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Environmental Laboratory

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Watershed Boundaries and Relationship Between Stream Order and Watershed Morphology at Fort Benning, Georgia

Mark R. Graves

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Preface

This report was prepared for the Ecosystem Characterization and Monitoring Initiative (ECMI), sponsored by the Strategic Environmental Research and Development Program (SERDP) Ecosystem Management Project (SEMP). The technical monitor was Dr. Robert Holst, SERDP Program Manager.

The work was performed under the direction of the Environmental Laboratory (EL), U.S. Army Engineer Research and Development Center (ERDC). The EL Principal Investigator was Mr. Mark R. Graves, EL. Project Manager for the ECMI is Mr. Harold W. West, EL, and Program Manager for the SEMP is Dr. Harold E. Balbach of the Construction Engineering Research Laboratory (CERL), ERDC, Champaign, IL.

Many individuals contributed to the support of this project, including the following: Mr. John Brent, Mr. Pete Swiderek, and Ms. Theresa Davo of Fort Benning, GA, the host site for the SEMP; Dr. Rose Kress, Mr. Scott Bourne, Mr. Jerrell R. Ballard, Jr., of EL, and Ms. Elizabeth Lord, Dyntel Corporation. Chief of the Ecosystem Evaluation and Engineering Division, EL, was Dr. David J. Tazik. Acting Director of EL was Dr. Edwin A. Theriot.

At the time of publication of this report, Dr. James R. Houston was Director of ERDC, and COL John W. Morris III, EN, was Commander and Executive Director.

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Executive Summary

This paper describes the procedures followed to develop a detailed watershed database for Fort Benning, Georgia, and the surrounding area. In addition the relationship between watershed morphology and stream order was examined. Watershed order and a number of variables describing surface topography and the stream network were computed and statistical analysis procedures were used to develop a predictive relationship. Watershed boundaries were computed from a digital elevation model and assigned an order using the Strahler stream-ordering technique. This procedure is rather tedious and requires that all the drainage network upstream of the area of interest be digitized. A number of physical parameters defining these watersheds were computed using a geographic information system (GIS) and the relationship of these parameters to stream order was examined. The purpose of this analysis was to determine if stream order could be predicted reliably using a number of computed physical parameters. Regression analysis showed that stream order had a highly significant relationship (r-square = 0.77) with two easily computed variables: total relief, and average slope. A procedure for estimating stream order, within an acceptable degree of error, could be beneficial for many applications, such as assisting in the parameterization of hydrologic models.

1 Introduction

Background

The Department of Defense (DoD) has established ecosystem management as its approach to managing military lands. The Strategic Environmental Research and Development Program (SERDP), Ecosystem Management Program (SEMP), was established in December 1997 to help address critical deficiencies in knowledge that prohibit the DoD from fully achieving this goal (SERDP 2000). One component of the SEMP is the Ecosystem Characterization and Monitoring Initiative (ECMI). The objectives of the ECMI, described in SERDP (2000), include developing and implementing methods of monitoring and characterizing ecosystems that can help land managers assess relationships between land use and management, and ecosystem structure, function, and pattern. Fort Benning, Georgia, was established as the first test site.

Watersheds, which provide linked gradients of terrestrial, riparian, and aquatic systems, were established as the critical, ecosystem delineation/mapping unit. A watershed (also known as a hydrologic unit, catchment, or drainage basin) is defined as that area of land draining into a particular stream or other surface water body. For any location in a stream, there is an associated area that contributes water to its flow. The watershed divide is that line which divides the area contributing water to the stream and that which contributes water to neighboring streams or water bodies. Therefore, each watershed is defined by its outlet or pour point (the point in the stream which receives all water in the watershed) and the associated watershed divide derived from that point and the local topography.

The primary goal of this project was to develop a detailed digital elevation model (DEM) and watershed boundaries to support the efforts of the SEMP ECMI. A secondary goal was to examine the relationship between stream order and watershed geomorphology. This paper documents the process by which watersheds were produced for the Fort Benning study area, as well as a statistical analysis of the relationship between stream order and watershed characteristics.

Although a number of early studies, such as Morisawa (1959), have analyzed the relationship between quantitative geomorphology and stream measurements, most of these studies were limited by the complexity of calculating detailed watershed variables. The development of geographic information systems (GIS) has made it possible to quickly define watershed boundaries and to compute geomorphic variables describing them.

Study Site Description

Fort Benning is located in west-central Georgia, south of the city of Columbus, Georgia. It occupies approximately 73,533 hectares (ha) in Chattahoochie, Muscogee, and Marion Counties in Georgia, and Russell County in Alabama. The base lies within the humid temporate domain, subtropical division, coniferous-broadleaved semi-evergreen forest province, as defined by Bailey (1995). Fort Benning falls within the southeastern plains ecoregion as defined by Omernik (1987). The base is located within hydrologic unit 03130003, as defined by the U.S. Geological Survey (USGS) (Figure 1).

The Fort Benning SEMP demonstration site is described in much greater detail in "Design Document for Long-Term Monitoring Program, Fort Benning, Georgia" (SERDP 2000).

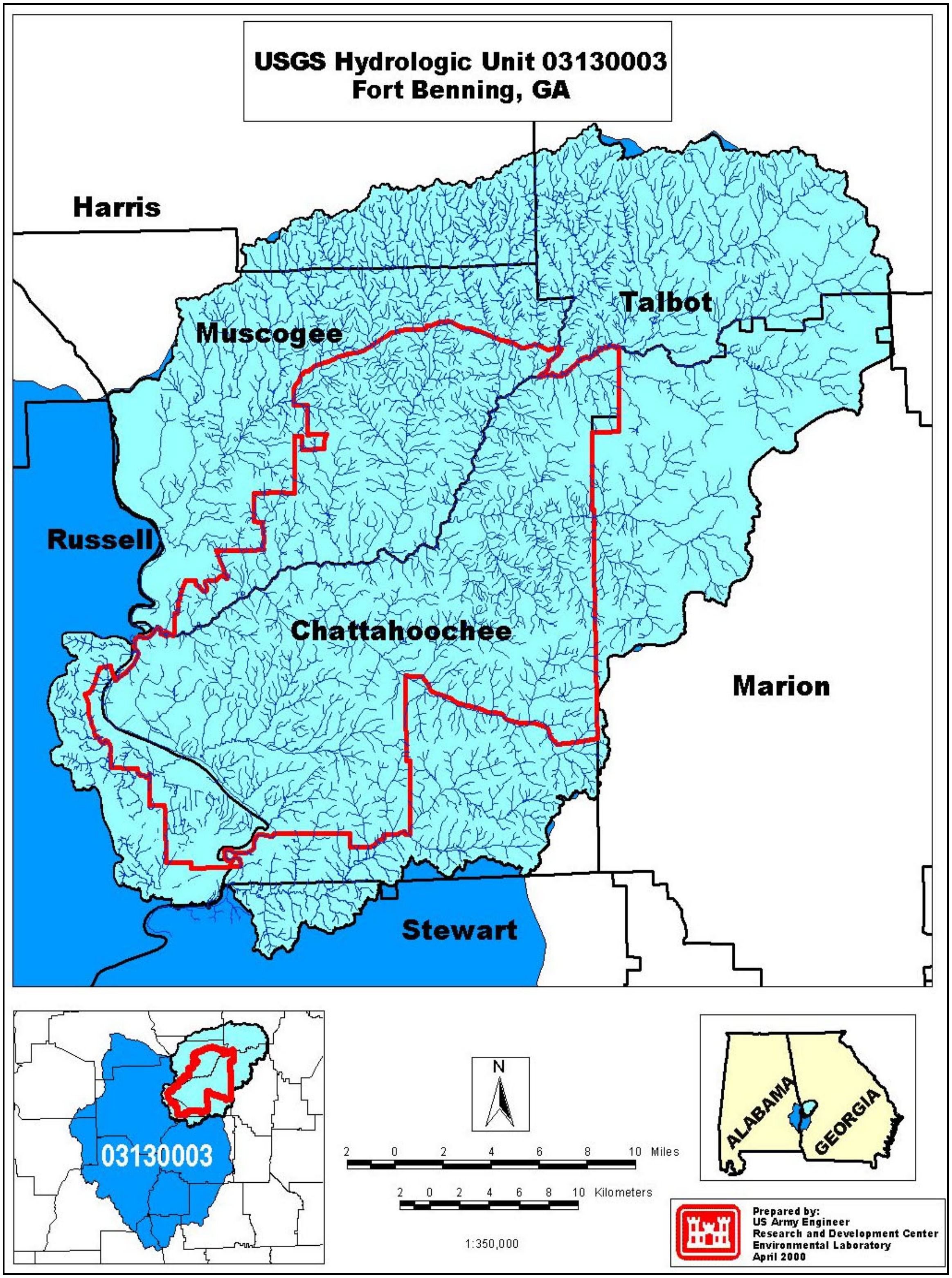

Figure 1. Fort Benning and associated hydrologic unit

2 Database Development

The development of watershed boundaries requires two types of data: detailed topographic information, and an accurate and topologically correct stream network. For this study, both types of data were derived from USGS 1:24,000 maps.

Arc/Info GIS software (ESRI 2000) was used to develop the database and for subsequent data processing.

Elevation Contours and Benchmarks

Digital versions of vector contour lines (Figure 2) were purchased from LandInfo International for each of the 1:24,000-scale USGS topographic quadrangle maps covering the hydrologic unit in which Fort Benning is situated.

The contour lines were appended into one file and the following steps were taken to ensure that the data were accurate:

a. The elevations of the contours lines were checked closely to verify that they represented the correct range of values for each source map sheet.

b. The digital files were plotted on clear Mylar overlays and compared with the paper source maps.

c. The files were inspected for contour lines carrying incorrect elevation attributes.

d. Contours that were located along edges of the source maps were edgematched and node errors were corrected.

To supplement the contour information, elevation benchmarks were digitized from each of the USGS quadrangle maps and the proper elevations were assigned as attributes to the resulting point coverage.

Stream Network

For this project, streams were identified as blue lines on the USGS 1:24,000 scale maps, as required by NI 170-304 SubPart C, 304.20(a) (NRCS, 1995). The

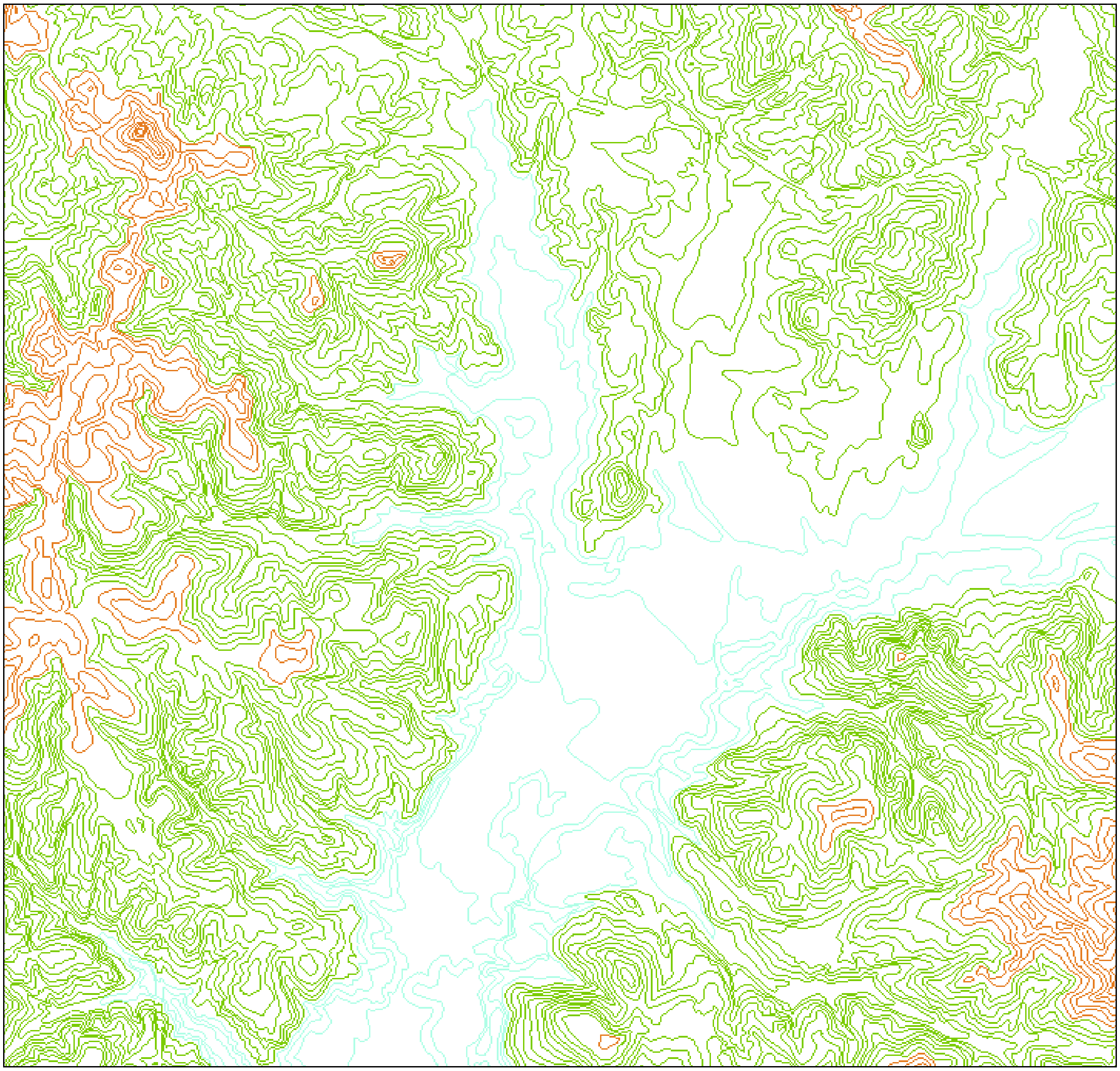

Figure 2. Vector topographic contours over portion of Fort Benning, Georgia

smallest streams were those with no tributaries, while the largest streams discharged directly to the Chattahoochie River.

A tablet digitizer was used to obtain the streams from each USGS map. The streams were then edgematched to ensure that they were properly connected. Check plots were produced to compare the digital versions of the stream segments to the source 1:24,000 maps.

The following steps were then followed to prepare the streams for the ordering process and the generation of an elevation model.

a. All stream segments were checked to ensure that they were connected and oriented (pointing) in a downstream direction. This is required for the stream ordering procedure.

b. The files were checked for accurate topology and to ensure that there were no overlapping line segments.

c. The streams were also inspected closely to assure that they crossed contours at the appropriate locations.

d. The stream segments were densified, i.e., the number of vertices in each stream segment was increased.

e. In areas where lakes or small ponds interrupted stream segments on the source maps, line segments had to be created to join both the inlet and outlet streams into a continuous line. This is a required for the stream ordering procedure.

3 GIS Analysis

Elevation Model Development

The TOPOGRID software in Arc/Info (ESRI, 2000) was used to produce the final surface elevation model. TOPOGRID is an interpolation method, specifically designed to generate hydrologically correct DEMs from elevation data and stream networks. It is based on the ANUDEM program developed by Michael Hutchinson (1988, 1989).

The data used to develop the elevation model are listed in Table 1:

Table 1
Data Used to Create the Digital Elevation Model

Coverage Name	Topology	Description
Contours	Line	Elevation contours from USGS 1:24,000 maps
Benchmarks	Point	Elevation benchmarks from USGS 1:24,000 maps
Streams	Line	Topologically correct stream network
Boundary	Polygon	Polygon representing boundary of interpolation

The following parameter file was used to generate the elevation model:

```
TOPOGRID output surface 10
ENFORCE ON
DATATYPE CONTOUR
MARGIN 0.0
ITERATIONS 30
TOLERANCES 2.5 1.0   0.0
XYZLIMITS # #   # # # #
CONTOUR contours ELEV-M
POINT benchmarks ELEV-M
STREAM streams
BOUNDARY boundary
OUTPUTS sinks drainage
```

A shaded relief depiction of the final elevation model is presented in Figure 3 and a portion of the elevation model is shown in a “hill-shaded” format in Figure 4.

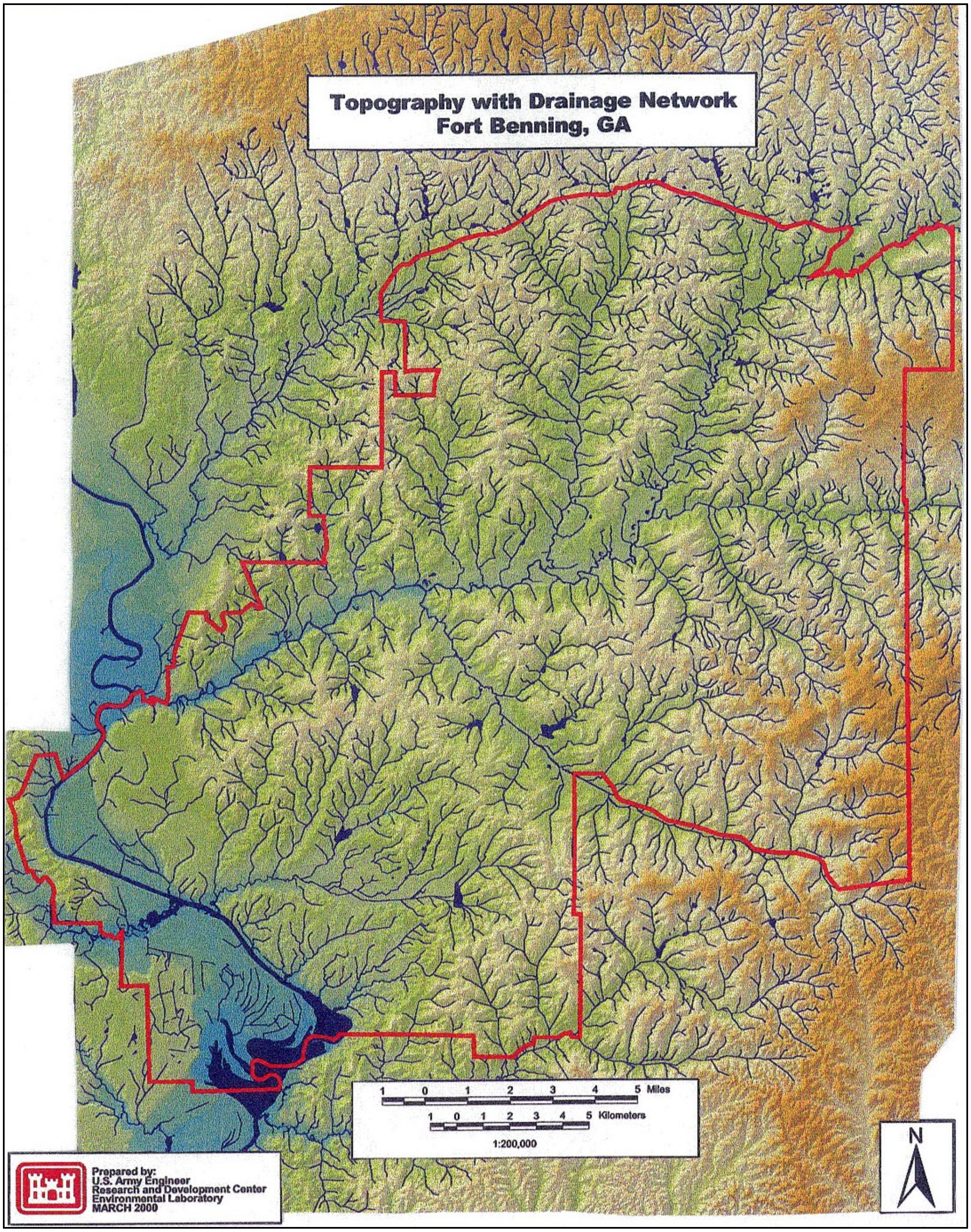

Figure 3. Shaded relief depiction of elevation model

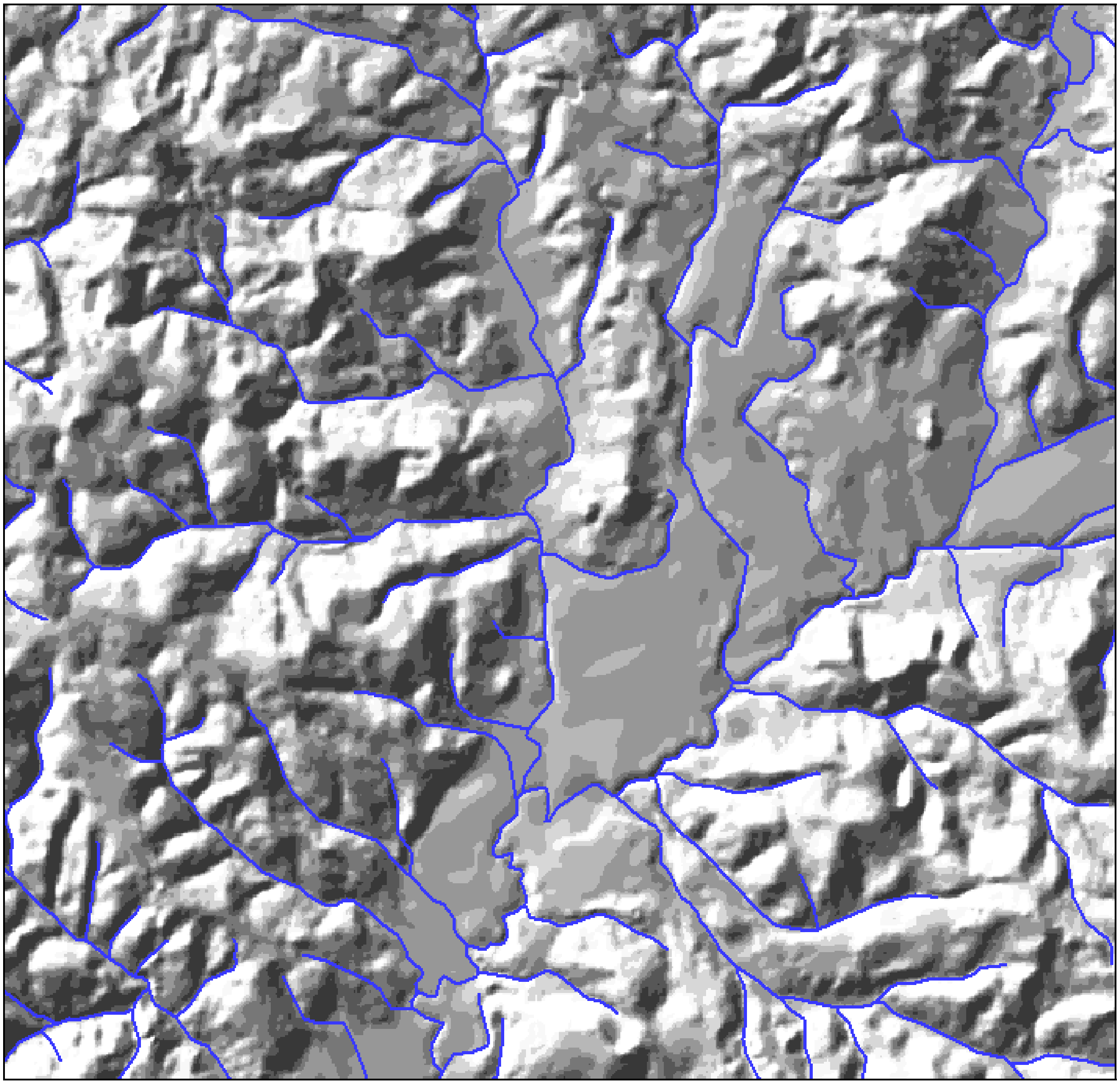

Figure 4. Stream network (blue) over a hillshade depiction of the digital elevation model

Stream Ordering Procedure

Stream ordering is a process of identifying and grouping stream segments and their corresponding watersheds in terms of size and complexity. Theoretically, watersheds of similar order display similar hydraulic properties and ecological function. There are four commonly described approaches to stream ordering. In this study, the approach used was that originally described by Horton (1945) and revised by Strahler (1952). In this ordering scheme, the smallest stream segments near the drainage divide are assigned the lowest order (i.e., first-order stream) and the stream segment at the watershed outlet is assigned the highest order. Each sub-basin identified is assigned the same order as the largest stream segment within it.

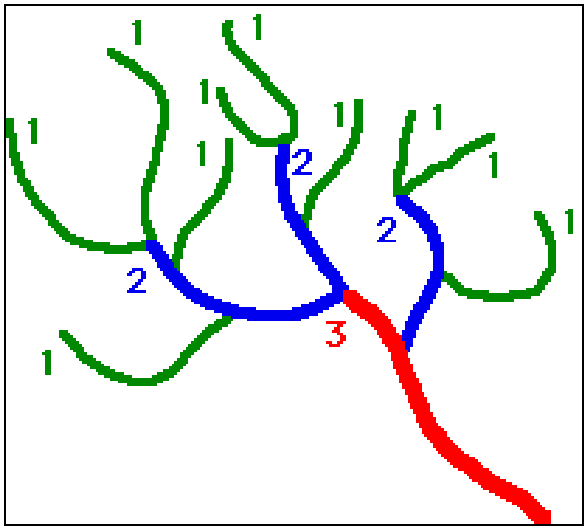

Figure 5. Diagram of the Strahler stream ordering procedure

The ordering system can be described by the following series of steps and is depicted graphically in Figure 5 (Chow, Maidment, and Mays 1988):

a. The smallest recognizable channels are designated order 1; these channels normally flow only during periods of wet weather.

b. Where two channels of order 1 join, a channel of order 2 results downstream; in general, where two channels of order *i* join, a channel of order *i* + 1 results.

c. Where a channel of lower order joins a channel of higher order, the channel downstream retains the higher of the two orders.

d. The order of the drainage basin is designated as the order of the stream draining its outlet, the highest stream order in the basin, *I*.

Every stream on the map could be ordered as long as its furthest upstream extent was known. This ordering was completed for all streams over 30 m (100 ft) in length on the USGS quadrangle maps on the Georgia side of Fort Benning, but was not done for the Chattahoochie River itself (as the area drained by this major river extends beyond the hydrologic unit study area).

This process was conducted for the Fort Benning drainage system using an automated Arc Macro Language (AML) script operating within the Arc/Info GIS software package. The program used to order the streams is listed in Appendix A.

Watershed Boundary Delineation

Several procedures within the GIS software were used to produce polygons defining the drainage area associated with each stream segment or group of segments. These polygons represent the various watersheds having different orders. Several steps were required by produce these watershed boundaries from the elevation model.

First, the Arc/Info GRID function FLOWDIRECTION was used to generate a raster file depicting flow direction from each cell in the elevation model to its steepest downslope neighbor. The method of deriving flow direction employed by the Arc/Info software is described in Jenson and Dominique (1988).

The watersheds, as described previously, are partly defined by their outlets. Points where two streams intersect define watershed outlets. The nodes where streams intersected were selected from the stream coverage and copied into a separate Arc/Info coverage. This coverage of outlets was then converted to a raster format.

Finally, the watershed boundaries were defined using the Arc/Info GRID WATERSHED function, with both the output of the FLOWDIRECTION process and the raster dataset of outlets used as input. The resulting watershed grid was then converted from a raster file into a polygon coverage. Manual editing was required to clean up the final watershed polygons to remove artifacts such as polygons representing very small areas, i.e., one cell in the source raster dataset.

The next step was to assign orders to the watershed polygons. The ordering of watersheds follows the ordering of the streams that drain them. If the outlet of an order i stream is that point where it joins another stream of order i or higher, an order i watershed corresponding to that stream can be derived from the surrounding topography. Although each reach of a stream will have a unique order, each area of land may belong to more than one order of watershed. In general, any order i watershed will contain at least two watersheds of order i - 1, and each order i watershed will be contained in some watershed of higher order. The IDENTITY command assigned the stream coverage order to the watershed polygons. This process was conducted for each order of stream, resulting in six different polygon coverages.

A total of 3348 watershed boundaries were delineated. The numbers of watersheds (by order) delineated in the study area are listed in Table 2. Maps of each watershed order are presented in Figures 6-11.

Table 2
Number of Watersheds Delineated in the Fort Benning Study Area (by order)

Watershed Order	Number of Watersheds
1	2570
2	596
3	142
4	31
5	8
6	1

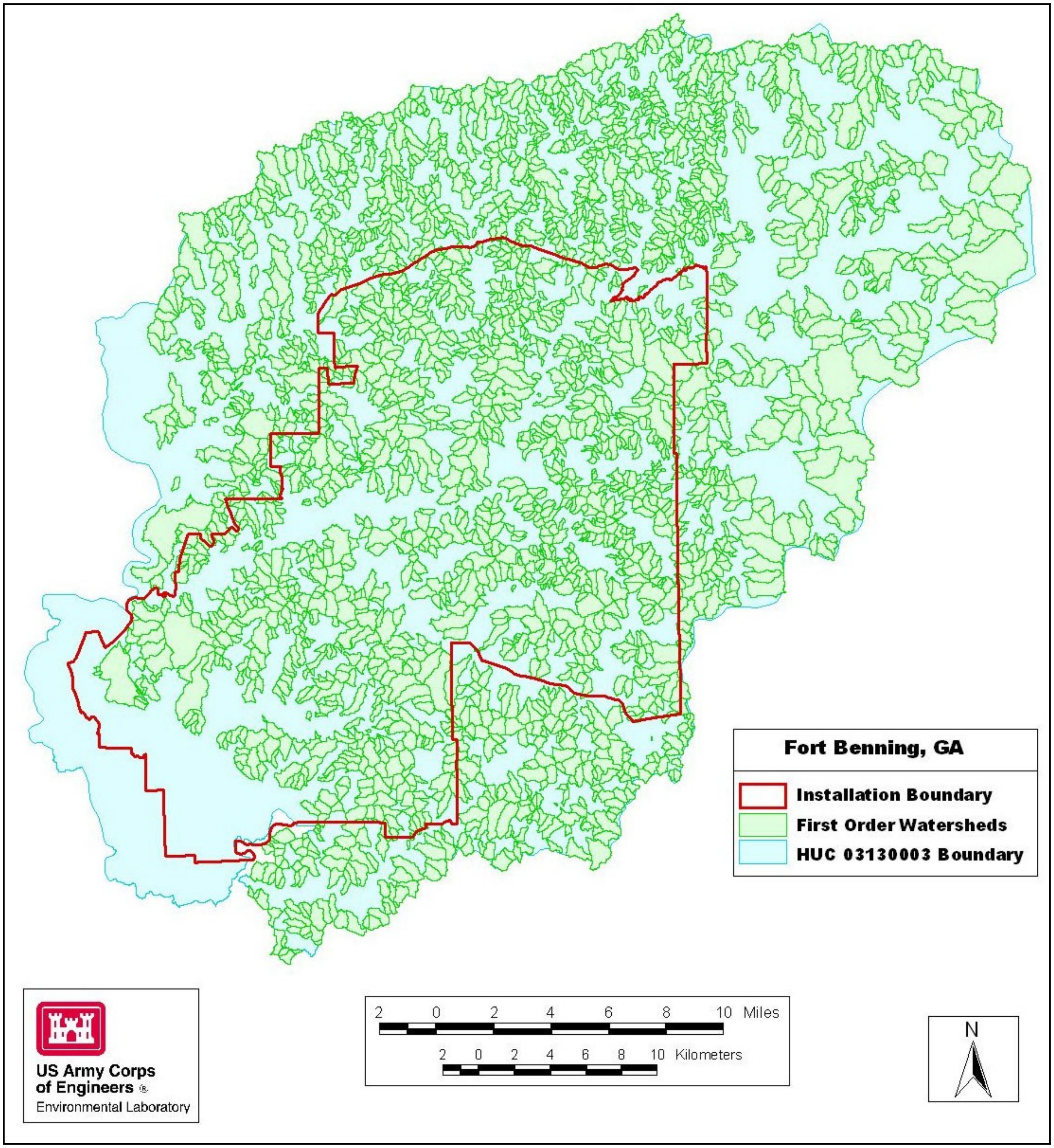

Figure 6. First order watersheds

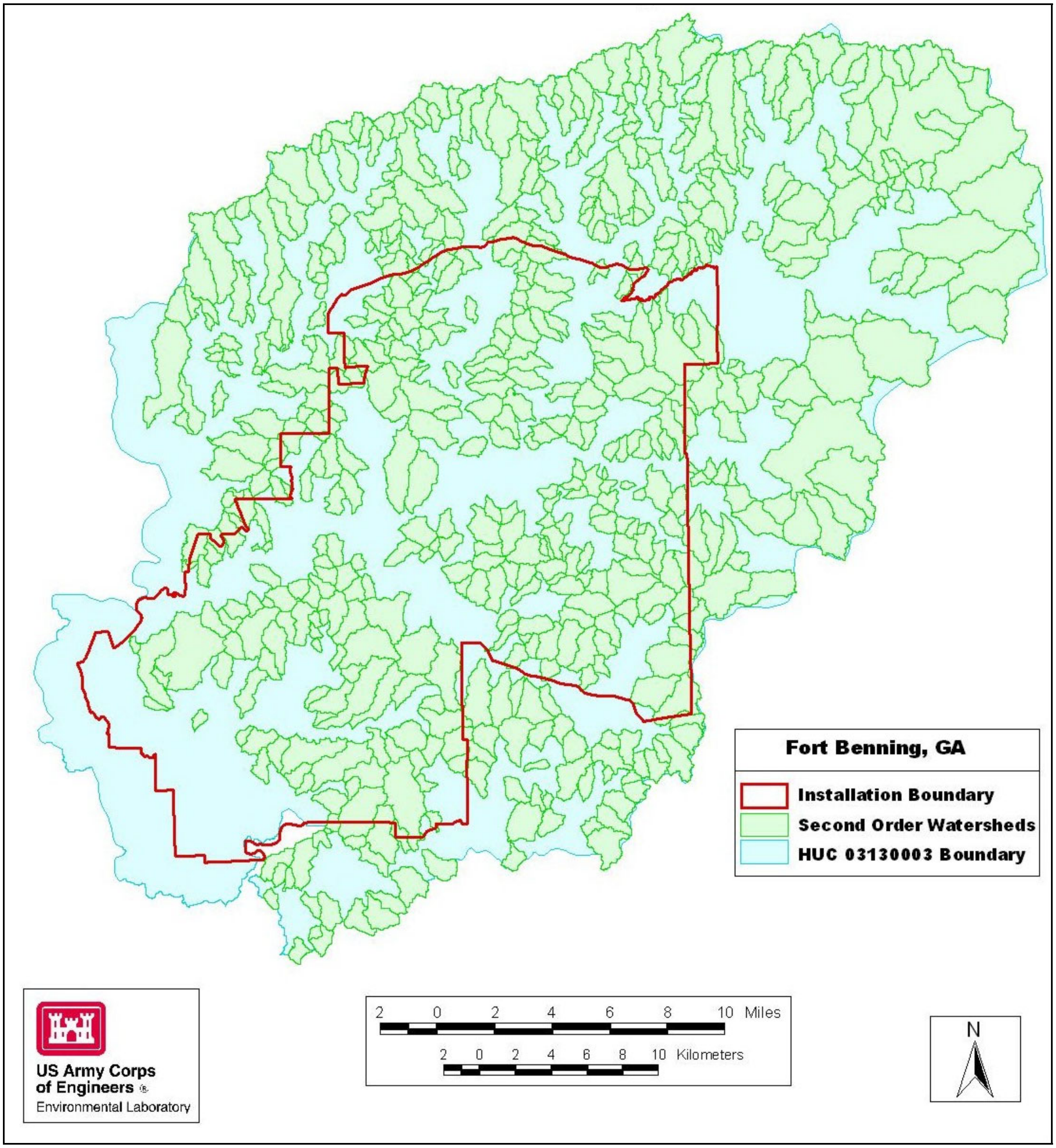

Figure 7. Second order watersheds

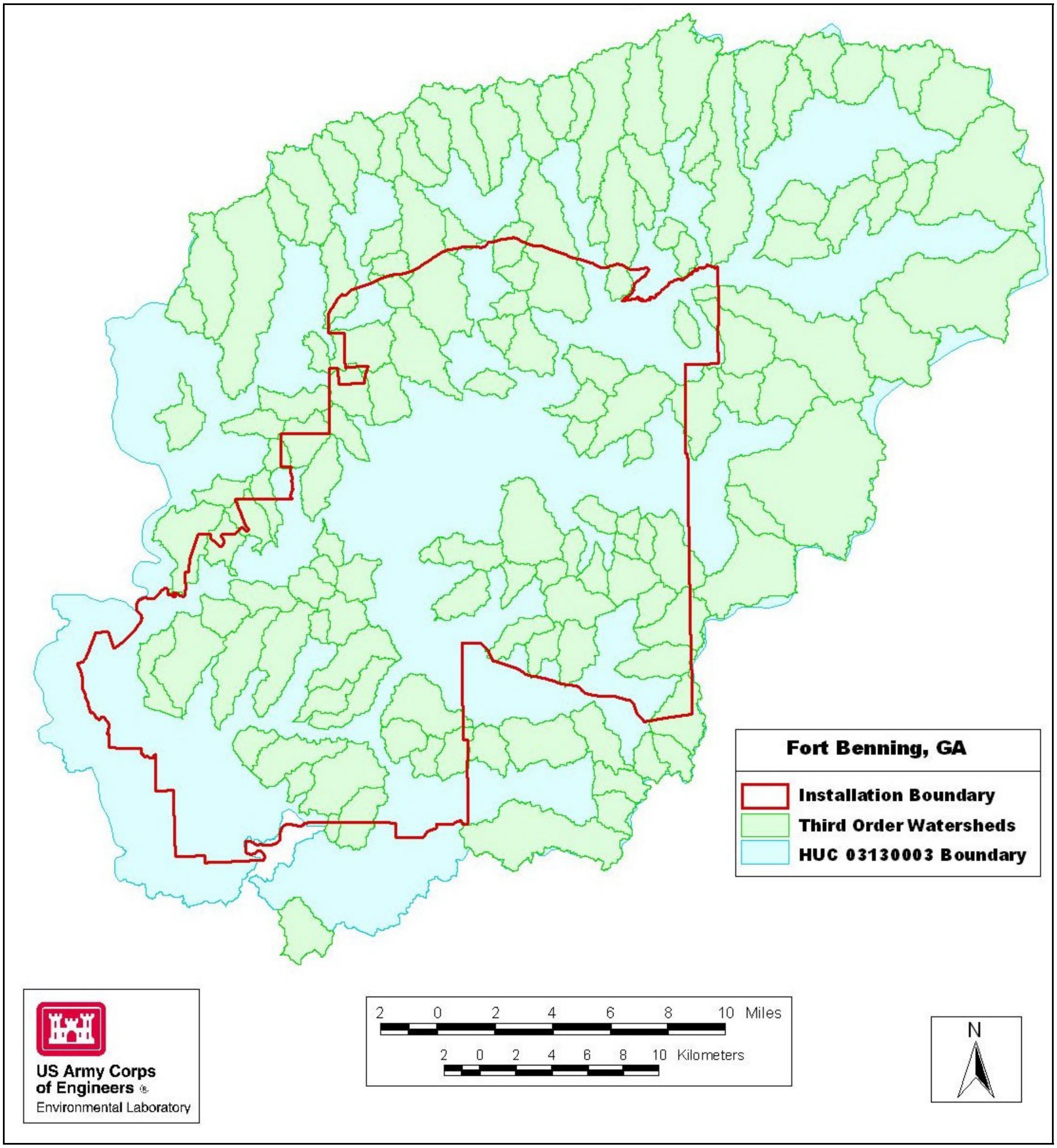

Figure 8. Third order watersheds

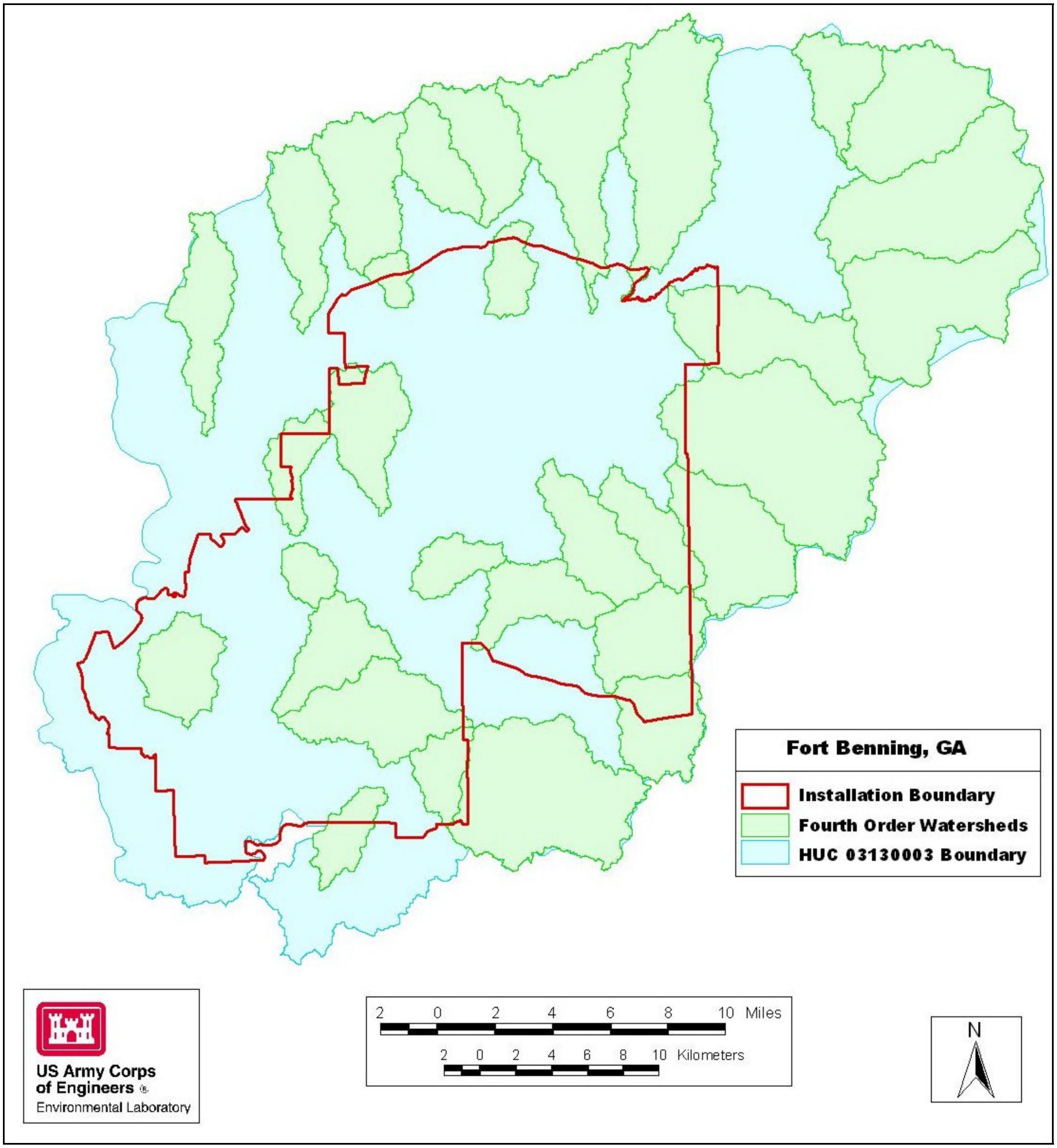

Figure 9. Fourth order watersheds

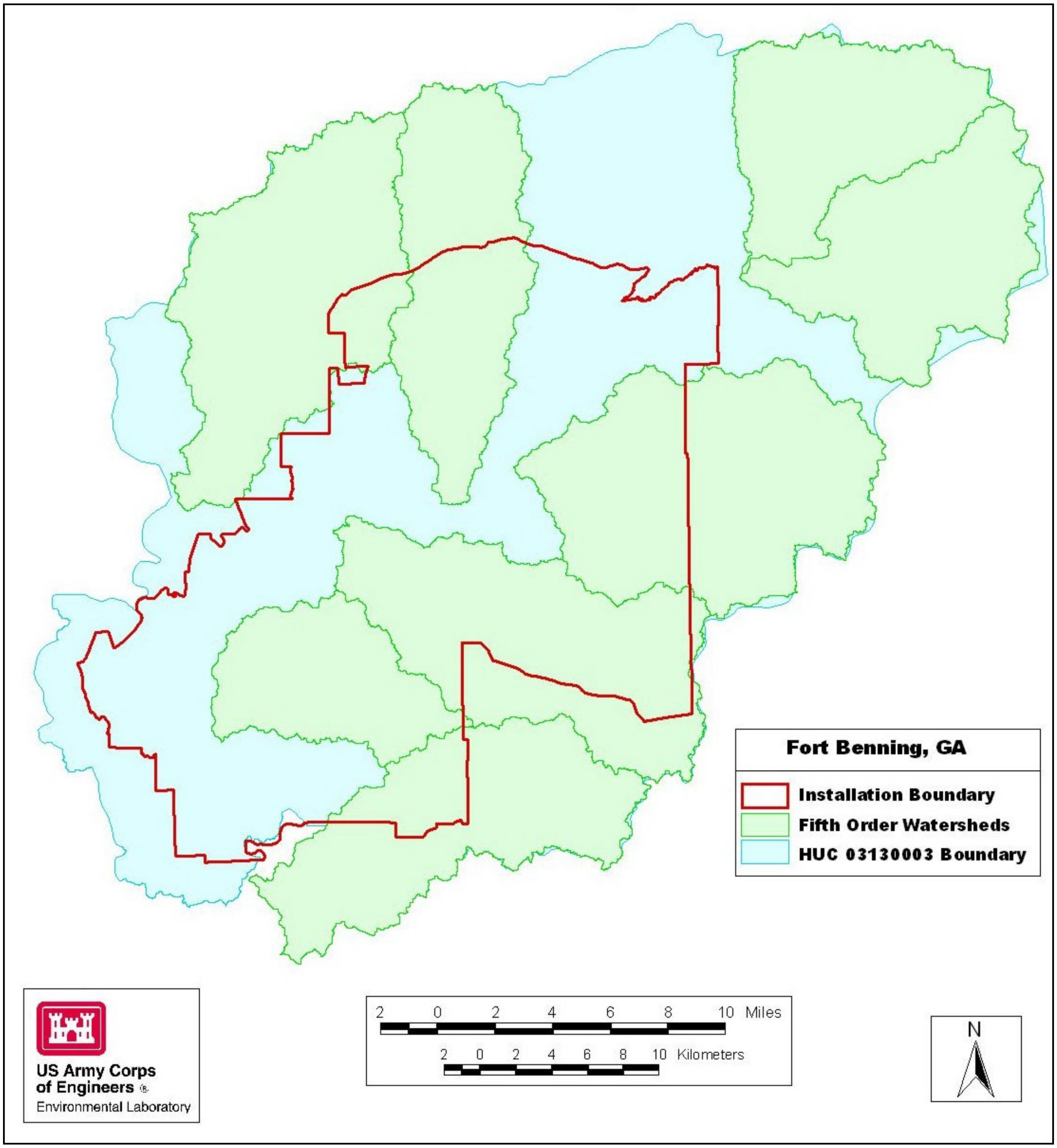

Figure 10. Fifth order watersheds

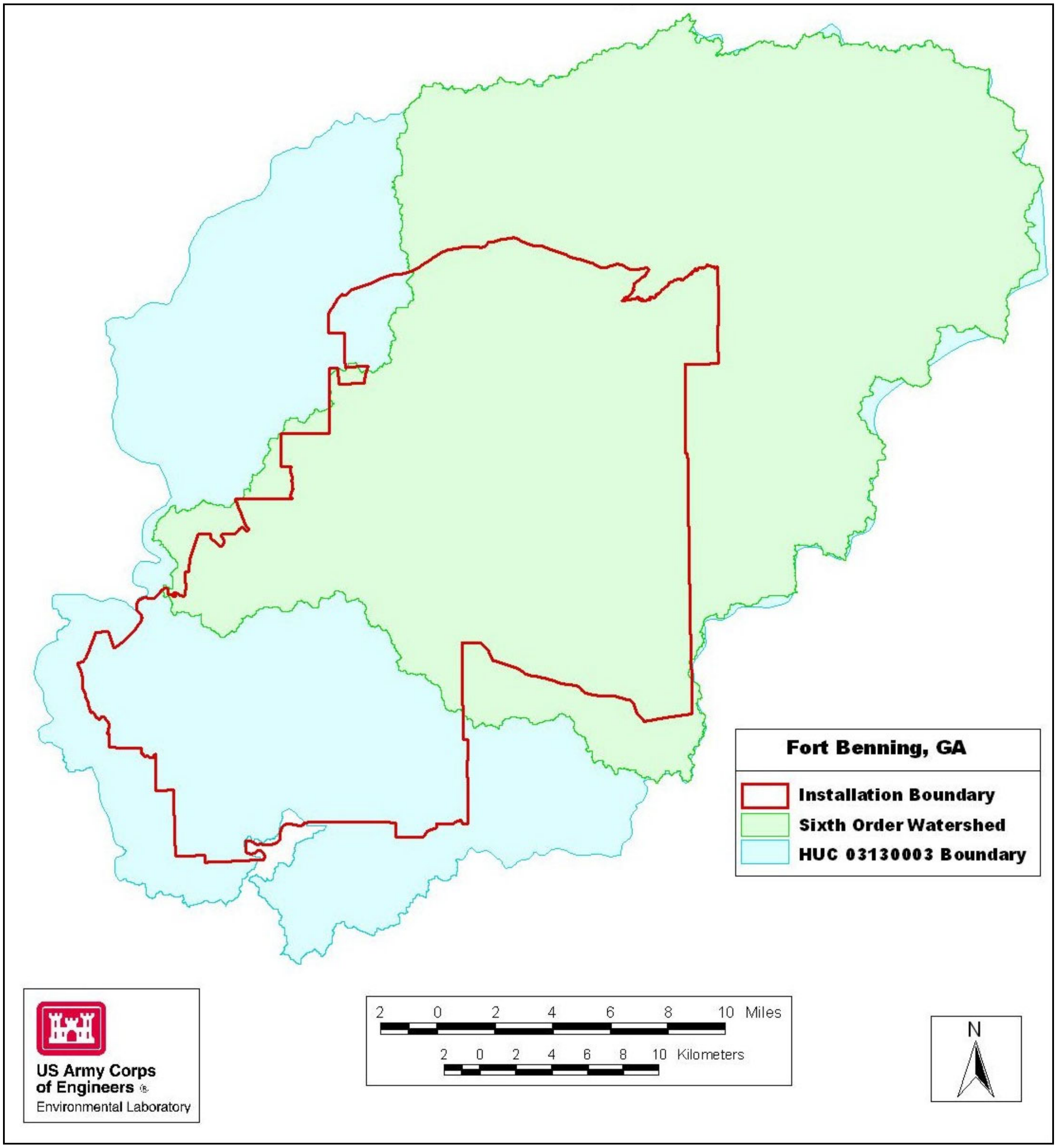

Figure 11. Sixth order watersheds

4 Statistical Analysis of Watershed Order

The goal of this analysis was to relate a number of physical variables to watershed order. These variables (Table 3) are fairly straightforward to measure within a GIS. The parameters that were measured are described in Table 3:

Table 3
Variables Used in the Statistical Analysis

Variable (Variable name)	Type of Variable	Unit of Measure	Description
Order (ORDER)	Interval	Unitless	Dependent Variable
Area (BASIN_AREA)	Ratio	Square meters	Total area of drainage area above an outlet
Number of Stream Segments (NUM_STREAM)	Interval	Integer value (unitless)	Count of total number of stream segments upstream from a watershed outlet
Total Length of Stream Segments (TOT_LENGTH)	Ratio	Meters	Total length of stream segments upstream from a watershed outlet
Perimeter (BASIN_PERIM)	Ratio	Meters	Total perimeter of drainage area above an outlet
Maximum Relief (TOT_RELIEF)	Ratio	Meters	Max elevation – min elevation
Average Slope (AVG_SLOPE)	Ratio	Degrees slope	Average slope in the area

Method

Of all the watersheds listed in Table 1, 30 from each order (orders 1 to 4) were randomly selected from the GIS database. This was done to make the sample from each order as equal as possible to prevent the first order watersheds from biasing the analysis. The random selection process resulted in a sample of 129 watersheds for the regression analysis. Variables listed in Table 3 were calculated using the Arc/Info GIS software (ESRI 2000). The complete dataset is attached (Appendix B).

A multiple regression approach, with stepwise backwards variable selection, was used to determine which independent variables were significant in determining stream order.

Results and Analysis

Model 1

In a model that included all six computed variables, four were found to contribute significantly to the first model (basin area, basin perimeter, total relief, and average slope). The model resulted in an r-square of 0.7741. It was somewhat surprising that neither of the variables directly related to the stream network (number of streams and total length of streams) was found to significantly add to the model.

Table 4
Model 1 Results

Variable	Parameter Estimate	Standard Error	*t* value	*Pr* > |*t*|	Variance Inflation
Basin Area	-6.87469×10^{-9}	1.558417×10^{-9}	-4.41	< 0.0001	9.60798
Basin Perim	0.00003411	0.00000727	4.69	< 0.0001	19.88638
Total Relief	0.01528	0.00356	4.30	< 0.0001	5.89787
Avg Slope	–0.10353	0.04209	–2.46	0.0153	1.21827

Close examination of this complete model shows a significant problem with multicolinearity. Variance inflation values are very high, indicating that several of the variables are highly correlated. Eigenvalues and condition index values are shown in Table 5.

Table 5
Model 1 Colinearity Diagnostics

Variable	Eigenvalue	Condition Index
Basin Area	1.18555	1.75120
Basin Perim	0.13026	5.28317
Total Relief	0.03451	10.26369
Avg Slope	0.01395	16.14182

Model 2

Given the amount of colinearity present in Model 1, a number of alternate models were tested by removing variables. This process of elimination showed that a model that included only two of the variables (total relief, and average slope) (Table 6) accounted for almost all the total variation of Model 1 (r-square of 0.7339), while eliminating colinearity problems (Table 7).

Table 6
Model 2 Results

Variable	Parameter Estimate	Standard Error	*t* value	*Pr* > |*t*|	Variance Inflation
Total Relief	0.02969	0.00160	18.59	< 0.0001	1.02589
Avg Slope	–0.17792	0.04159	–4.28	< 0.0001	1.02589

Table 7
Model 2 Colinearity Diagnostics

Variable	Eigenvalue	Condition Index
Total Relief	0.11886	4.89377
Avg Slope	0.03461	9.06855

Examination of observation diagnostics (DFFITS and DFBETAS) revealed that a number of observations were anomalous. The critical value of DFFITS (2*sqrt(p/n) = 0.25) and DFBETAS (2/(sqrt(n))=0.176) revealed a number of irregular observations. Also, the RSTUDENT diagnostic was used to evaluate outliers. Results of these analyses are presented in Table 8.

Obviously, observations should not be deleted randomly to improve the performance of a model. However, each of the questionable basins was displayed in the GIS, which showed that observations 18 and 103 were located in the easternmost portion of the study area. The streams in this area were digitized from reference maps that differed somewhat from the rest of the study area. These maps were produced during a different period from the rest of the maps and the streams on these source maps were noticeably less detailed than those on the source maps that had been used throughout the rest of the study area. Therefore, these two observations were deleted from the model.

Table 8
Influential Observations and Outliers (numbers given represent observation numbers in data listing – Appendix B)

DFFITS crit val = 0.25	DFBETAS crit val = 0.176	RSTUDENT crit val = 2.7
	4	
18		18
25	25	
43	43	
88	88	
101		101[1]
103	103	103[1]
	115	
	116	
	127	

[1] Observations very close to but not greater than critical value.

Model 3

Tables 9 and 10 (the final model) show the results of eliminating the two questionable observations. The final model produced an r-square of 0.7684, which is nearly as good as Model 1, which had four variables. There is no problem with multicolinearity in this model and observation and outlier diagnostics look very good.

The SAS program is presented in Appendix C.

Table 9
Model 3 Results

Variable	Parameter Estimate	Standard Error	*t* value	*Pr* > |*t*|	Variance Inflation
Total Relief	0.02998	0.00149	20.17	< 0.0001	1.02333
Avg Slope	–0.16417	0.03909	–4.20	< 0.0001	1.02333

Table 10
Model 3 Colinearity Diagnostics

Variable	Eigenvalue	Condition Index
Total Relief	0.12050	4.85925
Avg Slope	0.03417	9.12470

A Shapiro-Wilk analysis was conducted to examine the residuals for normality. Results are shown in Table 11.

Table 11
Model 3 Residual Normality Test

Test	Statistic		*p* Value	
Shapiro-Wilk	W	0.99492	Pr < W	0.9332

Table 12 summarizes the results of each of the models presented above.

Table 12
Results of Stepwise Backwards Multiple Regression Analysis

Model (Case)	Regression Equation	r^2	Std. Error of *Y*
1	-6.87(BA) + 0.00003411(BP) + 0.01528(TR) + 0.01395 (AS)	0.7741	0.22912
2	0.02969(TR) - 0.17792(AS)	0.7339	0.24058
3	0.02998(TR) – 0.16417(AS)	0.7684	0.22764
Note: BA = Basin Area; BP = Basin Perimeter; TR = Total Relief; AS = Average Slope.			

5 Conclusions

The primary objectives of this project were to develop a high-resolution DEM and to produce watershed boundaries and an ordered stream network from this DEM. As the SERDP ECMI monitoring plan is watershed-based, these products were critical to support both monitoring design efforts and future research efforts. The elevation model, stream network, and watershed boundaries have been placed on the ECMI Internet-based data repository and are available to SEMP researchers.

A secondary goal of this project was to statistically analyze of the watersheds to gain a better understanding of the geomorphic relationships between stream order and associated drainage areas. Strong relationships were developed between total relief and average slope.

Surprisingly, a model that included only total relief and average slope gave the best results. Before this analysis, basin area, the number of stream segments, and the total length of streams were thought to be much more important than relief and slope. Interestingly, this model requires absolutely no information whatsoever regarding the stream network. In addition, it is very easy to compute slope and relief using a GIS. Therefore, this model could prove useful for quickly determining the order of a stream in a study area, without requiring the compilation of detailed stream data further up the drainage basin.

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Appendix A
Stream Ordering Program

```
/* This program runs from within Arc/Info, specifically within
/* the Arcedit module of Arc/Info.
/* It is written in Arc Macro Language
/*

&args cover
/* shreve and strahler ordering a coverage

&if [show program] ne 'ARCEDIT' &then &do
   &type this starts from arcedit
   &pause &seconds 3
   &return
&end

/* assume the item JORDER numbers the arcs from the outlet,
/* and that there are no pseudo-nodes
ec %cover%
ef arc
&if ^ [iteminfo %cover% -ARC JORDER -exists] &then
  &return 'This program expects %cover% to have the item JORDER
&if ^ [iteminfo %cover% -ARC SHREVE -exists] &then
  additem SHREVE 4 4 I
&if ^ [iteminfo %cover% -ARC STRAHLER -exists] &then
  additem STRAHLER 2 2 I
sel all
calc %cover%-ID = %cover%#
calc SHREVE = 0
calc STRAHLER = 0

/* statistics
/*   maximum JORDER
/*   maximum %cover%-ID
/*   END
/* &set ord [show statistic 1 1]
/* &set maxid [show statistic 2 1]
/* &type %maxid% arcs up %ord% levels from the mouth.

sel dangle
resel jorder ne 1
calc SHREVE = 1
calc STRAHLER = 1  /* all sources are coded

sel SHREVE = 0
```

```
&label bigloop    /* look at every uncoded arc
  sel SHREVE = 0
  &s num [show number select]
  &ty We now have %num% uncoded arcs
  &if %num% eq 0 &then
     &goto done
  &do index = 1 &to %num%
     &s id = [show arc [show select %index%] item %cover%-ID]
     &set id%index% = %id%  /* write each one to an array
  &end
  &do index = 1 &to %num%   /* for each uncoded arc
    &set id = [value id%index%]
    sel %cover%-ID = %id%
/* &ty ID %index% is %id%
    &s jo = [show arc [show select 1] item jorder]
    select connect
    resel jorder gt %jo%
    &s upnum =  [show number select]
    &if %upnum% eq 0 &then
      &return Error looking upstream from %cover%-ID, arc %id%
    resel shreve gt 0
    &if [show number select] lt %upnum% &then
       &goto continue
    &s thisshreve = 0
    &s maxstrahler = 0
/* we can handle more than two upstream arcs, though results may not be
perfect
    &s ui = 1  /* build my own loop
    &label innerloop  /*****&do ui = 1 &to %upnum%
       &s ushreve = [show arc [show select %ui%] item shreve]
/*       &if %ushreve% eq 0 &then;&goto continue
       &s thisshreve = %thisshreve% + %ushreve%
       &s ustrahler = [show arc [show select %ui%] item strahler]
       &if %ustrahler% eq %maxstrahler% &then
         &s maxstrahler = %maxstrahler% + 1
       &if %ustrahler% gt %maxstrahler% &then
    &s maxstrahler = %ustrahler%
     &s ui = [calc %ui% + 1]
     &if %ui% le %upnum% &then; &goto innerloop        /******    &end
/* &ty recoding arc %index% %id%
    sel %cover%-ID = %id%
    calc shreve  = %thisshreve%
    calc strahler = %maxstrahler%
    &label continue  /* finished this arc
/* &ty that was arc %index% %id%
  &end  /* finished iteration through all uncoded arcs
&goto bigloop  /* look at all uncoded arcs again
&label done

save
```

Appendix B
Data Listing

Observation	POLY_ ID	ORDER	BASIN_AREA	BASIN_ PERIM	NUM_ STREAM	TOTAL LENGTH	TOTAL RELIEF	AVERAGE SLOPE
1	2	1	1100010.00	6880.03	1	1969.75	49.879	3.7370
2	3	1	204302.08	2460.01	1	352.40	65.147	10.2772
3	4	1	51700.54	1360.01	1	215.39	37.712	8.1660
4	5	1	91001.01	1640.01	1	313.46	32.593	9.0115
5	6	1	76499.72	1420.00	1	380.32	48.132	9.2110
6	7	1	639697.86	6459.99	1	1609.27	31.723	2.8279
7	8	1	216398.76	3159.99	1	782.25	39.899	5.2781
8	9	1	361197.63	3559.99	1	1099.00	34.753	3.9547
9	10	1	22300.22	1260.01	1	190.93	31.528	4.5983
10	11	1	155499.21	2459.99	1	796.23	26.227	2.9384
11	12	1	289698.57	3280.00	1	928.11	28.285	2.7722
12	13	1	101699.62	1760.00	1	419.08	34.092	6.4071
13	14	1	680490.61	4579.97	1	1083.48	43.280	4.5569
14	15	1	63700.76	1380.01	1	275.90	26.939	4.3450
15	16	1	133998.19	2099.98	1	402.07	34.040	5.4292
16	17	1	108497.82	2199.98	1	359.08	38.493	5.1055
17	18	1	436091.98	3839.97	1	973.42	50.859	4.4126
18	19	1	2480174.69	9239.96	1	2142.02	81.011	4.4848
19	20	1	473295.71	4279.98	1	998.50	56.261	3.9671
20	21	1	181998.29	2479.99	1	518.14	47.385	4.6057
21	22	1	130398.88	2479.99	1	284.55	35.134	4.8874
22	23	1	639092.34	5279.96	1	1360.53	50.851	4.9322
23	24	1	142298.77	2279.99	1	615.65	28.624	4.9934
24	25	1	422995.31	3879.98	1	509.08	39.042	3.4292
25	26	1	824389.98	5719.96	1	1503.39	75.698	7.4465
26	27	1	75099.09	1619.99	1	399.30	44.069	4.7137
27	28	1	339695.99	3759.98	1	712.09	76.114	5.3104
28	29	1	222197.74	2539.99	1	399.72	43.639	5.3262
29	30	1	187997.55	2439.99	1	512.54	54.106	8.3820
30	31	1	39399.99	1100.00	1	185.45	17.879	4.5225
31	2	2	3389831.05	13520.06	3	4874.81	78.004	6.3018
32	3	2	1868818.04	10260.05	5	4040.55	79.092	7.7679
33	4	2	3732231.19	14406.03	20	8715.67	95.106	5.3761
34	5	2	820756.72	6134.19	3	2212.93	47.167	5.4993
35	6	2	1876785.94	9439.97	5	3676.73	48.484	4.0766
36	7	2	785108.26	5000.03	5	1436.70	43.305	3.1473
37	8	2	454396.32	3579.98	3	1554.22	25.686	2.8995
38	9	2	3871898.63	13461.00	9	6080.64	85.159	3.9559
39	10	2	12704922.29	20879.96	13	12899.95	97.920	4.5522
40	11	2	1576174.24	8139.94	9	4022.90	93.547	4.8909
41	12	2	1396178.76	8599.95	3	2849.35	57.702	4.8727
42	13	2	2609377.52	10159.96	3	3481.65	70.236	5.7291
43	14	2	208698.30	2339.99	3	967.07	16.470	1.5838
44	15	2	1520786.00	7919.98	3	2508.85	69.940	4.9195
45	16	2	5520011.58	16139.86	13	10264.87	80.467	4.5053
46	17	2	469293.33	4379.97	3	1316.63	26.888	2.1181
47	18	2	2127477.57	10839.91	7	5127.01	102.179	5.1607
48	19	2	655493.72	4519.91	3	1747.16	54.904	4.7889
49	20	2	569092.70	3980.06	3	1144.91	53.594	5.7223
50	21	2	1469484.94	7919.97	7	3088.10	100.462	6.0767
51	22	2	1273187.04	6539.97	9	2974.12	71.043	6.4272

52	23	2	1626585.06	7519.97	5	2838.07	69.923	5.2725
53	24	2	1995578.72	8759.95	5	3537.68	64.527	4.9657
54	25	2	2378873.82	10239.94	7	4149.00	72.243	5.8163
55	26	2	1763282.46	7939.96	5	3321.59	71.110	6.8473
56	27	2	732996.18	4819.98	3	1402.67	43.941	5.9357
57	28	2	1709092.66	7459.99	3	2759.96	82.125	6.5794
58	29	2	691901.97	5080.01	3	1309.04	61.906	5.9709
59	30	2	1392115.61	8040.04	3	3495.20	88.042	6.2474
60	31	2	961009.78	6140.03	5	2159.52	61.021	6.0492
61	2	3	15770895.62	29918.69	78	37719.57	109.249	8.1428
62	3	3	7640569.18	15960.07	17	15999.78	102.042	7.1082
63	4	3	9684440.57	27418.57	37	21851.37	108.031	5.7343
64	5	3	8250308.52	20758.67	24	19664.02	107.337	6.3733
65	6	3	3732233.55	14406.42	20	8715.71	95.106	5.3761
66	7	3	6513670.95	17840.10	37	14823.08	70.088	5.4526
67	8	3	10899735.12	25239.93	21	20615.99	83.232	4.4883
68	9	3	4245539.27	12480.06	15	7987.95	70.166	5.2541

Stream Order / Basin Relationship Study

Observation	POLY_ ID	ORDER	BASIN_AREA	BASIN_ PERIM	NUM_ STREAM	TOTAL LENGTH	TOTAL RELIEF	AVERAGE SLOPE
69	10	3	4132939.38	13220.06	25	10554.42	80.037	5.6238
70	11	3	2147523.86	9860.05	13	5773.49	52.781	4.6207
71	12	3	3259182.50	11579.97	19	9771.41	52.970	3.5360
72	13	3	7254346.67	20219.94	24	16292.73	70.187	3.0031
73	14	3	2398425.92	9659.92	19	7864.12	58.777	3.7397
74	15	3	2729202.11	10040.01	17	7345.18	60.671	4.8187
75	16	3	2826321.35	10648.44	13	6994.46	53.800	3.3001
76	17	3	3888650.39	11399.93	8	7168.69	60.549	4.2469
77	18	3	25157270.20	42800.97	27	22163.76	109.761	3.4728
78	19	3	15063646.14	24619.98	19	16053.16	105.367	4.5693
79	20	3	2437118.06	9060.03	13	5486.92	84.195	5.1394
80	21	3	3663790.12	12735.79	13	7823.62	79.809	5.3764
81	22	3	3813647.36	12159.92	9	4498.62	82.582	4.4629
82	23	3	2412574.96	9198.84	7	5522.58	73.403	5.0170
83	24	3	2107279.07	9119.94	11	5064.85	73.229	5.4481
84	25	3	2125179.36	8579.96	13	6214.97	63.172	6.2861
85	26	3	10761819.24	24839.90	27	22436.60	84.170	5.1409
86	27	3	4174547.43	15252.36	15	8998.26	76.728	4.7143
87	28	3	7764853.54	18194.42	25	14890.87	92.075	7.0254
88	29	3	3207858.58	11419.92	13	6285.99	76.990	8.3604
89	30	3	6039185.99	14760.04	13	9211.65	75.113	6.1259
90	31	3	6731369.41	16580.09	27	14119.60	104.737	6.4811
91	2	4	56191882.95	63336.30	309	143717.46	145.641	6.3134
92	3	4	18652171.84	32900.15	33	35300.91	117.052	6.8378
93	4	4	41251300.08	42760.14	72	63453.84	104.324	4.5525
94	5	4	47321737.74	62166.85	231	120933.88	144.561	5.9401
95	6	4	24068549.45	37378.61	85	55943.51	114.786	5.7640
96	7	4	18119805.93	28166.36	70	44777.89	114.154	4.8435
97	8	4	63552781.37	57500.18	103	83650.82	122.376	5.0482
98	9	4	31419167.50	39799.93	159	83075.04	123.231	5.4059
99	10	4	24206929.33	39819.88	59	46802.58	136.369	4.2132
100	11	4	24168305.74	45279.74	54	38785.70	116.501	3.9637
101	12	4	11301485.13	21760.02	65	31337.82	66.718	4.3441
102	13	4	53775908.72	53000.03	75	62358.62	121.204	4.4769
103	14	4	5637083.33	14831.72	28	14313.86	56.421	2.9801
104	15	4	42668664.38	48941.36	71	45585.09	114.647	3.5154
105	16	4	84187617.06	60584.10	137	109778.63	137.981	4.4414
106	17	4	24544258.46	33997.81	80	46190.60	97.709	4.6276
107	18	4	12991071.70	26654.49	58	28275.32	100.514	5.1543
108	19	4	25319957.59	34859.83	134	65210.94	138.361	5.4314
109	20	4	37118802.20	40320.68	110	65184.05	131.062	5.6954
110	21	4	18011502.58	30573.10	83	42656.50	135.534	5.3345
111	22	4	11311537.73	22419.85	37	19768.72	72.984	4.9865
112	23	4	8079714.61	16039.91	35	17161.07	89.230	5.8796
113	24	4	21075933.36	35499.80	63	40853.99	119.317	5.2795
114	25	4	26785784.96	31999.66	64	45488.77	120.806	6.3245
115	26	4	21878206.23	34859.84	80	46932.32	77.128	4.2687
116	27	4	20663762.32	27812.55	32	28491.21	84.895	1.7033
117	28	4	33580609.11	43056.63	100	68271.47	99.415	4.3033
118	29	4	23941751.24	31075.66	80	44632.63	111.988	7.0199
119	30	4	65281381.83	55994.07	204	125214.10	118.143	6.6324
120	31	4	11833230.97	23920.04	35	21047.77	100.148	6.1876
121	2	5	115295622.70	80940.33	207	204224.37	148.607	5.5491
122	3	5	133881999.30	90346.13	528	321276.33	155.809	4.5782
123	4	5	131583439.50	89240.15	191	158761.41	130.557	4.7181
124	5	5	182565820.30	106919.51	612	377752.73	168.146	4.2073
125	6	5	198861746.90	97100.66	608	358490.63	156.084	4.9036
126	7	5	172652656.90	104795.05	465	301315.14	163.615	5.4982
127	8	5	83396055.60	65999.75	244	170440.54	122.762	4.4899
128	9	5	143098334.90	102620.10	435	275976.62	155.038	6.3726
129	2	6	1172786555.00	286513.22	3644	2230770.52	203.684	4.9803

Appendix C
SAS Program

```
OPTIONS NOCENTER PS=51 LS=80 NODATE NONUMBER;

FILENAME streamdat ‘C:\STREAMSTUDY\STREAM.DAT’;
DATA STREAMDATA;
TITLE 'Stream Order / Basin Relationship Study';
INFILE streamdat MISSOVER;
INPUT OBSIDPOLY_ID ORDER BASIN_AREA BASIN_PERIM NUM_STREAM TOT_LENGTH
TOT_RELIEF AVG_SLOPE;
logorder = log(order);
RUN;
;

*** DATA LISTING ****;

RUN;
PROC PRINT DATA=STREAMDATA;
RUN;

***  MULTIPLE REGRESSION ****;

TITLE2 "MULTIPLE REGRESSION ";
PROC REG DATA=STREAMDATA LINEPRINTER;
  MODEL ORDER = TOT_RELIEF NUM_STREAM TOT_LENGTH AVG_SLOPE / influence vif
partial collin selection = backward;
  PLOT RESIDUAL.*PREDICTED.;
  OUTPUT OUT=RESDATA P=YHAT R=E;
RUN;

***  RESIDUAL ANALYSIS ****;

proc univariate data=RESDATA normal plot;
var e;
run;

QUIT;
```

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14. ABSTRACT

This paper describes the procedures followed to develop a detailed watershed database for Fort Benning, Georgia, and the surrounding area. In addition, the relationship between watershed morphology and stream order was examined. Watershed order and a number of variables describing surface topography and the network were computed and statistical analysis procedures were used to develop a predictive relationship. Watershed boundaries were computed from a digital elevation model and assigned an order using the Strahler stream-ordering technique. This procedure is rather tedious and requires that all the drainage network upstream of the area of interest be digitized. A number of physical parameters defining these watersheds were computed using a geographic information system (GIS) and the relationship of these parameters to stream order was examined. The purpose of this analysis was to determine if stream order could be predicted reliably using a number of computed physical parameters. Regression analysis showed that stream order had a highly significant relationship (r-square = 0.77) with two easily computed variables: total relief, and average slope. A procedure for estimating stream order, within an acceptable degree of error, could be beneficial for many applications, such as assisting in the parameterization of hydrologic models.

15. SUBJECT TERMS

	Fort Benning, Georgia	Regression
DEM	GIS	Stream order
Elevation	Model	Watershed

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