# A Dynamic Optimization Technique for Siting the NASA-Clark Atlanta Urban Rain Gauge Network (NCURN)

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## Abstract

Because Atlanta is a model of rapid transition from forest/agriculture land-use to urbanization, NASA and other agencies have initiated programs to identify and understand how urban heat islands impact the environment in terms of land use, air quality, health, climate, and other factors. Atlanta's UHI may also impact the global water cycle by inadvertent forcing of precipitating cloud systems. Yet, a focused assessment of the role of urban-induced rainfall in Atlanta has not been a primary focus of past efforts. Several observational and climatological studies have theorized that the UHI can have a significant influence on mesoscale circulations and resulting convection. Using space-borne rain radar and a limited network of irregularly spaced, ground-based rain gauges, Shepherd et al. (2002) recently found evidence that the Atlanta, Dallas, and San Antonio urban areas may modify cloud and precipitation development.

To validate these recent satellite-based findings, it was determined that a higher density of rainfall gauges would be required for future work. The NASA-sponsored Study of PRecipitation Anomalies from Widespread Urban Landuse (SPRAWL) seeks to further address the impact of urban Atlanta on precipitation variability by implementing a dense rain gauge network to validate space-borne rainfall estimates. To determine the optimal location for the gauges, a Geographical Information System aided by a Spatial Decision Support System has been developed. A Multi-Criteria Decision Analysis technique was developed to locate optimal sites in accordance to the guidelines defined by the World Meteorological Organization (WMO). The Multi-criteria Decision Analysis (MCA) model for the optimization of prospective sites was applied to predict prime locations for the Tipping Bucket Rain Gauges. The MCA design required development of a spatial model by applying a series of linear programming methods, with the aid of spatial analytical techniques in order to identify land sites that meet a particular set of criteria.

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## Popular Summary

Recently, NASA satellites and ground instruments have indicated that cities like Atlanta, Georgia may create or alter rainfall. Scientists speculate that the urban heat island caused by man-made surfaces in cities impact the heat and wind patterns that form clouds and rainfall. However, more conclusive evidence is required to substantiate findings from satellites. NASA, along with scientists at Clark Atlanta University, are implementing a dense, urban rain gauge network in the metropolitan Atlanta area to support a satellite validation program called Studies of PRecipitation Anomalies from Widespread Urban Landuse (SPRAWL). SPRAWL will be conducted during the summer of 2003 to further identify and understand the impact of urban Atlanta on precipitation variability. The paper provides an overview of SPRAWL, which represents one of the more comprehensive efforts in recent years to focus exclusively on urban-impacted rainfall. The paper also introduces a novel technique for deploying rain gauges for SPRAWL.

The deployment of the dense Atlanta network is unique because it utilizes Geographic Information Systems (GIS) and Decision Support Systems (DSS) to optimize deployment of the rain gauges. These computer-aided systems consider access to roads, drainage systems, tree cover, and other factors in guiding the deployment of the gauge network. GIS and DSS also provide decision-makers with additional resources and flexibility to make informed decisions while considering numerous factors. Also, the new Atlanta network and SPRAWL provide a unique opportunity to merge the high-resolution, urban rain gauge network with satellite-derived rainfall products to understand how cities are changing rainfall patterns, and possibly climate.

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## 1. Introduction

It is estimated that by the year 2025, 60% of the world's population will live in cities (UNFP, 1999). In the United States, the current urban growth rate is approximately 12.5%, with 80% currently living in urban areas. Urbanization is one extreme example of land cover and land use changes due to human activities. Howard (1833a) made the first documented observation of a temperature difference between an urban area and its rural environment. Manley (1958) termed this contrast the "urban heat island (UHI)". The UHI has now become a widely acknowledged, observed, and researched phenomenon because of its broad implications. In cities, natural land surfaces are replaced by artificial surfaces that have very different thermal properties (e.g., heat capacity and thermal inertia). Such surfaces are typically more capable of storing solar energy and converting it to sensible heat. Other contributing factors to the onset of the UHI may be attributed to differences in surface albedo and anthropogenic heat release in the urban area. As sensible heat is transferred to the air, the temperature of the air in urban areas tends to be 2-10 ° C higher than surrounding non-urban areas. Figure 1 illustrates the UHI signature of the city of Atlanta, Georgia using infrared imagery captured by the airborne Advanced Thermal and Land Application System (ATLAS) on May 11 and 12, 1997).

The literature indicates that the signature of the "urban heat island effect" may be resolvable in rainfall patterns over and downwind of metropolitan areas. However, a recent U.S. Weather Research Program panel concluded that more <u>observational</u> and modeling research is needed in this area (Dabberdt et al. 2000). Rapid population growth in the last few decades has made Atlanta one of the fastest growing metropolitan areas in the United States. The population of the Atlanta metropolitan area increased 27% between 1970 and 1980, and 33% between 1980-1990 (Research Atlanta, Inc., 1993). From 1973 to 1992, the Atlanta area experienced a decline of nearly 20% in forestland. LANDSAT 5 data in figure 2 illustrate the rapid growth of urban surfaces in Atlanta. Because Atlanta is a model of rapid transition from forest/agriculture land-use to urbanization, NASA and other agencies have initiated programs such as the Atlanta Land-use Analysis: Temperature and Air Quality Project (ATLANTA) (Quattrochi et al. 1998). Project ATLANTA was a multi-disciplinary effort 1) to investigate and model the relationship between Atlanta urban growth, land cover change, and the development of the urban heat island; 2) to investigate and model the relationship between Atlanta urban growth and land cover change on air quality; and 3) to model the overall effects of urban development on surface energy budget characteristics across the Atlanta urban landscape through time at nested spatial scales from local to regional.

## 2. Motivation and Previous Work

Such focus has led to a wealth of information on Atlanta's urban heat island (UHI) environment. Atlanta's UHI may also impact the global water cycle by inadvertent forcing of precipitating cloud systems. Bornstein and Lin (2000) used data from Project ATLANTA's 27 mesonet sites and eight National Weather Service sites to investigate interactions of the Atlanta UHI, its convergence zone, and convective storm initiation. In an analysis of six precipitation events during the summer of 1996, they showed that the UHI could induce a convergence zone that could initiate convection. However, a focused assessment of the role of <u>urban-induced rainfall</u> in Atlanta has not been a <u>primary</u> focus of past efforts. Using space-time averaged rainfall estimates from the Tropical Rainfall Measuring Mission's (TRMM) Precipitation Radar (PR) and a limited network of irregularly spaced, ground-based rain gauges, Shepherd et al. (2002) recently found evidence that Atlanta and other urban areas may modify cloud and precipitation development. Using a 15-month (spanning three years) analysis of mean rainfall rates, the cities of Atlanta, Montgomery, Dallas, Waco, and San Antonio were examined. Shepherd et al. (2002) found that the average percentage increase in mean rainfall rate in a hypothesized "downwind maximum impact area" over the "upwind control area" was 28.4% with a range of 14.6 to 51%. Over the urban area, the average change was smaller (+5.8%) but exhibited a range of −27.7 to 24.7%.

There was a slight indication that regions orthogonal and to the right of the mean prevailing flow (within 50 km) experienced relatively significant increases in rainfall (10.7%). However, the downwind region or Maximum Rainfall Impact region exhibited the most significant changes. Shepherd et al. (2002) also demonstrated that maximum rainfall rates found in the maximum impact area exceeded the mean value in the upwind control area by 48 to 116%. This maximum value was found at an average distance of 39 km from the edge of the urban center or 64 km from the exact center. The range was 20-60 km downwind of the edge of the urban center.

Shepherd et al. (2002)'s results are consistent with previous work. For example, early investigations (Changnon 1968; Landsberg 1970; Huff and Changnon 1972a) found evidence of warm seasonal rainfall increases of 9 to 17% over and downwind of major cities. The Metropolitan Meteorological Experiment (METROMEX) was an extensive study that took place in the 1970s in the United States (Changnon 1978; Huff 1986) to further investigate modification of mesoscale and convective rainfall by major cities. In general, results from METROMEX have shown that urban effects lead to increased precipitation during the summer months. Increased precipitation was typically observed within and 50-75 km downwind of the city reflecting increases of 5%-25% over background values (Huff and Vogel 1978, Changnon 1979; Changnon et al. 1981; Changnon et al. 1991). More recent studies have continued to validate and extend the findings from pre-METROMEX and post-METROMEX investigations (Balling and Brazel 1987; Jauregui and Romales 1996; Bornstein and Lin 2000; Kusaka et al. 2000; Thielen et al. 2000; Baik et al. 2001; Ohashi, and Kida 2002a; Changnon and Westcott 2002).

Shepherd et al. (2002) established that space-based precipitation observing systems might be able to detect UHI-induced rainfall variability. Furthermore, the TRMM database now spans nearly 6 years rather as opposed to the 3 years of data used in the earlier study. This is particularly intriguing because understanding of urban effects on rainfall is far from complete. First, previous research used ground observations to study one or few selected cities. However, urban effects vary with the micro- to mesoscale features of individual cities. Globally assessment of urban climate over long periods of time is necessary to generalize the most important characteristics of urban effects. Second, previous studies, via different approaches, reached conflicting understanding on urban-rainfall relations. It is reported that urban reduces rainfall due to cloud microphysics (Ramanathan et al. 2001), although historical and more recent studies showed that urban enhances rainfall over and downwind of cities (see previous paragraph). The mechanisms of urban effects on rainfall are complex. On one hand, cloud microphysics, in response to increased urban aerosols may reduce rainfall, as suggested by Rosenfield (1999). On the other hand, local dynamics and thermodynamics associated with an UHI-induced convergence zone and a destabilized boundary layer may enhance urban rainfall (Shepherd et al. 2002, Changnon and Westcott 2002, Ohashi and Kida 2002a).

Shepherd et al. (2002) also demonstrated that the existing rain gauge network, the University of Georgia Automated Environmental Monitoring Network (AEMN) (Hoogenboom, 1996), (Figure 3-top panel a.) might not be sufficiently dense to capture the convective to meso-gamma scale rainfall anomalies associated with the urban heat island. In an analysis of AEMN rain totals for May-September (1998-2000), rainfall maxima located southeast of the city were consistent with TRMM-retrieved maxima in rainfall rates (Figure 3-top panel b). Rainfall totals were binned in the same manner as the TRMM PR data from 1998 to 2000. Figure 3 (bottom panel b) illustrates a broad maximum in TRMM-derived rain rates (mm/h) south-southeast of the city during the May to September period. Shepherd et al. (2002) determined that the southeast quadrant of Atlanta was the climatalogical downwind region relative to the 700 hPa steering flow. A similar distribution is found in the AEMN rain gauge totals (mm) in figure 3 (top panel a) but a significant gap (black oval) is also present. Though rates are compared to amounts, the consistency of the relative maxima provided encouraging validation for the PR. But, a close examination of figure 3 (top panel a) reveals that regions (particularly southeastern sections) of metropolitan Atlanta are poorly sampled by the AEMN network thereby leading to possible

biases or gaps in the data. This point illustrates the need for a higher density network near Atlanta to validate the TRMM satellite-indicated rainfall anomalies.

When designing field measurement networks, it is important to be aware of the influence that instrumentation, siting, and sensor exposure have upon the measurements (Thuillier 1995). Section 3 will discuss the evolution of a high-density rain gauge network around Atlanta. Section 4 will discuss an innovative, Multi-Criteria Decision Analysis (MCDA) technique that has been developed to locate optimal rain gauge sites. Section 5 will provide results of the MCDA analysis. Section 6 will offer conclusions and future work.


## 3. NASA Clark Atlanta Urban Rain Gauge Network (NCURN)

NASA is developing the NASA-Clark Atlanta University (CAU) Urban Rain Gauge Network (NCURN). NCURN will be operated in conjunction with faculty and students at Clark Atlanta University and supplement AEMN and National Weather Service sites. The network will consist of 25-30 gauges spaced at a resolution of approximately 25.0-km and centered on the geographic center of the Atlanta metropolitan area. Figure 4 is an idealized, non-optimized NCURN configuration. The NCURN is being implemented as a long-term observation system and to support the 2003 Study of PRecipitation Anomalies from Widespread urban Landuse (SPRAWL) experiment. SPRAWL is a NASA-funded effort to further examine the impact of urbanization on precipitation processes. It will supplement ongoing efforts to conclusively identify the existence of urban-generated rainfall and its physical forcing mechanisms. The specific objectives of SPRAWL are:

- To conduct an intensive ground validation campaign of TRMM PR findings during the summer of 2003 (July-August) using the dense NCURN network in Atlanta and surrounding areas.

- To utilize diverse datasets (e.g. TRMM, NCURN, AEMN, and WSR-88D) to identify and quantify "urban-induced" rainfall events over a 1-month period of intensive observation (IOP).

- To develop a "case study" validation dataset for comparison with simulations using the NASA Goddard Space Flight Center's version of the Mesoscale Modeling System (MM5) (Grell et al. 1994) coupled to the Parameterization for Land-Atmosphere-Cloud Exchange (PLACE) land surface model (Wetzel and Boone 1995)

    a) MM5-PLACE case studies will improve understanding of physical-dynamical processes that lead to urban-induced circulations. A new urban land parameterization is currently being implemented into PLACE to more accurately resolve critical urban parameters like roughness length, skin temperature, albedo, leaf-area index, and vegetative fraction. This parameterization is based on MODIS and airborne LIDAR-derived parameters.

- To develop a prototype continental-urban rainfall validation site for TRMM and future precipitation missions (e.g. Global Precipitation Measurement) to mitigate the problem of insufficient continental validation sites (Kummerow et al. 2000).

- To provide high spatial resolution, long-term rainfall monitoring capability around Atlanta.

SPRAWL is a joint effort between NASA and the Earth System Science Program (ESSP) at Clark Atlanta University. The University of Georgia and University of Virginia might also play key roles. SPRAWL's NCURN network will supplement the AEMN with a nested set of tipping

bucket rain gauges. To facilitate a meaningful comparison with satellite-based rainfall estimates, we will develop a set of rainfall products consistent with the TRMM PR and NCURN gauge measurements. Both TRMM and NCURN-gauge products will be objectively analyzed to a standard Cartesian reference grid. The standard products to be analyzed at 0.25 degree resolution daily, weekly, and monthly are: Mean/Median rainfall rate (mm/h), Total amount rainfall (mm), Total Days with Measurable Rain, and occurrence of 2-, 5-, 10-, 25-, 50-, and 100-year rainfall events. The tentative schedule for SPRAWL includes:

| | |
|---|---|
| June-August 2002 | Identify Potential NCURN sites with Dynamic Optimization Technique |
| August 2002-July 2003 | Install NCURN Gauges |
| August 2002-July 2003 | Develop software to merge/analyze NCURN/AEMN rainfall products |
| August 14-31 2003 | Intensive Observation Period (IOP) |

## 3.2    Preliminary IOP Operation Plan

SPRAWL scientists will monitor meteorological conditions daily to identify all convective storms (e.g. thunderstorms that produce rainfall at the ground) that develop within a 150 km-radius of the central Atlanta urban district. Development will be defined based on the initial appearance of a 30-dBZ-radar echo. The storms must not be associated with a large-scale weather system (e.g. frontal). National Weather Service WSR-88D radar, GOES satellite, and NCURN data will be utilized to establish the life cycle of the storm event.

Following identification, each storm event will catalogued. For each event, an analysis of surface conditions (e.g. temperature, moisture, convergence, wind field, precipitation amount, precipitation rate) and upper atmospheric conditions will be provided from 6 hours prior to the storm event until 6 hours after the event (e.g. 0-dBZ radar echo).

## 3.3    Post IOP Analysis

The post IOP analysis will seek:

- To identify case events that are non-urban-generated, urban-generated, or urban influenced (e.g. intensity change due to urban-induced forcing).

- To define Upwind Control Region, Urban Zone Region, and Downwind Impact Region based on the upper-level wind analyses for each storm event.

- To partition storm event origin, maturation, and decay by location relative to an Upwind Control Region, Urban Zone Region, and Downwind Impact Region.

- To link possible rainfall anomalies with surface, boundary layer, or upper level thermodynamic and dynamic states.

- To conduct GCE-PLACE and MM5-PLACE model simulations of selected event cases.

Prior to deployment and the IOP periods, a strategy was required to optimally site the NCURN rain gauges. The primary objective of the article is to discuss an innovative multi-criteria, Geographic Information System (GIS)-based technique to optimize the siting of the high-density network based on prescribed parameters. The following sections will discuss the philosophy, methodology, and results of this new technique within the context of planning the NCURN-SPRAWL network.

## 4. GIS-BASED Multi-Criteria Decision Analysis (MCDA) for Siting NCURN Gauges

### 4.1 Background

The success of SPRAWL and future long-term rainfall monitoring with NCURN depends on optimal siting of the rain gauges. The Qualimetrics Model 6011A tipping bucket rain gauge will be implemented in NCURN. This model has a tipping rate of 0.254 mm/tip. Table 1 includes additional characteristics of the gauge. Each gauge is also equipped with a Model Z005142 Precipitation Event Recorder/Data Logger that records data, time, and a variety of rainfall data. The logger enables flexibility to set totaling intervals from one second to eight hours. Data is archived on a computer with processing software.

**Table 1**

| | |
|---|---|
| Output: | 0.1 second switch closure |
| Accuracy: | +/-0.5% at 12.7mm/hr |
| Collector Orifice: | 207 mm |
| Size: | 210 x 445 mm |

Dense rain gauge networks like NCURN provide detailed measurements of precipitation to assess convective-mesoscale precipitation variability in space and time. Networks have been used to define rainfall-runoff relationships for basins, to evaluate weather modification endeavors, to assess the impact of urbanization on precipitation, and to define radar-rain gauge measurement relationships (Changnon 2002). To ensure success, NCURN gauges must be optimally sited (1) to capture mesoscale precipitation features, (2) to validate gridded TRMM rainfall products, (3) to be accessible, and (4) to meet World Meteorological Organization standards for siting gauges. Site search problems can be attributed to locating and configuring a finite area optimally to serve a given application. A site's suitability, area, cost and spatial relationships with other geographic features are important considerations. Spatial characteristics such as shape and contiguity are also important to consider. Early site suitability methods were conducted using the sieve-mapping procedure, which required tracing paper overlays in landscape architecture and facilities location (Mcharg, 1969) and optimal agricultural land use mapping (Bibby and Mackney 1969). These procedures adopted Boolean logic and integrated polygon overlay analysis and cartographic modeling.

The capacity of GIS for integrating information from a variety of sources in a spatial context makes them well suited to supporting decision-making procedures that must take account of multiple factors (Jones et al. 1996). Decision Support Systems (DSS) are approaches for applying information systems technology to increase the effectiveness of decision-makers in situations where the computer can support and enhance human judgement (Dhar and Stein 1997). DSS are also described as interactive computer programs that utilize analytical methods, such as decision analysis, optimization algorithms, and program schedule routines for developing models to help decision-makers formulate alternatives, analyze their impacts and interpret and select appropriate options for implementation (Adelman 1992).

We describe a technique to utilize GIS and DSS in a Multi-Criteria Decision Analysis (MCDA) approach for siting rain gauges. The MCDA provides optimal NCURN site location for hydrological-meteorological applications while demonstrating a more efficient approach for

siting future rain gauge or instrument networks. MCDA also demonstrates the feasibility of incorporating GIS/DSS systems in hydrological and meteorological applications.

## 4.2   Methodology

The primary study area is located within Georgia and extends north and south of the Atlanta Metro area. The Atlanta metro area includes seven counties – namely Clayton, Cobb, Dekalb, Fulton, and Gwinnett, but an additional 28 counties were included as part of the coverage area. Two separate databases, a spatial database and a temporal database, were developed. The boundaries of the spatial database were set in accordance with the location of the above-mentioned 40 county area. Figure 4 illustrates the spatial database boundaries. The boundaries of the temporal database were set within a three-year period extending from 1999 to 2002.

### i.   Data Acquisition

The data acquisition process required a concise analysis of the existing data and the varying data formats. From initial observations, there were two general types of geographic data models, vector and raster data. The existing spatial geo-database acquired from a series of well-known data repositories served as a foundation for building the final spatial geo-database. The data repositories were the Georgia GIS Clearing House, the Environmental Systems Research Institute – Data map series, the United States Geological Survey (USGS) and the Georgia Department on Natural Resources (DNR).

A point coverage depicting the proposed location of the tipping bucket rain gauge sites (refer back to Figure 4) was derived by digitizing each point at 25-km spacing. The specified spacing is based on the anticipated resolution of the Version 6 TRMM 3-hourly rainfall product (Adler et al. 2003a) and is one-half the resolution of the gridded TRMM 3A25 precipitation radar product used by Shepherd et al. (2002). The initial development of the spatial geo-database included a spatial subset based on 40 county coverage of the intended study area. Further data development based on the 40 county coverage involved the geo-processing methodology, where the creation of subsets of the drainage, road, landuse/landcover and elevation datasets was required for the final spatial geo-database. This process was followed by the development of a temporal geo-database. The geo-database derived from the Digital Environmental Atlas of Georgia was considered precise for the Multi-criteria Analysis and was compared to the datasets acquired from the other repositories for data consistency and suitability.

The Digital Environmental Atlas of Georgia is a CD-ROM set containing 37 digital map data sets covering the State of Georgia. The dataset includes: Towns and Cities, Public Lands, State Parks, Trails and Greenways, County Boundaries, Geographic Names, Hydrologic Units, Shorelines, Soils, Landcover, Major Roads, Public Airports, River Reach - Major Streams, Roads, Ground-Water Site Inventory, Hydrography, 7.5 Minute Quadrangle Index, Surface-Water Monitoring Stations, Elevation Contours, 1:250,000-scale Digital Elevation Model, 1:100,000-scale Digital Raster Graphic, 1:250,000-scale Digital Raster Graphic, 1:500,000-scale Digital Raster Graphic, Level-I Landuse/Landcover.

### ii.   Criteria Evaluation

Criteria evaluation parameters were based on specifications in the World Meteorological Organization handbook (WMO 1983). The basic requirements for rainfall measurements as defined by WMO consider several issues to mitigate error sources. There are many sources of error in rainfall assessment from rain gauges: sampling, exposure, evaporation, adhesion, splash, and wind ventilation effects.

The greatest source of rainfall measurement error from gauges is related to inherent sampling issues. Duchon et al. (1995) discuss issues related to spatial sampling error by random rain gauges in a network. They found that some degree of random gauge distribution in a network is required to minimize the standard error. They found that for lighter rainfall amounts (e.g. less than 1 mm), the standard error was 0.27 mm or a 53% variation with respect to the mean. At larger amounts (e.g. 11-15 mm), the standard error was 1.49 mm or 11% variation with respect to the mean.

The largest source of rain gauge error, after sampling error, is due to wind-induced precipitation loss (Brock et al. 1995). The "ideal" location for a gauge is a considerable distance from objects that might disturb the airflow. The recommended standard is that the distance from surrounding objects should be not less than twice the height of such objects, and ideally at least four times. Rainfall rarely falls vertically, but is usually blown to a greater or lesser degree in the wind. For consistent and accurate measurements, it is important that the rain gauge is located in an open area where nearby objects such as buildings, walls and trees won't deflect the entry of wind-blown rain into the gauge. Rain shadow can be surprisingly large and the standard recommendation is that the gauge be positioned at distance corresponding to two or four times the height of any nearby obstruction. Where this is difficult to achieve, providing good exposure to the most common directions of wind/rainfall should be the priority. Gauges should be positioned in a flat area away from obstructions and must be installed in an accurately horizontal plane for correct operation.

On the basis of the aforementioned guidelines a series of criteria input parameters were developed. The input parameters for initial consideration were drainage (rivers, streams, lakes, creeks etc.), Roads (major, minor, paths etc.), elevation (digital elevation model), landuse/landcover (Landcover classification based Supervised classification Method (ISODATA), using LANDSAT Thematic Mapper satellite imagery, and Soil data (Statsgo).

iii.    TRMM_MCE Model

A decision support model was developed to facilitate the optimal siting of the NCURN gauges. The TRMM_MCE model integrates GIS and multi-criteria analysis methods (Figure 5). These tools account for the context of the considered project and also identify and describe various alternatives. Multi-criteria analysis methods are then used to aggregate this information and choose the most adequate solutions considering the decision-makers preferences.

Identification of land that meets particular criteria is one of the main spatial analytical applications of GIS. Carver (1991) and others have shown that a systematic approach to site selection is provided by GIS-based approaches. The purpose of MCE is to help decision-makers like SPRAWL-NCURN scientists distinguish between several possible options in which the preferences for each of the options may depend upon several factors each of which might be regarded as having different levels of importance by different members of community.

The multi-criteria analysis method merges two well-known methods; the Boolean overlay and the weighted overlay methods. The Boolean overlay method can briefly be described as an overlay of thematic layers in a GIS in order to identify regions that combine selected attributes from each of the layers. A set of constraints is defined and the layers are then superimposed to identify regions of space that satisfy all constraints. Boolean logic can then be applied to a series of layers that are defined by conjunctions or Boolean operators.

The Boolean operators are applied in a scenario where the constraints, being evaluated are of a uniform value to a given situation. In most cases this is not valid and thus the weighted overlay method needs to be applied. In practice certain factors may be much more important than others and it may be desirable to differentiate between candidate sites according to how well they meet

the various criteria. The relative levels of importance of the different types of data can be taken into account by attaching numeric weights to each of the layers in an overlay operation.

The products of the multi-criteria analysis are a series of maps based on the different weighting assignments given in both the Boolean overlay and the weighted overlay method. This iterative procedure identifies cells that are ranked highest with respect to all objectives. A set of grids cells (pixels) defining the optimal sites is highlighted thus indicating areas of suitability. An overlay comparison of the results is then analyzed to determine the spatial distribution of optimal sites. This will minimize the number of sites to visit during the field survey to establish NCURN gauge locations

iv. Evaluation

A combination of guidelines from the World Meteorological Organization of the Untied Nations and previous success stories for siting Meteorological weather stations have produced accurate results and enhanced the process of weather prediction. These guidelines were adopted in this study to evaluate alternatives in the Multi-criteria Decision Analysis. Evaluation also involves other aspects such as efficiency, performance or conformance

In the last twenty years analysts and planners have faced the construction of a multidisciplinary evaluation methodology. One of the most widespread approaches is multi-criteria analysis (MCA), which is based on the mathematical formalization of the set of preferences of decision-makers, by means of formal choice theory, structured models and computer algorithms. Apart from various differences among MCA models, the general framework of this approach is based on the articulation of a complex problem into its simple components. The aggregation of performances of each choice possibility with respect to selected criteria yields final outcomes as a recommendation to the decision-maker (De Montis and Nijkamp 1999).

The process of spatial planning is largely enhanced by the selection of probable sites chosen on the basis of our desired criteria defined in the weighted overlay method. Thus, the MCA was considered a vital apparatus for the preliminary site selection. Two approaches were adopted in order to implement the methodology. This consisted of blending spatial analysis and modeling; and multi-criteria decision analysis. Within these approaches a subsystem was created which entailed the development of a temporal and a spatial database. The spatial analytical approach involved the development of thematic layers, which consisted of landuse/landcover, drainage network, road network, Soil and a digital elevation model, by refining the attributes that were of important to this study. Each data set had to be processed in order to extract the relevant data specifically defined within the boundary of the spatial database.

This approach was followed by the development of a process model (figure 6), which defines the interaction of the objects that are modeled in the representation model. Each component within the process flow diagram is appraised for its usefulness to the multi-criteria decision analysis by consulting the guideline handbook of the WMO and other policies for optimum siting of weather stations, but with specific reference to rain gauges. An initial model run is executed to ascertain any flaws, which could be rectified before the final model run. There were six defined phases within model from the database design and development to the final output phase.

The second approach involved data interpretation of each thematic layer in order to build criteria and effectiveness scores and to aggregate them in a final ranking of choice possibilities. The landuse/landcover and soil data sets were classified into broad classes to ease data interpretation and visualization. The Digital Elevation Model (DEM) was converted from its digital height measurements to slope values in order to arrive at an overall gradient value. A distance buffer surrounding the drainage network and road network was defined with each measured distance representing a variety of comfort zones.

## 5. Results

Data visualization specifically reflects the nature of each dataset or combinations of classified values, in order emphasize a defined phenomenon. The classification methods chosen for this study were the equal area and equal interval classification methods. The equal area method was chosen for the polygons derived from the landuse/landcover and elevation datasets. The equal interval classification was chosen on the basis of the gradient levels found in the buffer distances surrounding both the drainage and road networks. Furthermore, to effectively reflect the diverse nature of each of the above-mentioned datasets these methods were considered the most appropriate. The equal area method involves a process by which the polygon features of the landuse/landcover and elevation datasets were collectively defined by a series of break points found in the attribute values. The absolute area of each polygon class is thus uniform and broken into series of stages defined by a class boundary. The equal interval method processes the data sets into ranges of attribute values, which are stored as equal sized sub-ranges. In the case of the drainage and road networks each buffer distance ranged from 0 – 30,000 meters.

The reclassification process was the penultimate stage to the optimal location of each prospective rain gauge site by defining a grid cell. In order to evaluate the combined datasets, the processed grid datasets were normalized to a uniform scale. The integration of the reclassified dataset was executed by converting each layer to a common scale, grouped within a data range of 1-10; the higher values are translated into high suitability, whilst the lower values are less suitable.

To reclassify landcover, open spaces and areas with less dense vegetation cover were ranked higher where there is less likely influence from trees that won't deflect the entry of wind-blown rain into the gauge. Areas of thick vegetation were given lower values and least suitable for siting rain gauges.

The reclassification of distances was defined by the process of buffering (grid cells), areas in close proximity to road and drainage networks, such highway drainage or runoff zones are given lower values and least suitable for siting rain gauges. While areas "at distance corresponding to two or four times the height of any nearby obstruction", were ranked high and therefore suitable. In reclassifying the slope layer, steep gradients are given lower values and least suitable for siting rain gauges. As previously defined, gauges should be positioned in a flat area away from obstructions and must be installed in an accurately horizontal plane for correct operation. The soil dataset was not consider as a decisive factor and therefore not included in the final ranking Figures 7-10 present the classification and reclassification of landuse/landcover, road networks, drainage networks, and elevation.

After the data have been processed, they become the input of MCA procedures. Different algorithms may then be used in order to compare the final resulting rankings. The weighted overlay method results in the intersection of multiple grid (raster) layers. The weighted sum is given by the following mathematical model.

$$\sum w_i * p_{ik} \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(1)$$

$$I \qquad \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots(2)$$

$$\sum w_i * x_{kij}$$

$$i=1$$

The application of a uniform scale (1-10) defines the degree of suitability, which was finally integrated into a linear program. The datasets are converted to percentages, where higher percentages are assigned to datasets (criteria) that are considered highly influential to the decision-making process/MCA model.

Dividing each assigned percentage value by 100 normalized the resulting percentages. A series of iterations were executed and weights (in percentage -%) were assigned based on order of importance. Sparsely vegetated open spaces were considered the highest priority, followed by a level gradient surface and thus assigned larger weights (%). The other decisive factors, distance from road and drainage networks, were considered to be of lower priority. Each implementation map is the result of differential weight assignments. The resultant provides an interpretation of the optimization output and displays it as an implementation map.

Finally, the implementation map is overlain with the point coverage depicting the proposed location of the tipping bucket rain gauge sites. The coverage grid is shifted and rotated onto the calculated optimal sites and the coordinates derived are tabulated for the eventual field verification (Figure 11). Areas in red represent optimal locations. The original, theoretical grid points (green dots) are utilized as guidance. With this guidance, NCURN scientists can scout and deploy gauges. The final location is determined by constructing a 10-km radius around each grid point (green dot). The shortest distant between the gridpoint and the closest optimized region (red) is considered the optimized location. If there is no optimized region within 10km of a grid point, then the next closest region will be used. Appendix A includes recommended optimized locations (latitude and longitude) for NCURN.

## 6.    Conclusions and Future Work

NASA is seeking to provide additional observational and modeling resources to address questions about the effects of urbanization on precipitation variability. Additionally, the agency seeks to provide robust ground validation for current and future precipitation satellite missions. To this end, a new NCURN, urban rainfall network has been funded. To determine the optimal siting of the new NCURN rain gauge network, a Geographical Information System aided by a Spatial Decision Support System has been developed. A Multi-Criteria Decision Analysis technique was developed to locate optimal sites in accordance to the guidelines defined by the World Meteorological Organization (WMO). The Multi-criteria Decision Analysis (MCA) model for the optimization of prospective sites was applied to predict prime locations for the Tipping Bucket Rain Gauges. The MCA design required development of a spatial model by applying a series of linear programming methods, with the aid of spatial analytical techniques in order to identify land sites that meet a particular set of criteria. In the summer of 2003, the optimally sited NCURN gauges will be used in SPRAWL and for long term precipitation monitoring around Atlanta.

SPRAWL will provide one of the first opportunities to evaluate the siting provided by the techniques presented herein. It is anticipated that various components of the procedure will need to be adjusted to further optimize the network and provide applicability for other siting requirements.

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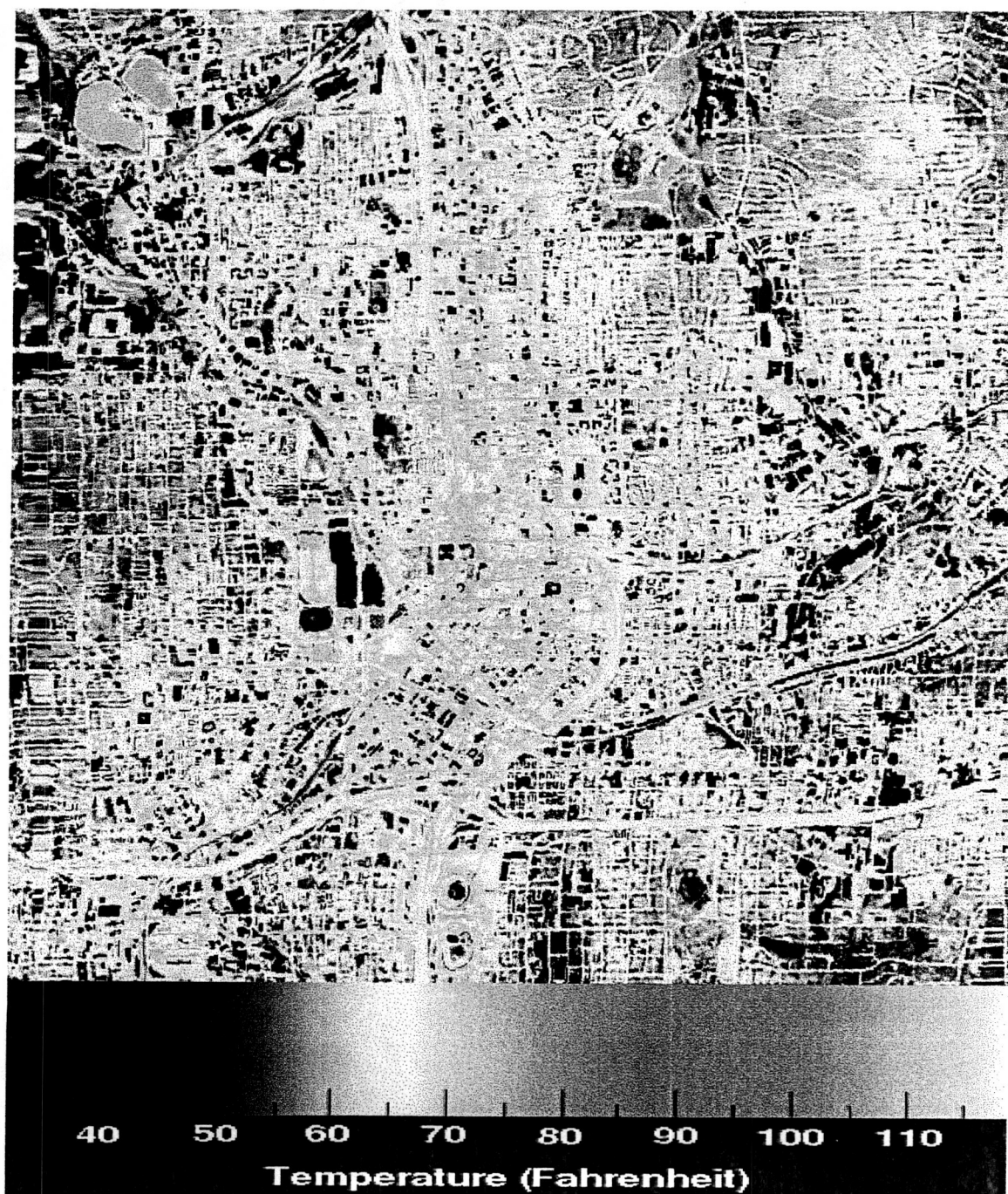
**Figure 1-** Urban heat island signature of the city of Atlanta, Georgia using infrared imagery captured by the airborne Advanced Thermal and Land Application System (ATLAS) on May 11 and 12, 1997).
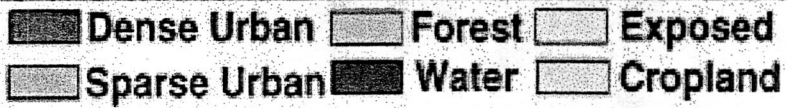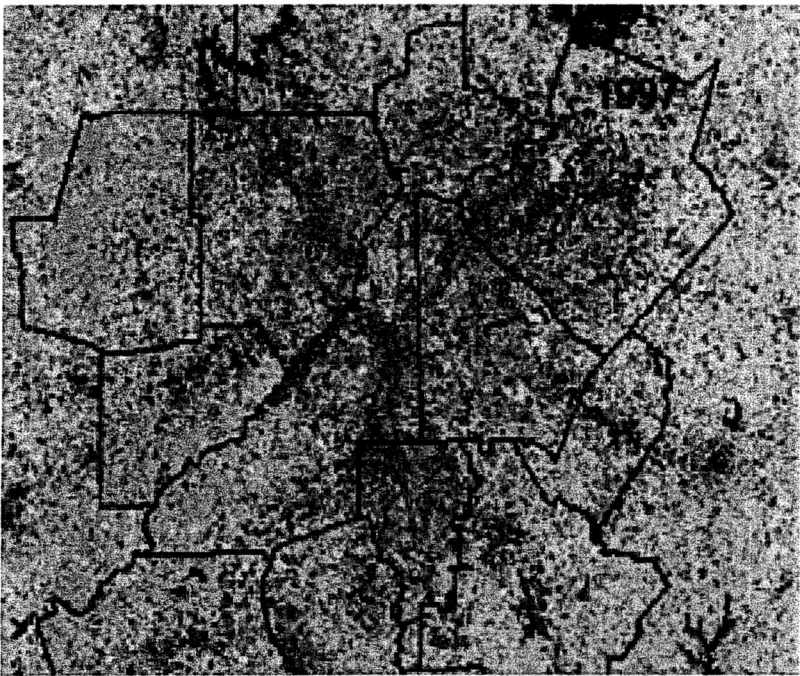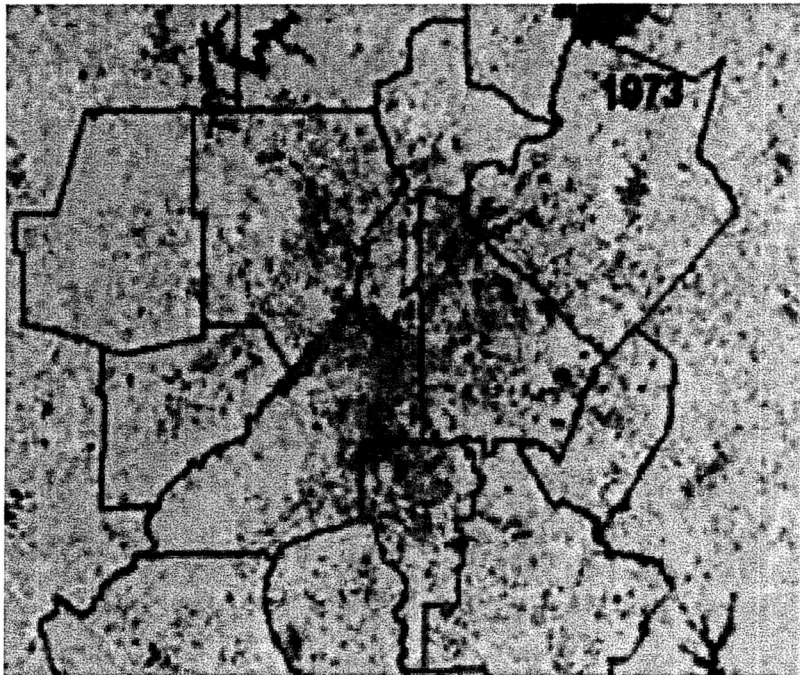
**Figure 2**-LANDSAT-5 images of rapid growth (decline) of urban (rural) surfaces in the metropolitan Atlanta area.

# Top Panel
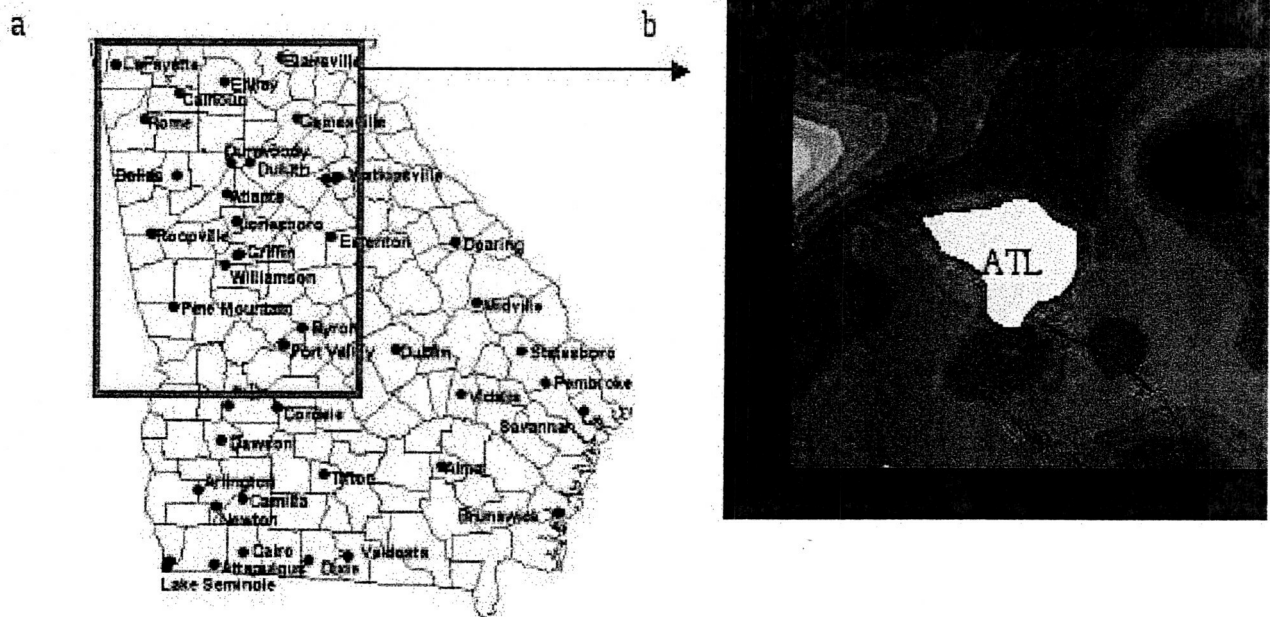


# Bottom Panel
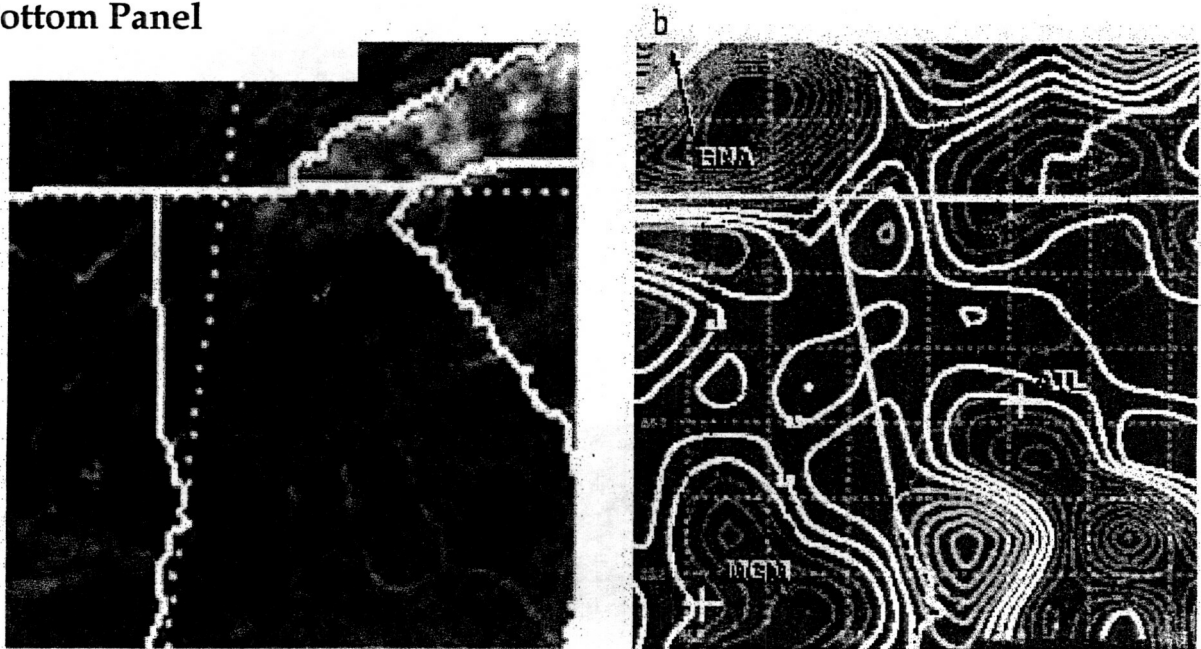


**Figure 3-Top Panel** (a) Georgia AEMN Network following Hoogenboom (1996) (b) AEMN Mean rainfall totals (mm) from 1998-2000 (May-September). **Bottom Panel** (a) GOES 3.9 micron thermal signature of Atlanta heat island (b) TRMM-derived mean rainfall rates over the period 1998-2000 (May-September). Values in red (blue) are greater (less) than 4.4 mm/h (3.6 mm/h).
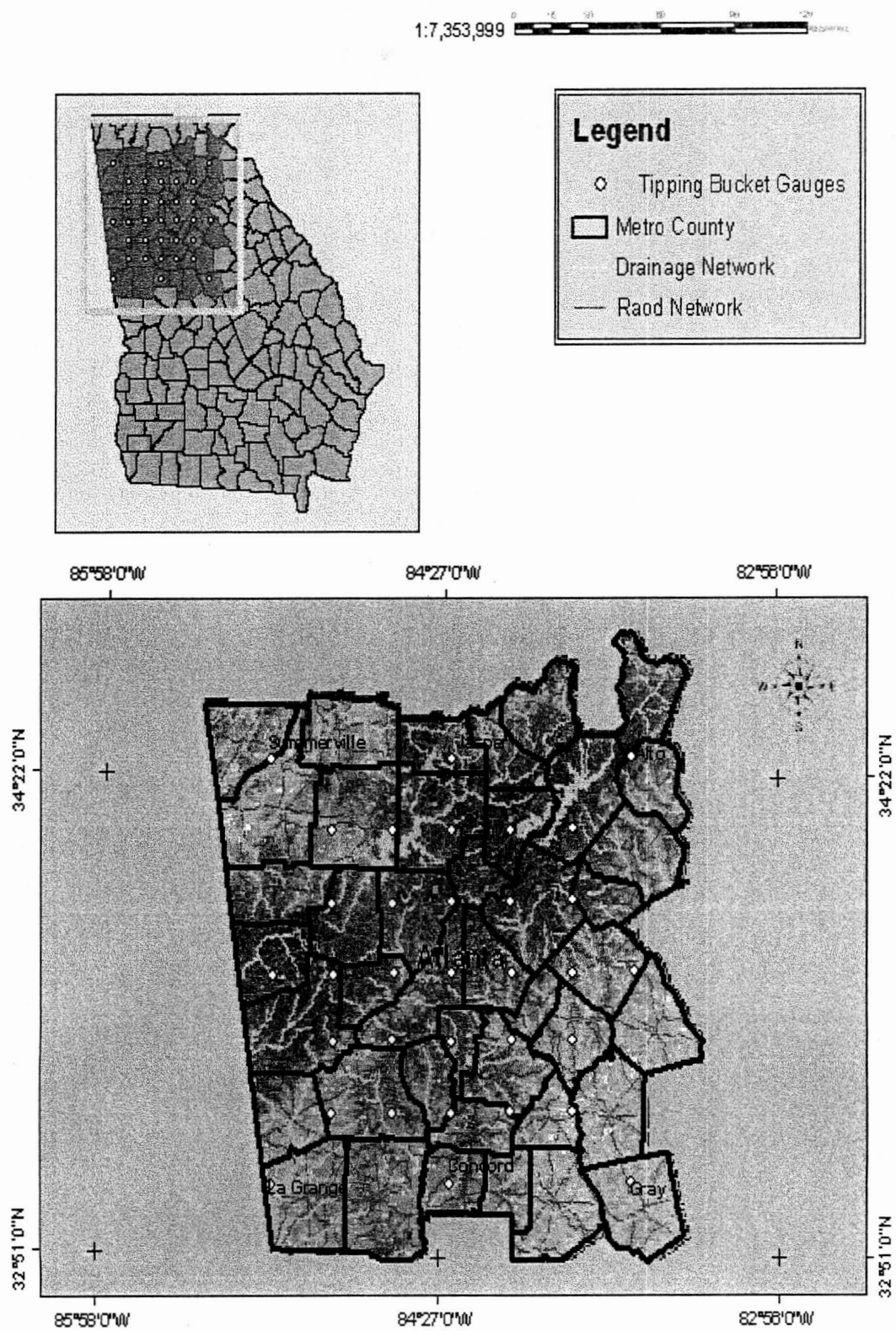
**Figure 4**-Idealized, non-optimized NCURN sites (yellow dots) and Georgia counties.
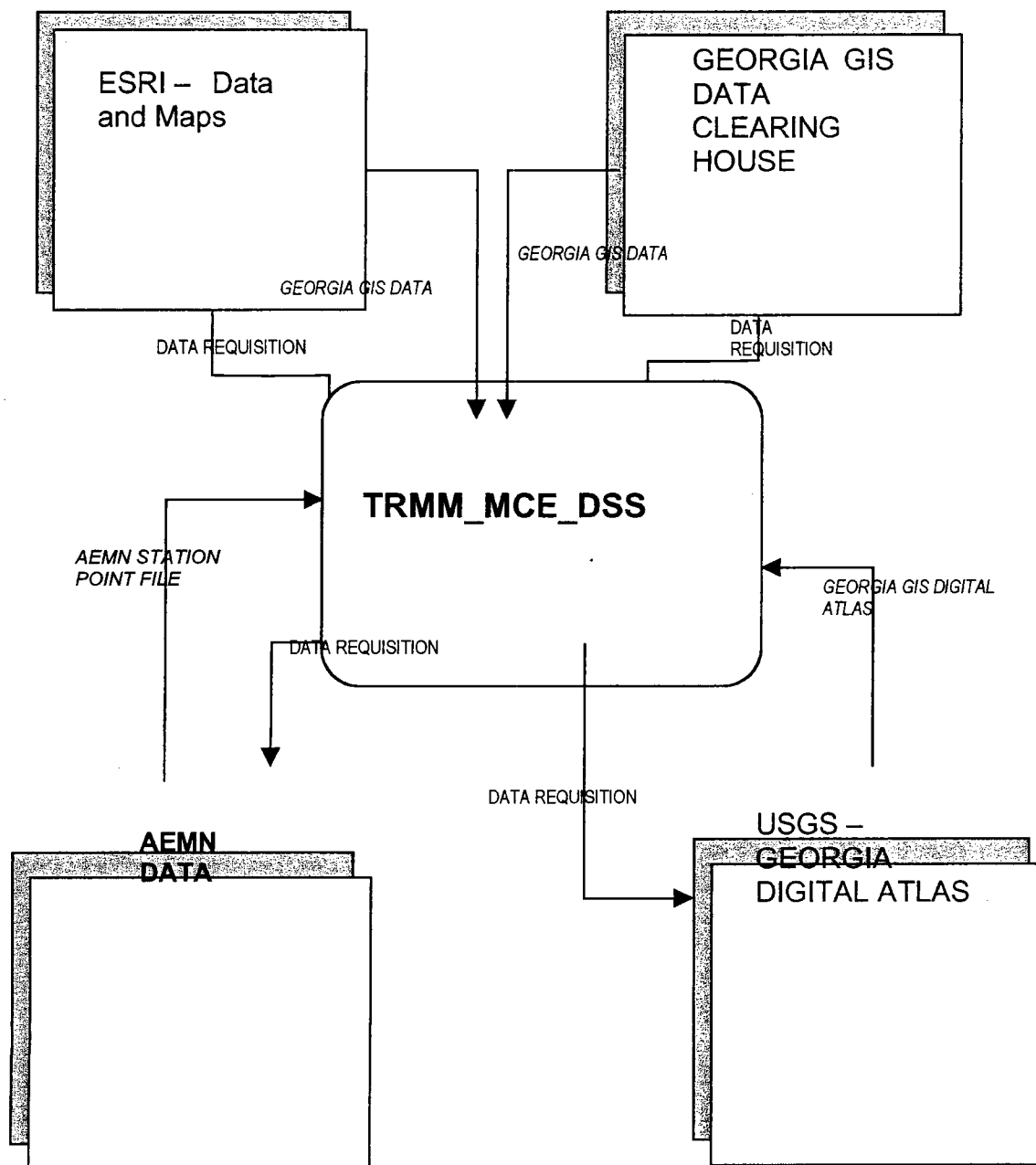
**Figure 5**-TRMM MCE decision support system model with GIS integration
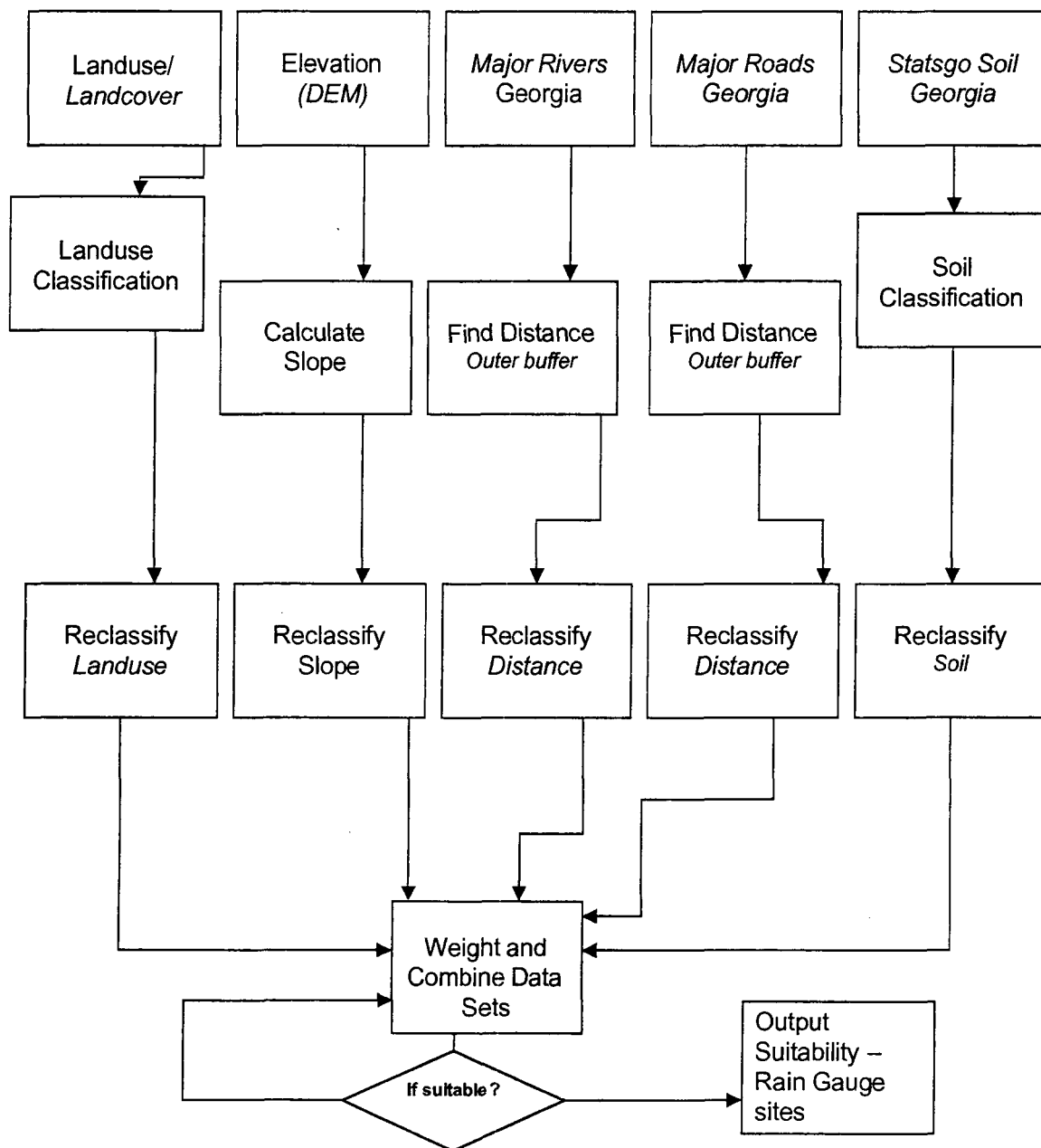
**Figure 6**-TRMM MCE flow process.
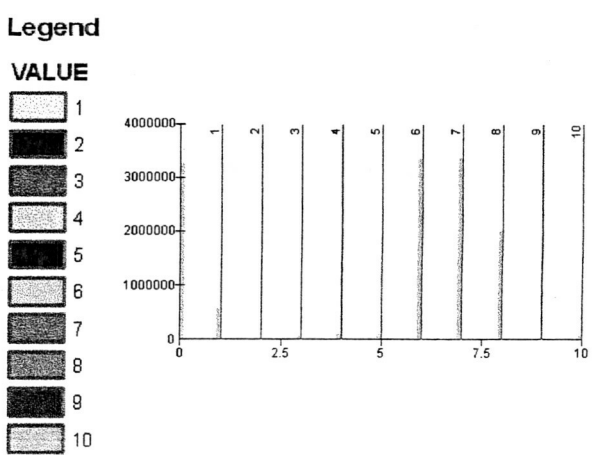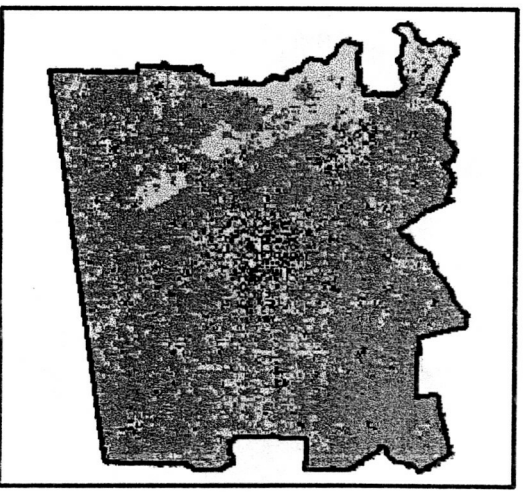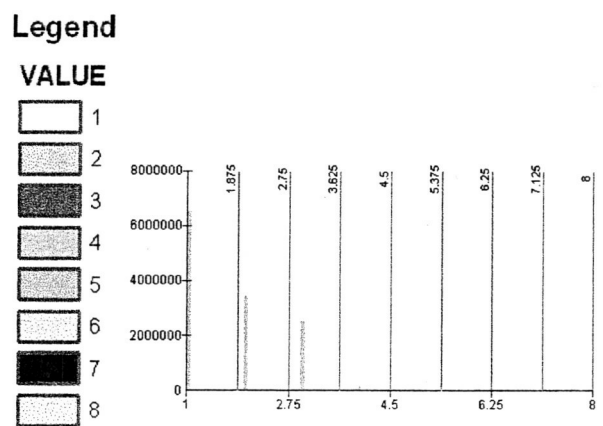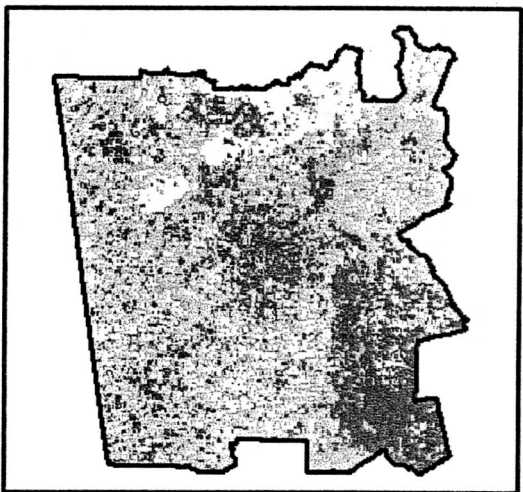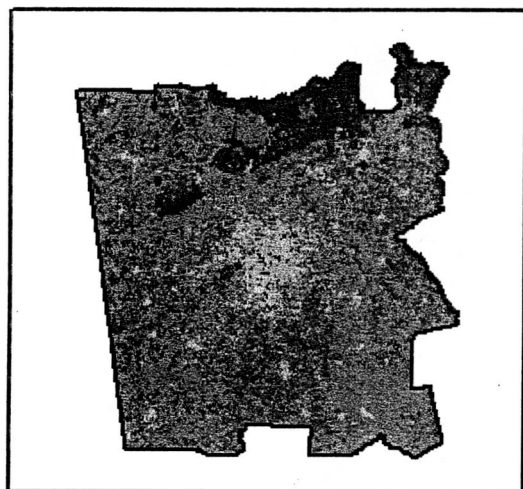
Figure 7-Landuse/Landcover classification (top) and re-classification (bottom).
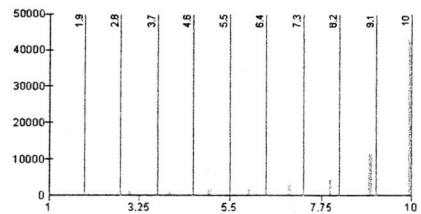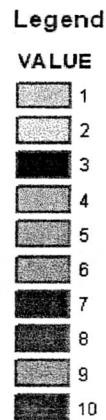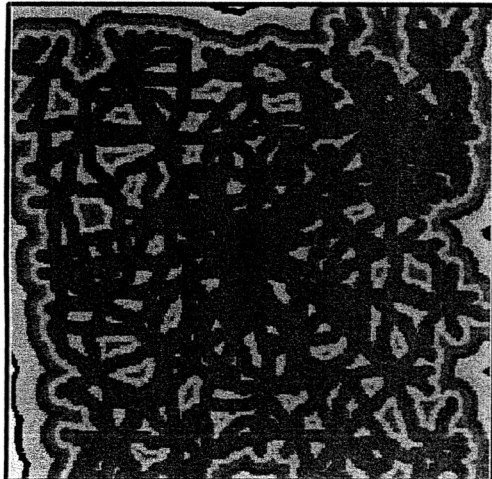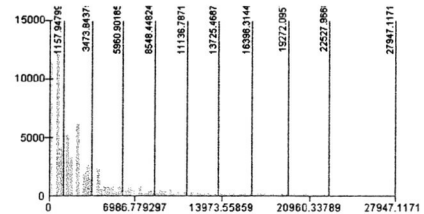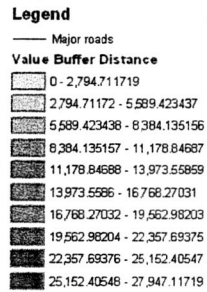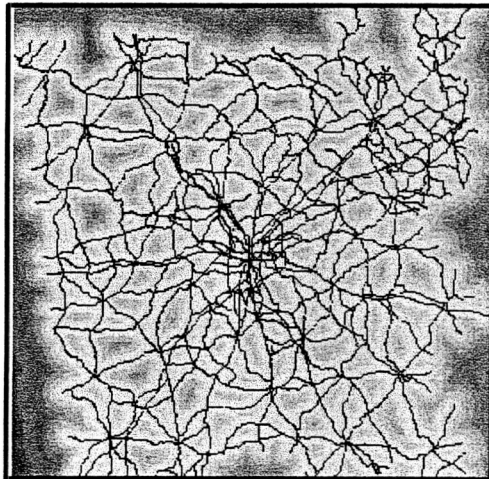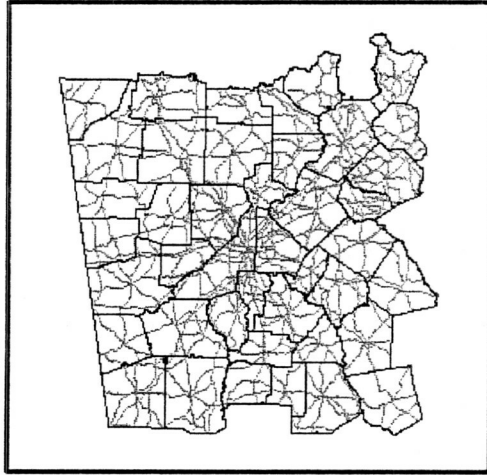
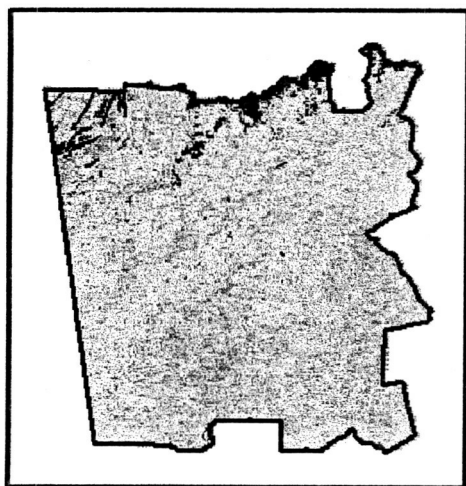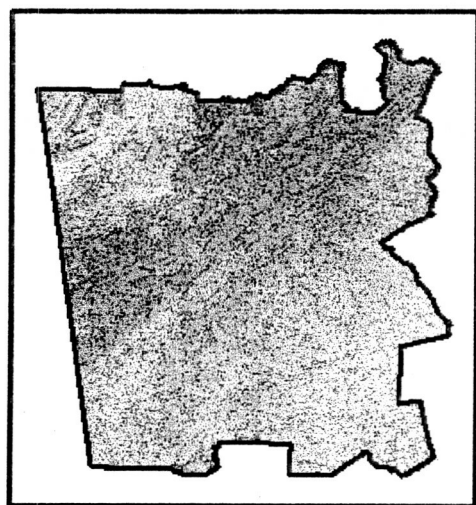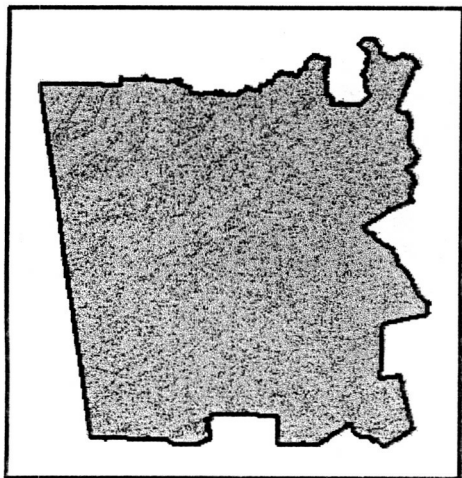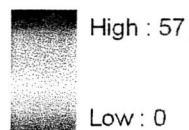Figure 8-Road network classification (top) and re-classification (bottom).
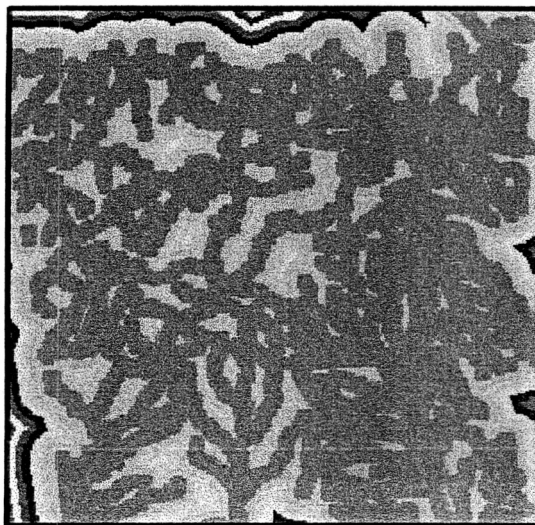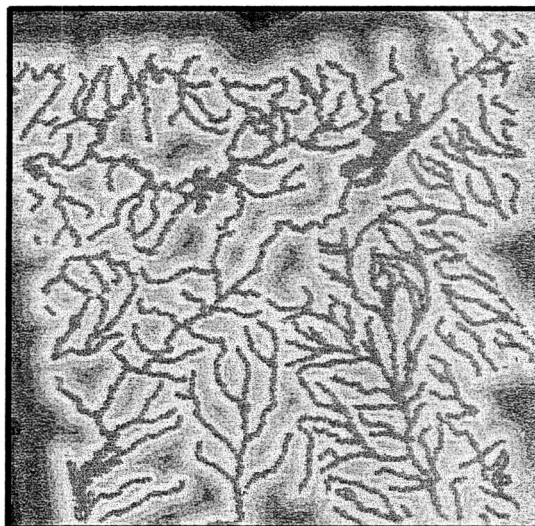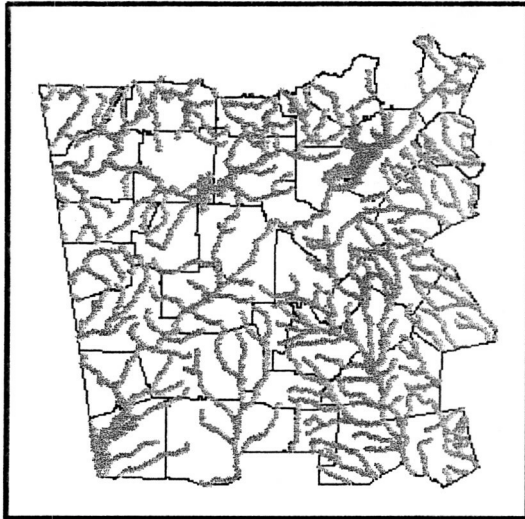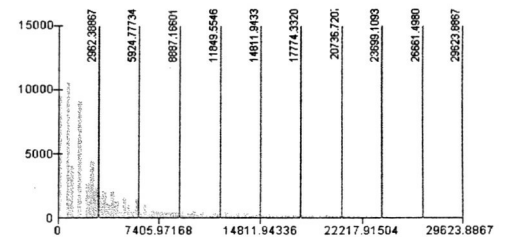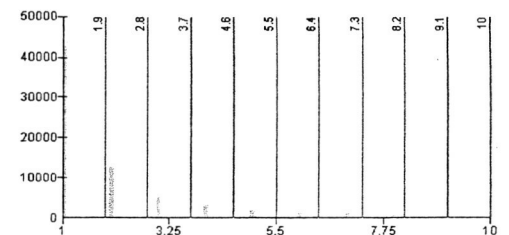
Figure 9-Drainage network classification (top) and re-classification (bottom).
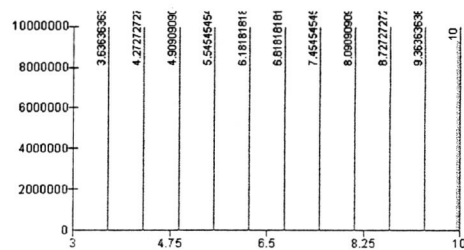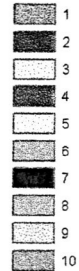
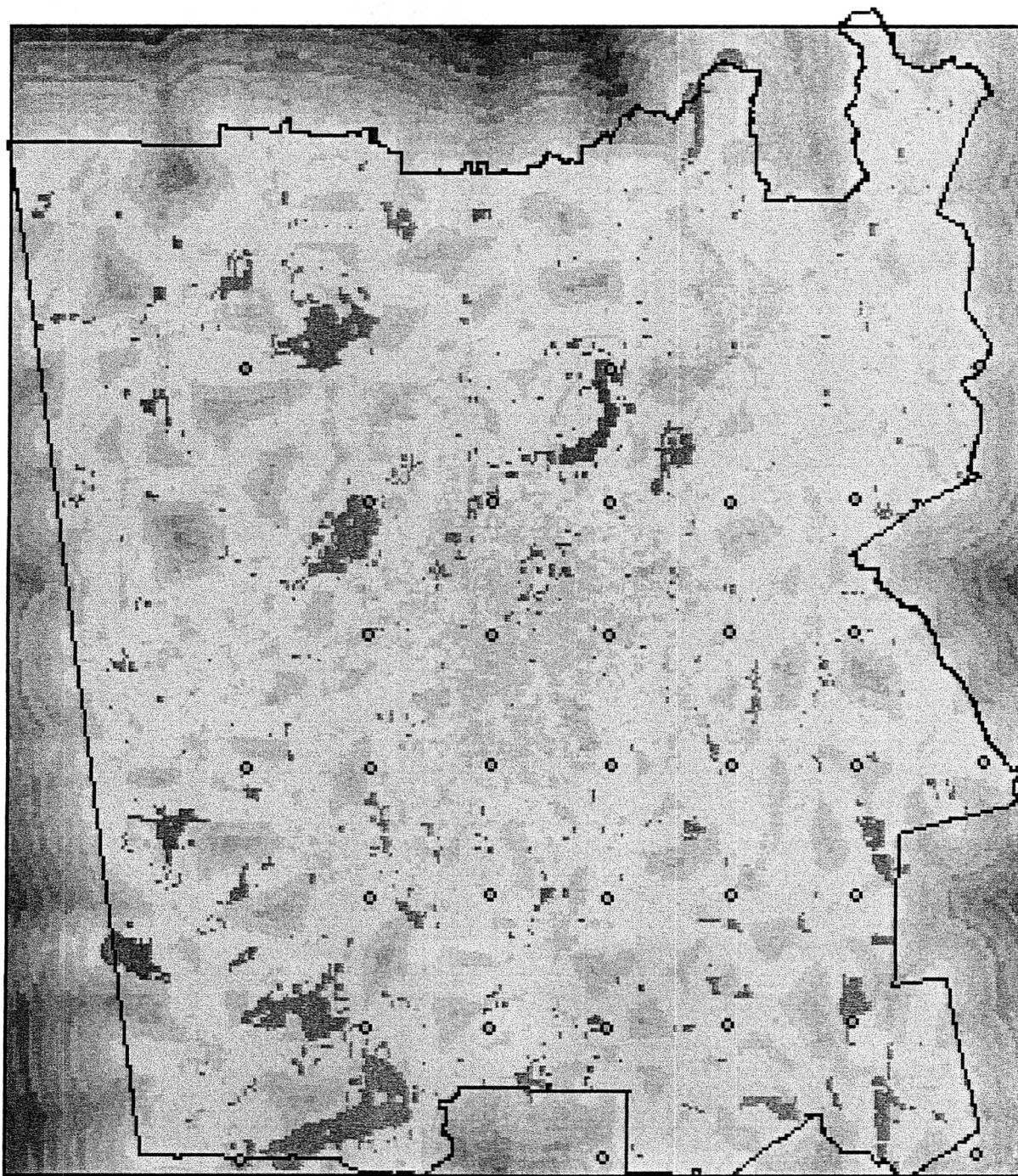Figure 10-Elevation classification (top) and re-classification (bottom).

**Figure 11**-TRMM MCE-indicated optimized regions (red shading) for NCURN gauge siting relative to the non-optimized, initial placement grid (green dots) from figure 4.

# Appendix A: Optimal Siting Locations

| Points | X | Y |
|--------|---|---|
| 1 | 85 09 36.18 W | 34 18 40.94 N |
| 2 | 84 20 58.68 W | 34 19 22.18 N |
| 3 | 83 31 49.13 W | 34 19 56.41 N |
| 4 | 84 53 23.68 W | 34 05 34.06 N |
| 5 | 84 37 03.49 W | 34 05 44.66 N |
| 6 | 84 21 06.96 W | 34 06 02.46 N |
| 7 | 84 05 10.24 W | 34 06 08.39 N |
| 8 | 83 48 26.28 W | 34 06 21.94 N |
| 9 | 84 53 09.21 W | 33 52 00.88 N |
| 10 | 84 36 40.01 W | 33 52 06.72 N |
| 11 | 84 20 52.20 W | 33 52 29.28 N |
| 12 | 84 04 46.54 W | 33 52 44.92 N |
| 13 | 83 48 17.23 W | 33 52 58.39 |
| 14 | 85 08 34.33 W | 33 38 27.27 N |
| 15 | 84 52 20.80 W | 33 38 40.01 N |
| 16 | 84 36 18.79 W | 33 38 40.01 N |
| 17 | 84 20 40.65 W | 33 39 17.64 N |
| 18 | 84 04 38.60 W | 33 39 23.57 N |
| 19 | 83 48 01.31 W | 33 39 27.37 N |
| 20 | 83 31 24.01 W | 33 39 38.45 N |
| 21 | 84 52 18.81 W | 33 25 36.05 N |
| 22 | 84 36 19.60 W | 33 25 46.39 N |
| 23 | 84 20 43.61 W | 33 25 44.66 N |
| 24 | 84 04 32.69 W | 33 26 00.34 N |
| 25 | 83 47 58.28 W | 33 26 13.81 N |
| 26 | 84 52 16.16 W | 33 11 53.12 N |
| 27 | 84 36 08.20 W | 33 12 13.26 N |
| 28 | 84 20 35.00 W | 33 12 21.18 N |
| 29 | 84 04 38.49 W | 33 12 36.80 N |
| 30 | 83 48 18.56 W | 33 12 50.25 N |
| 31 | 85 07 55.63 W | 32 58 04.49 N |
| 32 | 84 20 40.06 W | 32 59 00.71 N |
| 33 | 83 32 02.19 W | 32 59 31.29 N |