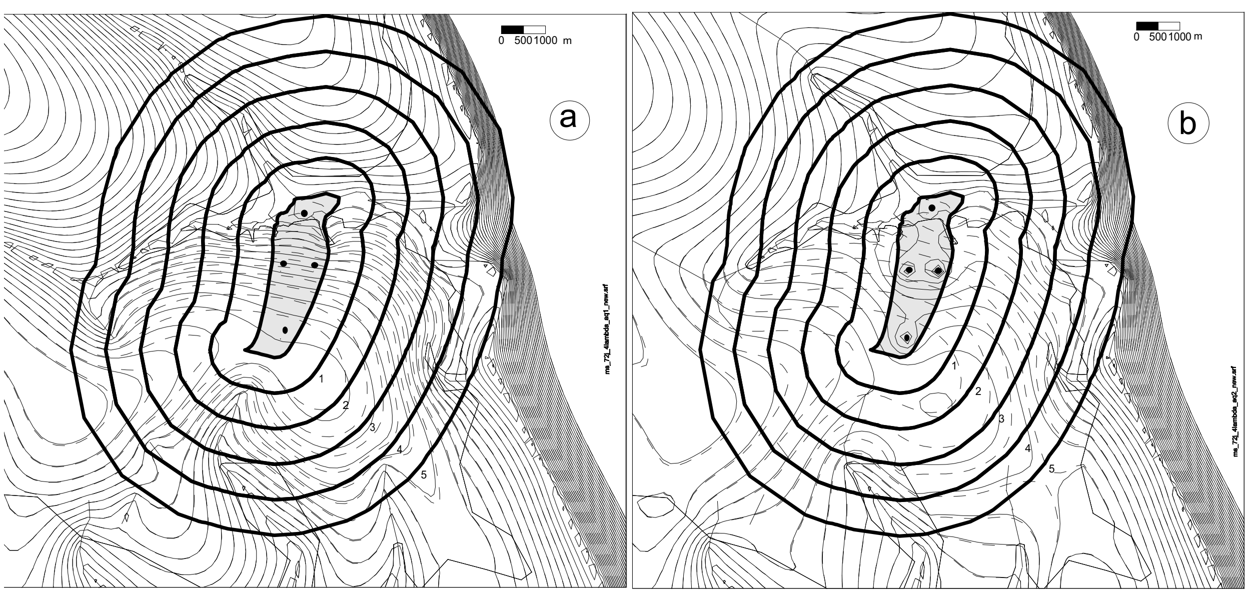


Figure 14. Tim^{ML} solution showing heads in the: (a) surficial (aquifer 1); and (b) Yorktown (aquifer 2) under the influence of hypothetical pumping wells. The solid contours are the heads under the influence of the pumping and the dashed contours are for the solution not including the pumping wells. The bold lines show buffers of 1,2,3,4, and 5 times the characteristic length away from the Lizzie Yorktown catchment

The MODFLOW grid conditioned by the analytic element solutions is shown in Figure 15. The size of the model domain and the cell size are designed based on the leakage factor. The analytic element models GFLOW1 and Tim^{ML} pass the constant head boundary conditions and initial conditions. We are now ready for MODFLOW.

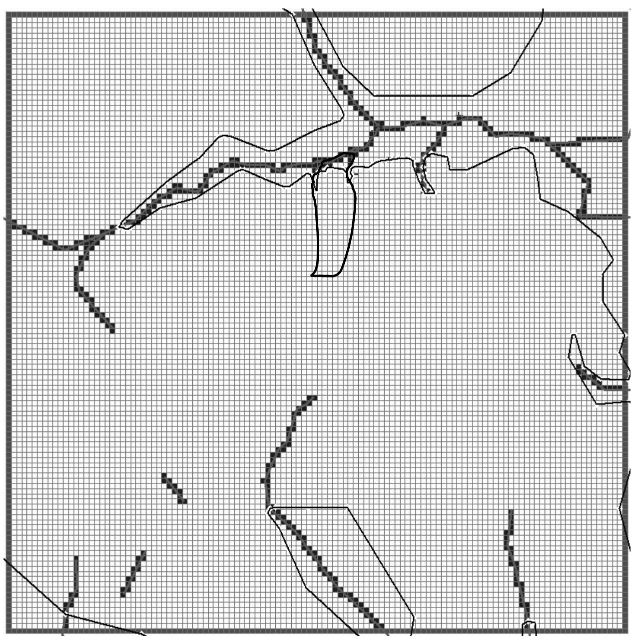


Figure 15. A two-layer MODFLOW grid (120 x 120) conditioned by the regional analytic element modeling. The cell size is 0.1 times the leakage factor. The artificial constant head boundary conditions (dark filled cells) are supplied by Tim^{ML} for both layers. The constant head rivers (lighter filled cells) are interpolated along the Tim^{ML} line sinks.

Summary

A step-wise and progressive modeling approach was demonstrated for the Lizzie site in the Middle Coastal Plain of North Carolina. The conceptual model of the subsurface geohydrologic system was evolved from simple to more complex in the pursuit of understanding, not necessarily simulation. Simple “back-of-the-envelope” calculations helped justify a steady state analysis. Analytic element modeling supports the hypothesis that increased recharge and divergent flow lines in the Sandy Run alluvium lead to the dominance of surficial aquifer water type and younger waters in the alluvial aquifer. It was also demonstrated how analytic element modeling can pre-condition a MODFLOW grid for future simulation modeling of additional complexity, such as heterogeneous stratigraphy. The detailed modeling is needed before we can conclude that the conceptual model and advective flow field has sufficient complexity for reactive transport simulation.

Acknowledgments

This paper has been reviewed in accordance with the U.S. Environmental Protection Agency's peer and administrative review policies and approved for presentation and publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

The research contained in this document has been funded in part by the United States Environmental Protection Agency under Interagency Agreement to USGS and contract to University of Georgia. The establishment of the Lizzie Research Station was funded by NCDENR, USGS, and NCGS.

The authors thank Dr. Henk Haitjema of Indiana University and Dr. Mark Bakker of the University of Georgia for their helpful comments on the modeling.

References

Bakker, M., 2003a, Tim^{ML}: A multilayer analytic element model, version 1.1, http://www.engr.uga.edu/~mbakker/timml.html.

Bakker, M., 2003b, Analytic element modeling of multi-aquifer inclusions, Ground Water, submitted .

Bakker, M., and O.D.L. Strack, 2003, Analytic elements for multi-aquifer flow, Journal of Hydrology, 271,119—129.

Doherty, J., 2001, PEST-ASP User's Manual, Watermark Numerical Computing, Bisbane, Australia, http://members.ozemail.com.au/~wcomp/index.html.

Farrell, K.M., and H.E. Mew, Jr., 2001, A geomorphic and stratigraphic conceptual model for evolving valleys and interfluves on the Coastal Plain: Little Contentnea Creek Watershed of the Neuse River Basin, North Carolina, USA. Abstract in proceedings 7th International Congress on Fluvial Sedimentology, Lincoln, Nebraska, August.

Farrell, K.M., and H.E. Mew, Jr., 2003, A geomorphic and stratigraphic conceptual model for evolving valleys and interfluves on the Coastal Plain: Little Contentnea Creek watershed of the Neuse River basin, in preparation.

Haitjema, H.M., 1995, Analytic Element Modeling of Groundwater Flow, Academic Press, 1995.

Haitjema, H.M., 2003, GFLOW2000 Modeling System version 1.3.2, Haitjema Software, Bloomington, IN, http://www.haitjema.com.

Haitjema, H.M., V. Kelson, and W. de Lange, 2001, Some cell-size selection criteria for MODFLOW, In: MODFLOW 2001 and Other Modeling Odysseys Vol I, International Ground Water Modeling Center, Golden, CO, 96-97.

Harbaugh, A.W., Banta, E.R., Hill, M.C., and McDonald, M.G., 2000, MODFLOW-2000, the U.S. Geological Survey modular ground-water model -- User guide to modularization concepts and the Ground-Water Flow Process: U.S. Geological Survey Open-File Report 00-92, 121 p.

Hunt, R., M.P. Anderson, and V.A. Kelson, 1998, Improving a complex finite-diference ground water flow model through the use of an analytic element screening model, Ground Water,36(6):1011-1017.

Hunt, R., H. Haitjema, J. Krohelski, and D. Feinstein, 2003, Simulating ground water-lake interactions: approaches, analyses, and insights, Ground Water,41(2):227-237.

Kraemer, S.R., H.M. Haitjema, and V.A. Kelson, 2003, Working with WhAEM2000: source water assessment for a glacial outwash wellfield, Vincennes, Indiana, EPA/600/R-99/110, US Environmental Protection Agency Report, updated March.

Leahy, P.P., and M. Martin, 1993, Geohydrology and simulation of ground-water flow in the Northern Atlantic Coastal Plain aquifer system, USGS Professional Paper 1404-K.

Mew, H.E., Jr., 1999, Lizzie Field Guide, NC Dept. Environment and Natural Resources, Division of Water Quality, Groundwater Section, Raleigh NC.

Mew, H.E., Jr., and T. Spruill, 2000, Lizzie Research Station Pamphlet, NC Dept. Environment and Natural Resources, Division of Water Quality, Groundwater Section, Raleigh, NC, 4p.

Mew, H.E., Jr., D.K. Hirth, D.V. Lewis, R.B. Daniels, and A.J. Keyworth, 2003, Methodology for compiling ground water recharge maps in the Piedmont and Coastal Plain provinces of North Carolina, Ground Water Bulletin Number 25, N.C. Department of Environment and Natural Resources, Division of Water Quality, Ground Water Section.

Rutledge, A.T., 2002, Program User's Guide for PART, US Geological Survey, http://water.usgs.gov/ogw/part/

Tesoriero, J., T. Spruill, H.E. Mew, and K.M. Farrell, 2003, Reconstructing

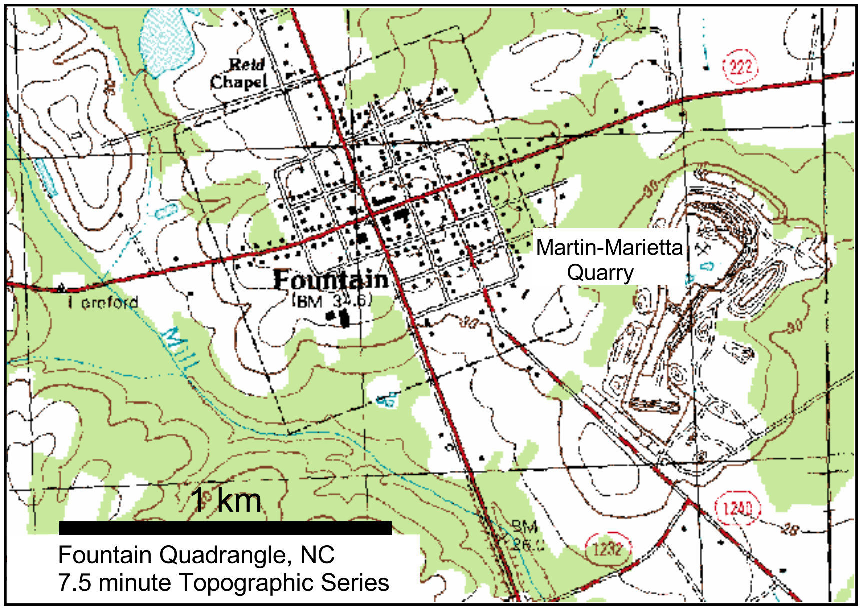
nitrogen transport and transformations using hydrologic and chemical tracers: influence of geomorphology on flow paths and residence times, submitted to Water Resources Research, summer.

Townley, L.R., 1995, The response of aquifers to periodic forcing, Advances in Water Resources, 18, 4795-4812.

USEPA, 2003, Environmental Research Brief on the Lizzie Research, in preparation.

Field Stop 1: Martin Marietta Quarry at Fountain, NC

8 a.m. Depart Sheraton on Salisbury St. in downtown Raleigh, NC; drive 3 blocks and turn left on South St; turn left on Wilmington St.; turn right onto New Bern Ave (Rt. 64E). Proceed on Rt. 64 east towards Rocky Mount. Exit onto 264E heading towards Greenville. Take exit 53 to Fountain. At end of exit ramp, turn left onto Rt. 222. Drive several miles to Fountain. At stoplight intersection of Rt. 222 and Rt. 258 in Fountain, turn right onto Rt. 258. Proceed about 1 mile, turn left onto Allen-Gay Road. Allen-Gay Road leads to entrance for Martin Marrietta Aggregates. Park at overlook.



Stop 1, Figure 1. Digital Raster Graphic that shows location of Martin-Marietta Quarry at Fountain, NC.

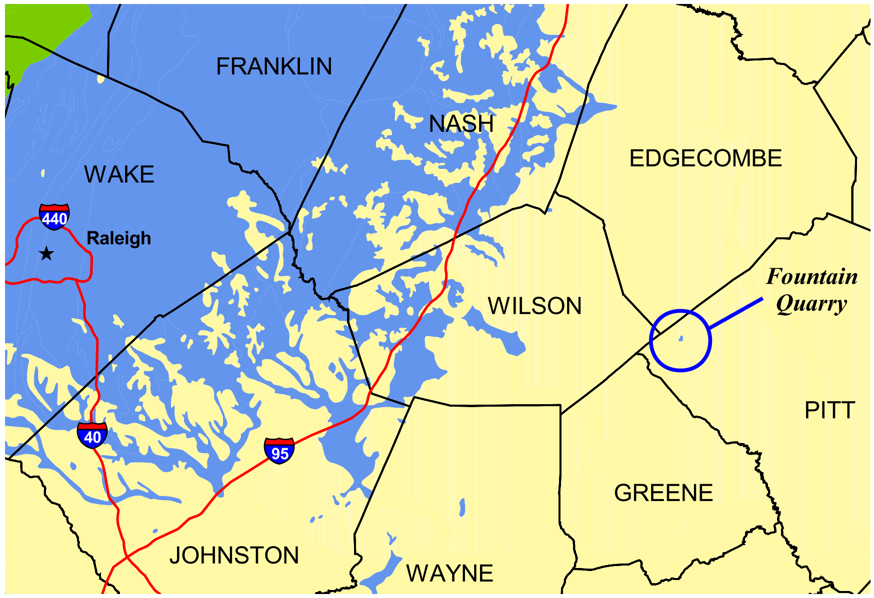
STOP 1A: Bedrock Geology of the Martin Marietta Quarry at Fountain, NC.
Leader: Tyler Clark

PURPOSE: Discuss the granite exposed in the Martin-Marietta Aggregates Quarry.

DESCRIPTION: The Fountain granite forms an elongate topographic ridge oriented in a north-south orientation, now buried by the overlying Coastal Plain sediments. This north-south orientation is parallel to both the foliation of the quarry rocks themselves and to local magnetic anomaly trends (Zietz and others, 1980). The ridge is approximately 400 m wide and over 1000 m in length. The ridge has very steep to near-vertical walls that can be clearly observed in the western portion of the quarry. Brown (1959) suggested that the Fountain granite was a buried monadnock that at one time rose over 120 m above the surrounding crystalline rocks.

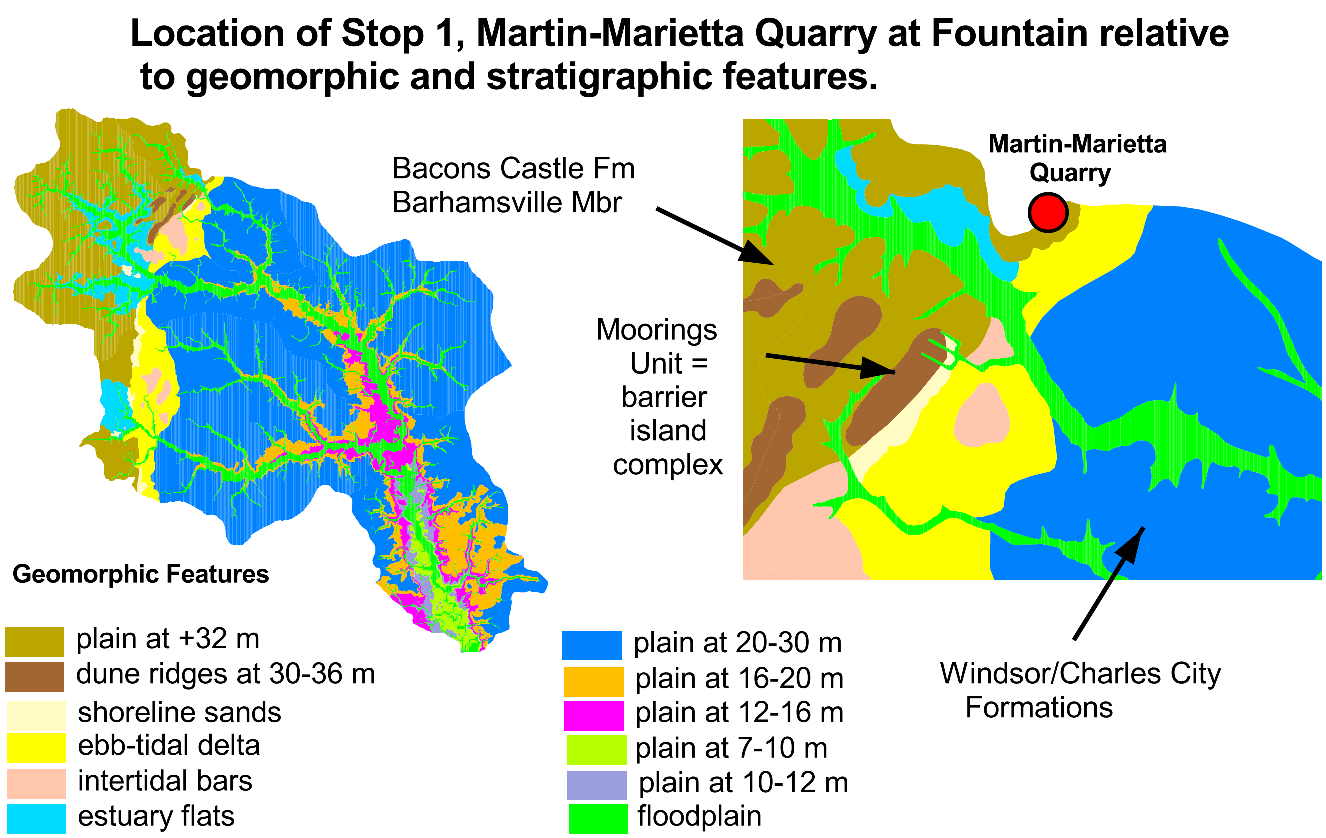
The Fountain granite was originally known by only as a small patch of surface outcrop at the present location of the quarry. Many unsuccessful attempts were made to quarry dimension stone from the site in the early half of the twentieth century (Councill, 1954). Martin Marietta later purchased the property and production of crushed stone began in 1961. Mauger and others (1983) described the majority of the bedrock geology in the Fountain quarry as medium-grained, equigranular, light-gray peralkalic metagranite. Their petrologic studies indicated that the granite contains quartz, albite, microcline, aegirine, and NaFe-amphiboles, as well as a rare Ba(Fe,Mn)Ti silicate, bafertisite. Whole rock geochemistry is similar to other silicic peralkalic igneous rocks of eastern North Carolina. They also report a high-scatter Rb/Sr whole-rock scatterchron analyses that yielded an early Paleozoic original crystallization age.

Mauger and others (1983) identified several dikes of amphibolite, metarhyolite, and basalt that cut the granite. They interpreted the amphibolite and metarhyolite dikes as intruding prior to peak metamorphic conditions. These dikes are possibility related to similar rhyolitic dikes reported by Stoddard (1983). The basaltic dikes were presumed to be Mesozoic in age, related to the rifting of the supercontinent Pangea



Stop 1, Figure 2. Geologic map (NCGS, 1985) that shows the location of the Fountain quarry in eastern Pitt County, NC. Undifferentiated Coastal Plain shown in yellow, igneous and metamorphic rocks in blue, and Triassic basin sedimentary rocks in green. Source: Geologic Map of North Carolina, 1985.

STOP 1B: Stratigraphy of the Martin Marietta Quarry. ***Leader:*** **Kathleen M. Farrell**
PURPOSE: To discuss stratigraphy at the Martin Marietta Quarry.



Stratigraphic units exposed in the quarry include the equivalents of the Yorktown Formation, the Bacons Castle Formation, and the Moorings unit. Beneath the Yorktown thin slivers of Cretaceous deposits (Cape Fear and Black Creek Formations) are exposed.

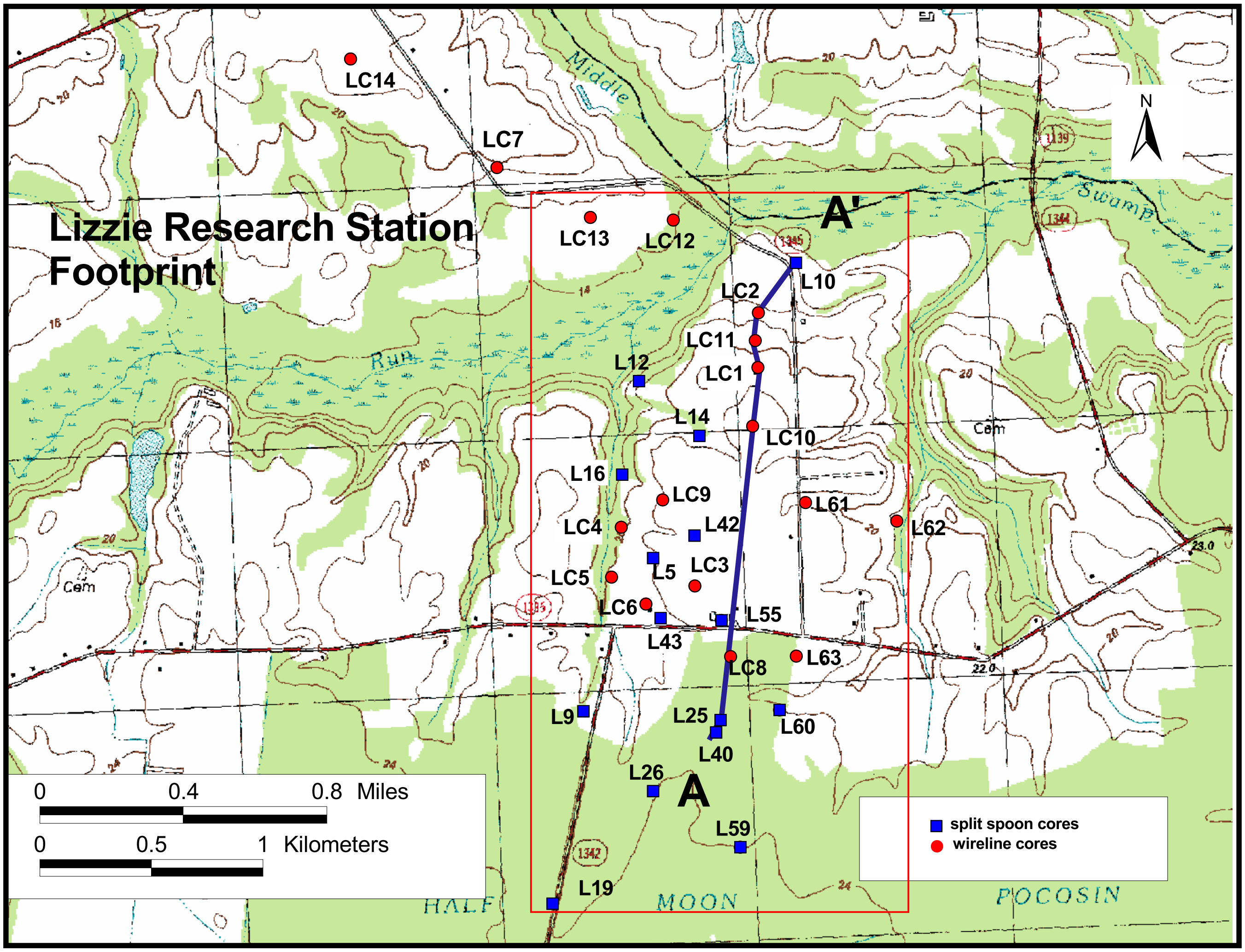
Regionally Mappable Unconformity-Bounded Unit	Approximate elevation of highstand shoreline in NC	Morphologic Expression in Little Contentnea Creek Watershed	Equivalent unit at Lizzie	Relative Age
Tabb Formation includes 3 members	**~ 9 m (30 ft)** Suffolk paleoshoreline	fluvial terraces at 7-10 m with relict meander belts.	Not Present at surface	Late (?) Pleistocene
?	?	fluvial terraces at 10-12 m with relict meander belts.	Likely buried under modern flood plain	Late middle? Or Late? Pleistocene
Shirley Formation	**~ 16 m (50 ft)** Unnamed paleoshoreline	fluvial-estuarine flats at 12-16 m	N-Unit	Late Middle Pleistocene (Johnson and Berquist, 1989 Mixon and others, 1989)
Chuckatuck Formation	**~ 20 m (65 ft)** Unnamed paleoshoreline	fluvial-estuarine flats at 16-20 m	PL-Unit	Middle Pleistocene (Johnson and Berquist, 1989 Mixon and others, 1989)
Charles City Formation	**~ 26 m (85 ft)** Unnamed paleoshoreline	dissected flats at 20-26 m; part of Wicomico plain (Daniels and others, 1984).	W-Unit	Early Pleistocene (Johnson and Berquist, 1989 Mixon and others, 1989)
Windsor Formation	**~ 30 m (100 ft)** Surry paleoshoreline	dissected flats at 26-30 m; part of Wicomico plain (Daniels and others, 1984).	Not Present	Early Pleistocene (Johnson and Berquist, 1989 Mixon and others, 1989)
Moorings Unit	**~ 35 m (115 ft)** Surry paleoshoreline	coast-parallel dune ridges at 30-36 m; part of Sunderland plain (Daniels and others, 1984)	Not Present	Late Pliocene or Early Pleistocene (Johnson and Berquist, 1989 Mixon and others, 1989)
Bacons Castle Formation Barhamsville Member	**~ 52 m* (170 ft)** Kenly paleoshoreline	highly dissected flats at +32 m; part of Sunderland plain of Daniels and others (1984).	Not Present	Late Pliocene (Johnson and Berquist 1989; Mixon and others, 1989) (1.8-2.05 ma, Krantz, 1991)
Yorktown Formation - Morehouse Member?/ (Chowan River Formation?)	**~ 75 m** (246 ft)** Wilson Mills paleoshoreline	None	CR-Unit	Late Pliocene (3.0-3.2 ma?; Krantz, 1991)
Yorktown Formation Morgarts Beach Member Rushmere Member	**~ 84 m** (275 ft)** Coats/Orangeburg paleoshoreline	None	Ty-4 Ty-3	Pliocene 4.0-3.2 ma Krantz, 1991
Yorktown Formation (?) Unnamed Member	**~ 84 m** (275 ft)** Coats/Orangeburg paleoshoreline	None	Ty-2	Pliocene (?)

* highstand estimate from Ramsey (1987, 1988)
** toe elevation from Daniels and others (1984); (toe elevations may be lower than actual highstand position).

Figure 13. Regionally correlated unconformity bounded units: from the Virginia map (Mixon and others, 1989) to Little Contentnea Creek Watershed.

Field Stop 2: The Lizzie Research Station, near Farmville, NC.

At 1 pm, exit the Martin-Marietta Quarry by turning left onto Rt. 258 towards Farmville. In downtown Farmville, follow signs for Rt. 258: turn left on Rt. 264A/258, go 0.5 miles and turn right onto Rt 58S; proceed 3.0 miles on Rt. 58, turn left onto Rt. 1347; after 2.0 miles turn left on Rt 13, and make an immediate right onto Rt. 1345. Go across bridge over Sandy Run and slow down. Leaders (Kathleen Farrell and Tim Spruill) will direct vehicles to parking areas.



Stop 2, Figure 1. DRG image that shows the location of the Lizzie Site on the Farmville Quadrangle, 7.5 minute series.

STOP 2A: A brief overview of geomorphology and stratigraphy at the Lizzie site.
Leader: Kathleen M. Farrell

PURPOSE: to summarize the geologic conceptual model at Lizzie.

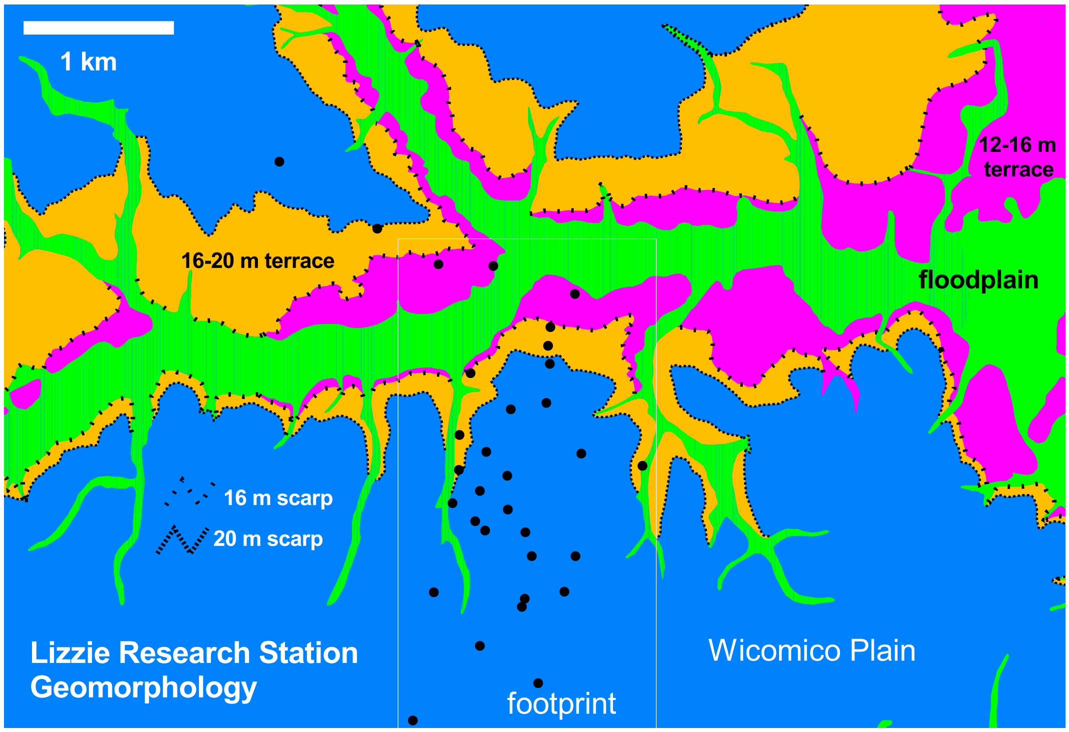


Figure 9. A. Geomorphology in the Lizzie site area.

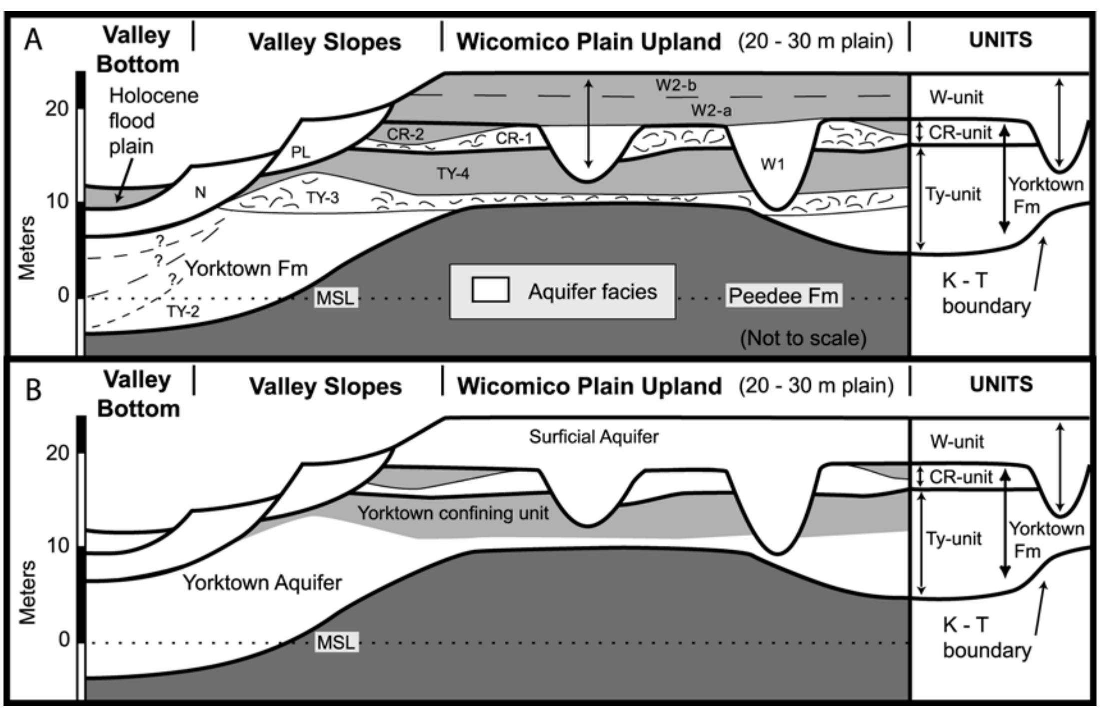


Figure 11. Sketch that shows the a) stratigraphic and b) hydrologeologic framework at the Lizzie site.

<table>
<tr><th colspan="2">Geologic Unit</th><th>Age</th><th>Surficial Geomorphology</th><th>Facies</th><th>Facies Summary</th><th>Facies Geometry</th><th>Origin</th><th>Hydrogeologic characteristics</th></tr>
<tr><td colspan="2">Floodplain</td><td>Holocene</td><td>< 12 m terrace</td><td>FP</td><td>Quartz sand, upward fining to mud and detrital plant debris.</td><td>shoestring-shaped valley fill</td><td>fluvial channel and flood plain</td><td rowspan="5">Shallow Aquifer</td></tr>
<tr><td colspan="2">N-unit</td><td>middle? Pleistocene</td><td>12-16 m terrace</td><td>N</td><td>Quartz sand, fining upward into muddy sand and mud, bioturbated to tidally bedded.</td><td>shoestring-shaped valley fill</td><td>estuarine to fluvial valley fill</td></tr>
<tr><td colspan="2">PL-unit</td><td>early-mid? Pleistocene?</td><td>16-20 m terrace</td><td>PL</td><td>Quartz sand, fining upward into muddy sand and mud, bioturbated to tidally bedded.</td><td>shoestring-shaped valley fill</td><td>estuarine to fluvial valley fill</td></tr>
<tr><td colspan="2" rowspan="2">W-unit</td><td rowspan="2">early Pleistocene 1.6 - 0.7 Ma (Krantz, 1991)</td><td rowspan="2">20-30 m terrace</td><td>W-2</td><td>Heterolithic - mud, sandy mud and sand; bioturbated to tidally bedded.</td><td>irregular sheet with shoestring sands</td><td>tidal flat/ indistributary bay/salt marsh.</td></tr>
<tr><td>W-1</td><td>Flaser to wavy bedded quartz sand; locally feldspathic.</td><td>lens to ovoid-shaped inlet/ valley fills</td><td>tidal inlet/valley fill</td></tr>
<tr><td rowspan="5">Yorktown Fm
? ↓</td><td rowspan="2">Morehouse Mbr. Equivalent</td><td rowspan="2">Pliocene 3.0 – 3.2 Ma (Krantz, 1991)</td><td rowspan="2">none at study site</td><td>CR-2</td><td>Sandy mud, mostly leached of carbonate fossils</td><td>irregular sheet</td><td>marine shelf/ open embayment</td><td rowspan="3">Yorktown confining unit</td></tr>
<tr><td>CR-1</td><td>Muddy phosphatic shelly sand and gravel, locally leached of carbonate fossils; with dissolution fabrics.</td><td>irregular sheet</td><td>shallow marine lags, inlet fill and shoals</td></tr>
<tr><td>Morgarts Beach Member</td><td rowspan="2">Pliocene 4.0 - 3.2 Ma (Krantz, 1991)</td><td rowspan="2">none at study site</td><td>Ty-4</td><td>Sandy mud with thin (dm-cm) shell beds dominated by Mulinia congesta. Minor phosphate and glauconite.</td><td>irregular sheet</td><td>marine shelf/ open embayment</td></tr>
<tr><td>Rushmere Member</td><td>Ty-3</td><td>Phosphatic, gravelly shelly sand; locally muddy; locally cemented grainstone; locally leached.</td><td>very thin sheet with local mounds and valley infills</td><td>lags, marine shoals, inlet fill</td><td rowspan="2">Yorktown aquifer</td></tr>
<tr><td>new unnamed member</td><td>Pliocene?</td><td>none at study site</td><td>Ty-2</td><td>Gravelly sand, predominantly quartz; with local intervals of detrital wood or shell hash.</td><td>shoestring-shaped valley fill</td><td>multi-origin, multi-age? paleovalley fill</td></tr>
<tr><td colspan="2">"Peedee" Formation</td><td>Cretaceous (Santonian)</td><td>none</td><td>K</td><td>Dark gray very fine to fine muddy sand; burrowed, glauconitic with phosphate nodules, locally shelly.</td><td>irregular sheet</td><td>marine shelf/open embayment</td><td>Cretaceous confining unit</td></tr>
</table>

Figure 13. Regionally correlated unconformity bounded units: from the Virginia map (Mixon and others, 1989) to Little Contentnea Creek Watershed.

STOP 2B: Lizzie Research Station: LIDAR data and landscape analysis. *Leader: Amy Keyworth*

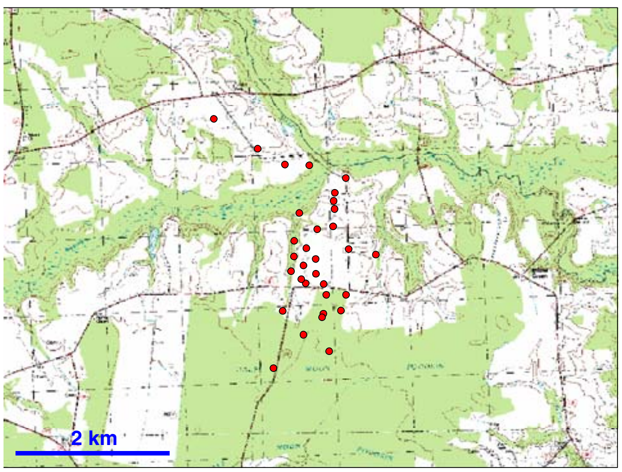
PURPOSE: To present examples of LIDAR display and compare them to traditional mapping techniques.

DESCRIPTION: LIDAR, an acronym for Light Detection and Ranging, is a remote sensing technique used to gather elevation data at a fine scale. Laser pulses are emitted from airborne instruments, returning up to five reflections or "returns" per pulse (Fact Sheet, 2003). The multiplicity of returns are due to objects encountered between the instrument on the airplane and the ground, for example trees, birds or cars. The data is post-processed, generating bare-earth elevation data, then interpolated to produce a regularly spaced grid of elevation points. Raw LIDAR data is said to have a vertical accuracy of ± 25 cm per 1m x 1m tile (Metadata, 2002).

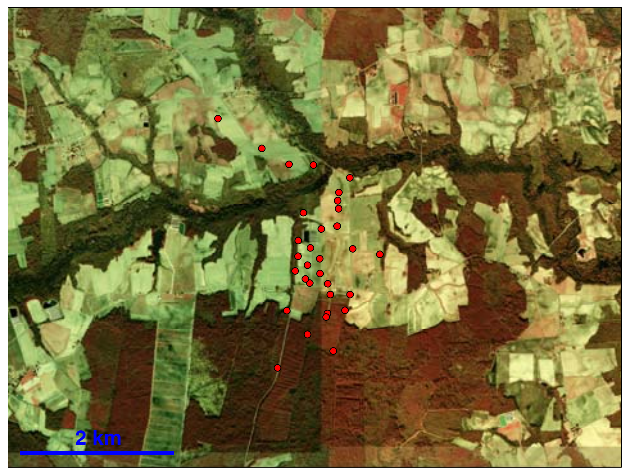
The LIDAR data for this project was obtained from the North Carolina Floodplain Mapping Program (http://www.ncfloodmaps.com/), the cell size used is 20 feet x 20 feet. Individual ASCII tiles, 10,000 x 10,000 foot squares, were downloaded from the NCFMP website, converted to raster grids in ArcGIS, mosaiced together in ArcInfo, and clipped to watershed boundaries in ArcMap. The ArcGIS extension Spatial Analyst was used to create Hillshade and Slope datasets, helpful in creating a three dimensional display. Contour lines can also be created using Spatial Analyst, and topographic profiles can be created using ArcGIS 3D Analyst.

The set of diagrams included here are intended to convey some of the variety of display possibilities using LIDAR. With a small cell size, a vertical accuracy of ± 25 cm, and infinite display possibilities, LIDAR data brings landscape analysis to a whole new level.

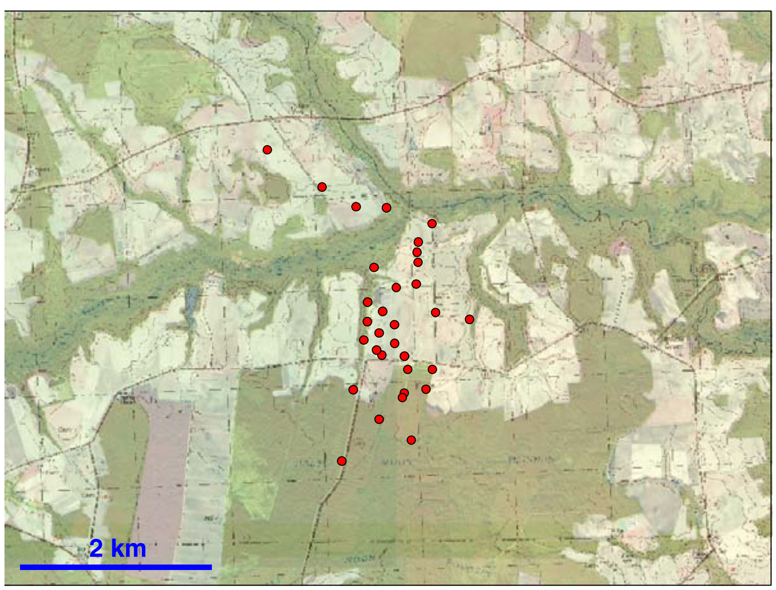
Figure 1. Traditional technology used in landscape analysis, highlighting the Lizzie site.



A. USGS 7.5 minute quadrangle topographic map (DRG).

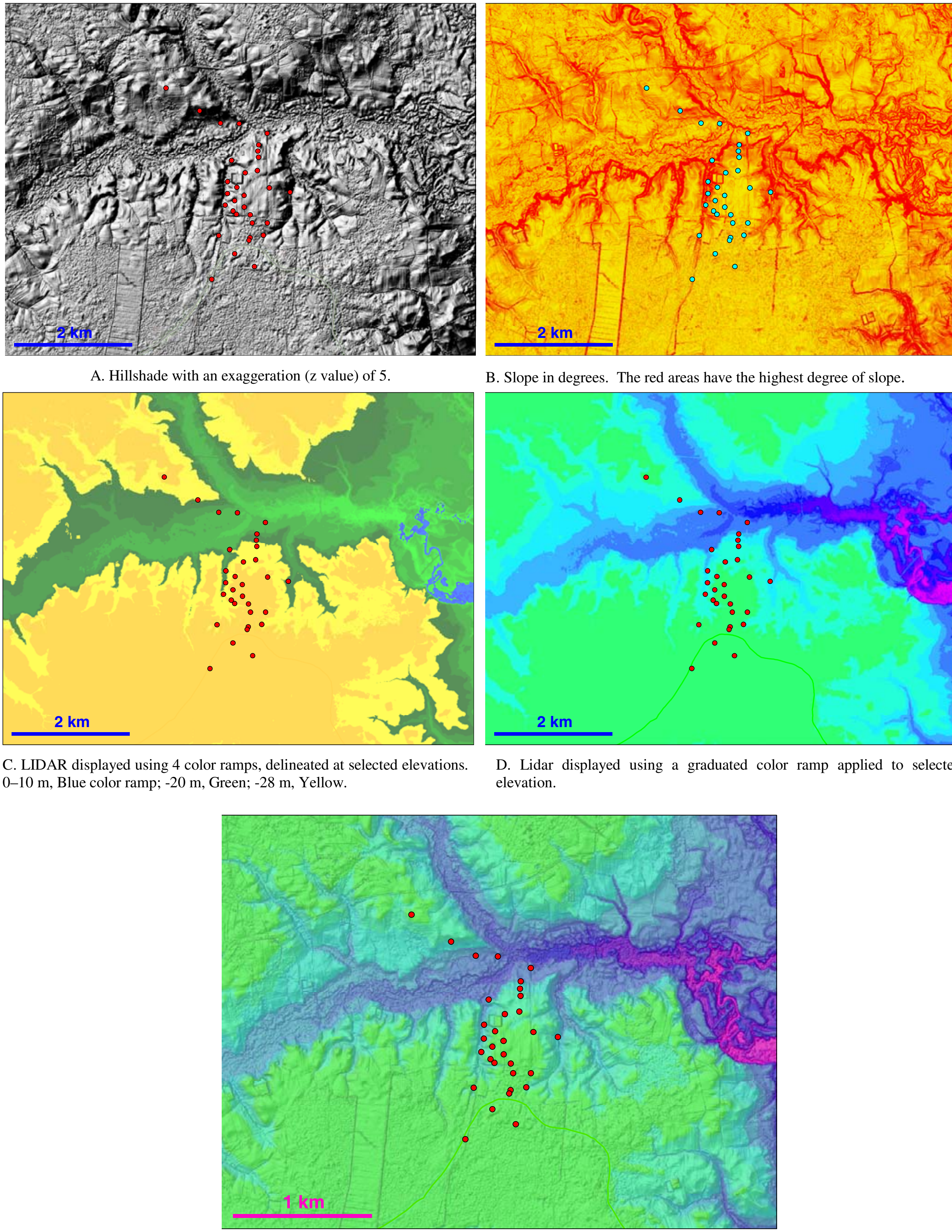


B. Digital Orthophoto Quarterquad map (DOQQ).



C. DRG draped over the DOQQ. The DRG was given a transparency of 35 %.

Figure 2. Lidar technology highlighting the Lizzie site.



A. Hillshade with an exaggeration (z value) of 5.

B. Slope in degrees. The red areas have the highest degree of slope.

C. LIDAR displayed using 4 color ramps, delineated at selected elevations. 0–10 m, Blue color ramp; -20 m, Green; -28 m, Yellow.

D. Lidar displayed using a graduated color ramp applied to selected elevation.

E. Graduated colors draped over Hillshade and Slope. Note the 3 dimensional effect of the display. Adding contour lines to the display can help delineate selected areas even more.

STOP 2C: Lizzie Research Station: Background, Study Focus, and Summary of Activities, 1993-2002.
Leaders: Tim Spruill, Ted Mew, Steve Kraemer, Jim Tesoriero, Kathleen M.Farrell

Backgound and Site History:

- NCDENR DWQ-GW Section began recharge study in 1993.
- USGS Albemarle-Pamlico NAWQA Study Unit selected the area in 1995 for a secondary flowpath study site-5 wells sampled for major ions and nutrients along a flow system from recharge to discharge area.
- EPA discussed work at a site where adequate hydrogeologic information exited to conduct a study to provide data for testing environmental models as part of the MIMS (Multi-media Integrated Modeling System) project. USGS looked at available sites and recommended Lizzie site because of the availability of hydrogeologic information about the site. Field monitoring at the MIMS site began during Spring 1999.
- NCGS was brought into site characterization by DWQ-GWS in 1999.
- MIMS project expanded in area to include streams in lower Neuse Drainage from Kinston to Ft. Barnwell. Field monitoring of wells and surface-water sites continued until 2002.

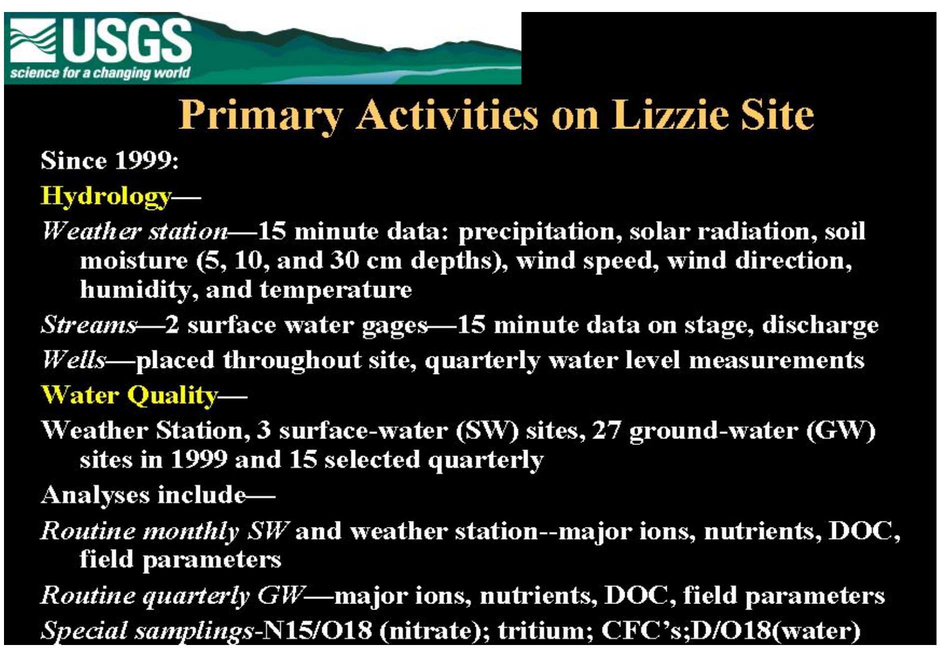
A follow-up study began in 2003 to establish background information for establishment of new technology to treat hog wastes generated on the farm.

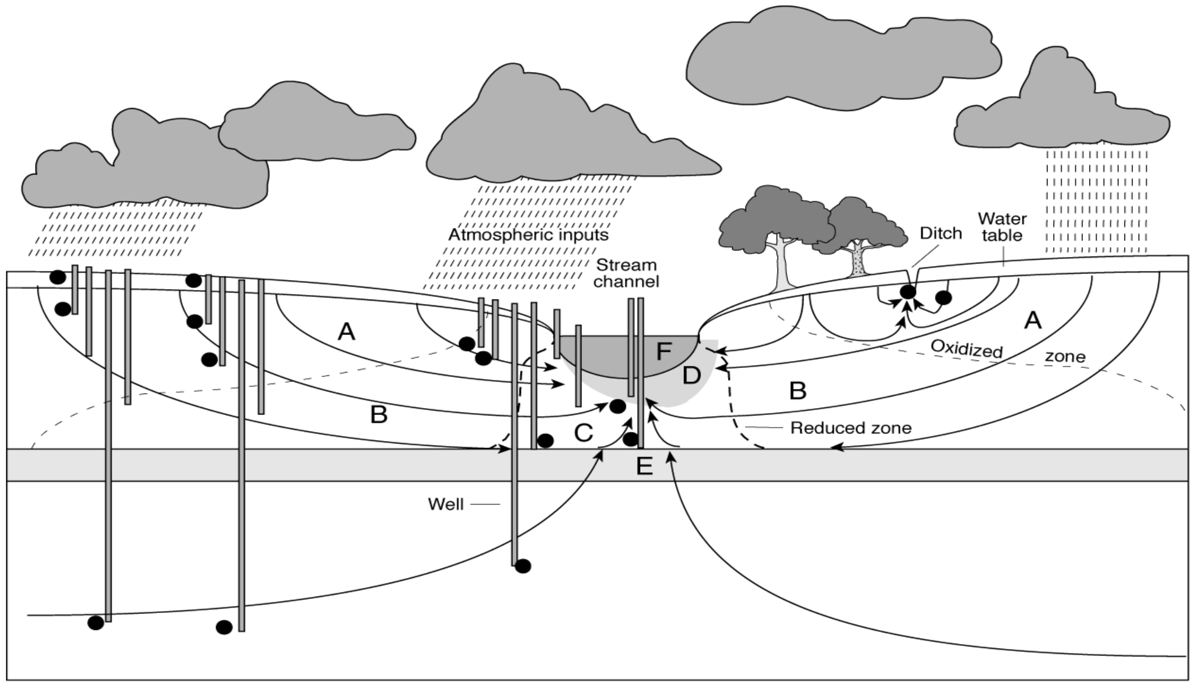
The USGS and the North Carolina Department of Environment and Natural Resources (NCDENR) began data collection activities in March 1999 as part of a cooperative project with EPA to:

1. *Provide hydrogeologic and water quality information on transport and fate of nitrogen in a small watershed (the Lizzie Research Station) located in the Little Contentnea Creek subbasin.*
2. *Characterize nutrient loading and behavior in the middle and lower Neuse drainages from small, low order streams in Contentnea Creek to large, high order streams to Fort Barnwell*

Problem and Need

Eutrophication has been identified as a primary problem of the Albemarle-Pamlico estuaries (and excess growths of algae and causes of fish kill in the estuaries has been attributed to the occurrence of excess nutrients, particularly nitrogen. The Neuse River Basin in North Carolina, specifically, has exhibited eutrophication problems, thought to be primarily due to non-point sources of N and P. In addition, significant new sources of nutrients in the Basin since 1990 (increases due to swine farms). There is a need to understand where nutrients are derived from different media and how they behave in a watershed and river system to effectively manage water quality.





EXPLANATION

● CORE SAMPLE--mineral, elemental, carbon analysis
WATER SAMPLE--major ion, nutrient, CFC, gases, O^{18}, tritium, N^{15}

A OXIDIZED ZONE--low carbon, high dissolved oxygen, oxidized compounds, low iron dissolution of minerals

B TRANSITION ZONE

C REDUCED ZONE--high carbon, low oxygen, reduced compounds

D HYPORHEIC ZONE--reduction zone in presence of elevated carbon, phosphorus

E CROSS FORMATION REDUCTION ZONE--ion exchange, dissolution

F SUPER-OXIDATION--precipitation of metals, potential nitrification

REFERENCES CITED

Brown, P.M., 1959, Geology and groundwater resources in the Greenville area, North Carolina, North Carolina Geological Survey Bulletin 73, 45 p.

Councill, R.J., 1954, The commercial granites of North Carolina, North Carolina Geological Survey 67, 35 p.

Fact Sheet: LIDAR and Digital Elevation Data, January 2003, North Carolina Floodplain Mapping Program, North Carolina Division of Emergency Management, 6 p.

Mauger, R.L., Spruill, R.K., Christopher, M.T., and Shafiqullah, M., 1983, Petrology and Geochronology of peralkalic metagranite and metarhyolite dikes, Fountain quarry, Pitt County, North Carolina, Southeastern Geology, v. 24, n. 2, p. 67-89

Metadata: NC Floodplain Mapping: Neuse Basin; 20 ft Digital Elevation Model, May 2002, Floodplain Mapping Program, North Carolina Division of Emergency Management, p. 3

Zietz, I., Haworth, R.T., Williams, H., and Daniels, D.L., 1980, Magnetic anomaly map of the Appalachian orogen, St. Johns, Newfoundland, Appalachian Research Fund, Memorial Univ. Newfoundland.