A Dynamic GIS–Multicriteria Technique for Siting the NASA–Clark Atlanta Urban Rain Gauge Network

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(Manuscript received 2 June 2003, in final form 17 February 2004)

ABSTRACT

Because Atlanta, Georgia, 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 (UHIs) impact the environment in terms of land use, air quality, health, climate, and other factors. Atlanta’s UHI may also impact the regional 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 UHIs can have a significant influence on mesoscale circulations and resulting convection. Using spaceborne rain radar and a limited network of irregularly spaced, ground-based rain gauges, evidence that the Atlanta and Houston, Dallas, and San Antonio, Texas, urban areas may modify cloud and precipitation development was recently found.

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 spaceborne rainfall estimates. To optimize gauge location to a given set of criteria, a geographical information system (GIS) aided by a spatial decision support system (DSS) has been developed. A multicriteria decision analysis (MCDA) technique was developed to locate optimal sites in accordance to the guidelines defined by the World Meteorological Organization (WMO). A multicriteria analysis model for the optimization of prospective sites was applied to identify prime locations for the tipping-bucket rain gauges. The MCDA 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.

1. Introduction

It is estimated that by the year 2025, 60% of the world’s population will live in cities (UNFPA 1999). In the United States, the current urban growth rate is approximately 12.5%, with 80% of the population currently living in urban areas. Urbanization is one extreme example of land cover and land use changes due to human activities. Howard (1833) made the first documented observation of a temperature difference between an urban area and its rural environment. The difference has been termed 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 air temperature in urban areas tends to be 2°–10°C higher than surrounding nonurban 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 11 and 12 May 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 observational 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 and 1990 (Hartshorn and Ihlanfeldt 1993). From 1973 to 1992, the Atlanta area experienced a decline of nearly 20% in forestland. Landsat-5 data in Fig. 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, the National Aeronautics and Space Administration (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 multidisciplinary effort to 1) investigate and model the relationship between Atlanta urban growth, land cover change, and the development of the urban heat island; 2) investigate and model the relationship between Atlanta urban growth and land cover change on air quality; and 3) 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.
Fig. 2. *Landsat-5* images of rapid growth (decline) of urban (rural) surfaces in the metropolitan Atlanta area (courtesy of GSFC SVS).
2. Motivation and previous work

Such focus has led to a wealth of information on Atlanta’s UHI environment. Atlanta’s UHI may also impact the regional 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 urban-induced rainfall in Atlanta has not been a primary focus of past efforts. Using space–time-averaged rainfall estimates from the Tropical Rainfall Measuring Mission (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. Dixon and Mote (2003) recently investigated the patterns and causes of Atlanta’s UHI-initiated precipitation. Their results focused on the role of moisture in the initiation of UHI-forced convection. Many results of recent studies are consistent with previous work. For example, early investigations (Changnon 1968; Landsberg 1970; Huff and Changnon 1972) found evidence of warm seasonal rainfall increases of 9%–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 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, 1991). More recent studies have continued to validate and extend the findings from pre- and post-METROMEX investigations (Balling and Bazel 1987; Jauregui and Romales 1996; Bornstein and Lin 2000; Kusaka et al. 2000; Thielan et al. 2000; Baik et al. 2001; Ohashi and Kida 2002; Changnon and Westcott 2002).

Understanding of urban effects on rainfall is far from complete. The mechanisms of urban effects on rainfall are complex. On the one hand, cloud microphysics, in response to increased urban aerosols, may reduce urban rainfall (Rosenfeld 1999), while on the other hand, local dynamics and thermodynamics associated with an UHI-induced convergence zone and a destabilized boundary layer may enhance it (Shepherd et al. 2002; Shepherd and Burian 2003; Changnon and Westcott 2002; Ohashi and Kida 2002).

Shepherd et al. (2002) also demonstrated that the University of Georgia Automated Environmental Monitoring Network (AEMN) (Hoogenboom 1996) (Fig. 3) might not be sufficiently dense to capture the convective- to meso-gamma-scale rainfall anomalies associated with the urban heat island. Figure 3 reveals inadequacies in sampling coverage, particularly southeast of the city (at the time of their study), by the AEMN network. This fact could be deleterious to any effort to identify convective-scale precipitation anomalies in an urban area and lead to possible biases or gaps in the data. It is important in any spatiotemporal sampling to set the spacing between recorded samples at a maximum of half the wavelength of the spatial variation/periodicity of the process. Gridded TRMM PR data used in these studies are typically 0.5° (~50 km) in spatial resolution. The scale of mesoscale–convective rainfall in this region drives the need for a higher-density network (~25 km or less) near Atlanta.

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 discusses the evolution of a high-density rain gauge network around Atlanta. Section 4 discusses an innovative use of a multicriteria decision analysis (MCDA) technique that has been developed to locate optimal rain gauge sites. Section 5 provides results of the MCDA analysis. Section 6 offers conclusions and suggestions for future work.

3. NASA–Clark Atlanta Urban Rain Gauge Network

NASA has deployed the NASA–Clark Atlanta University (CAU) Urban Rain Gauge Network (NCURN), operated in conjunction with faculty and students at...
Clark Atlanta University to supplement AEMN and National Weather Service sites. The network consists 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. NCURN was implemented as a long-term observation system and to support the 2003–04 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 is supplementing ongoing efforts to conclusively identify the existence of urban-generated rainfall and its physical forcing mechanisms. The specific objectives of SPRAWL are the following.

- To conduct an intensive ground validation campaign
of TRMM PR findings during the summer of 2003 and 2004 (July–August) using the dense NCURN network in Atlanta and surrounding areas.

- To utilize diverse datasets [e.g., TRMM, NCURN, AEMN, and Weather Surveillance Radar-1988 Doppler (WSR-88D)] to identify and quantify “urban induced” rainfall events over a 2-month intensive observation period (IOP).
- To develop a “case study” validation dataset for comparison with simulations using the NASA Goddard Space Flight Center’s version of the fifth-generation Pennsylvania State University–National Center for Atmospheric Research Mesoscale Model (MM5) (Grell et al. 1994) coupled to the Parameterization for Land–Atmosphere–Cloud Exchange (PLACE) land surface model (Wetzel and Boone 1995). 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 integrated 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 Moderate Resolution Imaging Spectroradiometer (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 will also play key roles. SPRAWL’s NCURN supplements the AEMN with a nested set of tipping-bucket rain gauges. To facilitate a meaningful comparison with satellite-based rainfall estimates, we have developed 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 are <0.25° (rain gauge) and ~0.5° (satellite) latitude resolution on a daily, weekly, and monthly basis; mean/median rainfall rate (mm h⁻¹); total amount rainfall (mm); total days with measurable rain; and occurrence of 2-, 5-, 10-, 25-, 50-, and 100-yr rainfall events. The schedule for SPRAWL includes the following:

<table>
<thead>
<tr>
<th>Time Period</th>
<th>Task Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>June–August 2002</td>
<td>Identify potential NCURN sites with dynamic optimization technique</td>
</tr>
<tr>
<td>August 2002–July 2003</td>
<td>Install NCURN gauges</td>
</tr>
<tr>
<td>August 2002–July 2003</td>
<td>Develop software to merge/analyze NCURN/AEMN rainfall products</td>
</tr>
</tbody>
</table>

### 4. GIS-based MCDA for siting NCURN gauges

#### a. Background

The success of SPRAWL and future long-term rainfall monitoring with NCURN depends on optimal siting of the rain gauges relative to a set of criteria. Qualimetrics Model 6011A tipping-bucket rain gauges and NovaLynx Corporation Model 260-2501 tipping-bucket rain gauges were implemented in NCURN. Each Qualimetrics gauge is also equipped with a Model Z005142 precipitation event recorder/datalogger that records date, time, and rainfall data. Each NovaLynx gauge is equipped with a Model 260-2101 datalogger that records date, time, and rainfall data. The logger enables flexibility to set totaling intervals from 1 s to 8 h. Data are archived on a computer with processing software. Table 1 lists the characteristics of the two gauges. Two different vendors were used for gauges because Qualimetrics, Inc., was acquired during the time period of the preparation for the study.

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 (WMO) 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 (DSSs) 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). DSSs 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).

Herein, a technique is described to utilize GIS and DSS in an MCDA approach for siting rain gauges. MCDA provides 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.

b. Methodology

The primary study area is located within Georgia and extends north and south of the Atlanta metropolitan area, encompassing 40 counties. 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 extended metropolitan area. Figure 4 illustrates the spatial database boundaries. The boundaries of the temporal database were set within a 3-yr period extending from 1999 to 2002.

1) 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 geodatabase acquired from a series of well-known data repositories served as a foundation for building the final spatial geodatabase. The data repositories were the Georgia GIS Clearing House, the Environmental Systems Research Institute (data map series), the U.S. Geological Survey (USGS), and the Georgia Department of Natural Resources (DNR).

A map depicting the proposed location of the tipping-bucket rain gauge sites (Fig. 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. 2003) and also accounts for the anticipated scale of the mesoscale–convective rain events. The initial development of the spatial geodatabase 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, land use/land cover, and elevation datasets was required for the final spatial geodatabase. This process was followed by the development of a temporal geodatabase. The geodatabase derived from the Digital Environmental Atlas of Georgia1 was utilized in the multicriteria analysis (Alhadeff 2001).

2) Criteria Evaluation

Criteria evaluation parameters were based on specifications in the WMO (1983) handbook. 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

1 The Digital Environmental Atlas of Georgia is a CD-ROM set containing 37 digital map datasets 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, land cover, major roads, public airports, river reaches/major streams, roads, groundwater site inventory, hydrography, 7.5-min 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, and level I land use/land cover.
Table 2. Summary of rain gauge siting criteria sources.

<table>
<thead>
<tr>
<th>File name</th>
<th>Data description</th>
<th>Data type</th>
<th>Geometric registration</th>
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<tbody>
<tr>
<td>County</td>
<td>County boundaries</td>
<td>ARC/INFO coverage formats</td>
<td>Albers equal area map projection</td>
</tr>
<tr>
<td>Landuse1</td>
<td>Level I land use/land cover</td>
<td>ARC/INFO coverage formats</td>
<td>Albers equal area map projection</td>
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<tr>
<td>Landuse2</td>
<td>Level II land use/land cover</td>
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<td>mjr_rds</td>
<td>Major roads</td>
<td>ARC/INFO coverage formats</td>
<td>Albers equal area map projection</td>
</tr>
<tr>
<td>rt3mjr</td>
<td>River reach–major streams</td>
<td>ARC/INFO coverage formats</td>
<td>Albers equal area map projection</td>
</tr>
<tr>
<td>statsgo</td>
<td>Soils</td>
<td>ARC/INFO coverage formats</td>
<td>Albers equal area map projection</td>
</tr>
<tr>
<td>dem250.tif</td>
<td>Digital elevation model</td>
<td>Tagged image file formats (.tif)</td>
<td>Albers equal area map projection</td>
</tr>
</tbody>
</table>

The process of spatial planning is largely enhanced by the selection of probable sites chosen on the basis of the 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 multicriteria decision analysis. Within these approaches a subsystem was created that entailed the development of a temporal and a spatial database. The spatial analytical approach involved the development of thematic layers, which consisted of land use/land cover, drainage network, road network, soil, and a DEM. The attributes of importance were then refined. Each dataset had to be processed in order to extract the relevant data specifically defined within the boundary of the spatial database.

3) TRMM MCE MODEL

The multicriteria evaluation (MCE) method is concerned with techniques that employ geographically referenced information to identify locations, paths, and spatial interactions that are optimal or at least in some sense preferable, when measured against the factors of interest. Decision support tools in GIS should be regarded as there to assist in the decision-making process, not to make decisions.

A decision support model was developed to facilitate the optimal siting of the NCURN gauges. The TRMM MCE model integrates GIS and multicriteria analysis methods (Fig. 5). These tools account for the context of the considered project and also identify and describe various alternatives. Multicriteria analysis methods are then used to aggregate this information and choose the most adequate solutions considering the decision maker’s preferences.

This approach was followed by the development of a process model (Fig. 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 multicriteria decision analysis by referencing the WMO (1983) guideline handbook and relevance to the four criteria, 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 the 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 land use/land cover and soil datasets were classified into broad classes to ease data interpretation and visualization. The 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.

The multicriteria 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 criteria [see section 4b(2) and Table 2] is defined and the layers are then superimposed to identify regions of space that sat-
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 importance 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 multicriteria 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.

5. Results

Data visualization specifically reflects the nature of each dataset or combinations of classified values, in
order to 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 land use/land cover 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 land use/land cover and elevation datasets were collectively defined by a series of break points found in the attribute values. This process is an application of the natural breaks approach of Jenks and Caspall (1971). 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 datasets into ranges of attribute values, which are stored as equally sized subranges. In the case of the drainage and road networks, each buffer distance ranged from 0 to 30,000 m.

The reclassification process was the penultimate stage to the optimal location of each prospective rain gauge site by defining a grid cell. This stage is important because in order to evaluate the combined datasets, the processed grid datasets should be normalized to a uniform scale. Applying a percentage influence normalized the derived dataset; this allowed us to combine each data type to a common scale. Each derived dataset was thus divided by 100, enabling us to execute the suitability model. 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, while the lower values are less suitable.

To reclassify land cover, open spaces and areas with less dense vegetation cover were ranked higher where there is less likely influence from trees that will not deflect the entry of wind-blown rain into the gauge. Areas of thick vegetation, given lower values, were 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 as highway drainage or runoff zones, are given lower values and considered least suitable for siting rain gauges. Areas at distances corresponding to 2–4 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 are 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 considered a decisive factor and therefore was not included in the final ranking. Figures 7–10 present the classification and reclassification of land use/land cover, 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.

Saaty’s (1980) analytical hierarchy process (AHP) is a well-established procedure for assigning weights to a set of factors, which may correspond to the layers of an overlay; furthermore, this method employs a matrix of pairwise comparison (ratios) between factors. It uses an interactive user interface designed to solicit weights and ensure that they become appropriately normalized. Due to the nature of factors used in the analysis, the weighted overlay operation was chosen over Saaty’s AHP; giving the decision maker full control of what weights to apply. Implementation maps are 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 overlaid 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 as shown in Fig. 11. Areas in red represent optimized (to the study criteria) locations. The original, theoretical grid points (green dots) are utilized as guidance. With this guidance, NCURN scientists scouted and deployed gauges. The final location was determined by constructing a 10-km radius around each grid point (blue dot). The shortest distance between the grid point and the closest optimized region (red) is considered the optimized location. If there is no optimized region within 10 km of a grid point, then the next closest region will be used. The appendix 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 relative to a set of criteria, a geographical information system aided by a spatial decision support system has been developed. A multicriteria decision analysis (MCDA) technique was developed to locate optimal sites in accordance with the guidelines defined by the World Meteorological Organization (WMO) and a set of four specific criteria. The MCDA model for the optimization of prospective sites
Fig. 7. (top) Land use/land cover classification, (middle) classification of land cover suitability (e.g., open spaces and low vegetation are classified with a higher ranking), and (bottom) reclassification of dataset to a common scale (e.g., higher values are more optimal).
was applied to predict prime locations relative to flatness, terrain, soil, drainage systems, and roads for the tipping-bucket rain gauges. The multicriteria analysis (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 were first used
Fig. 9. (top) Drainage network, (middle) classification of distance from drainage networks, and (bottom) reclassification of “distance from drainage networks” to a common scale (e.g., higher values are more optimal).
Fig. 10. (top) Elevation (white=low, dark green=moderate, brownish-red=high), (middle) classification of elevation, and (bottom) reclassification of elevation to a common scale.
in SPRAWL and will continue to be used for long-term precipitation monitoring around Atlanta. SPRAWL provided one of the first opportunities to evaluate the siting provided by the techniques presented herein. One key finding from deploying NCURN was that all of the gauges were considered optimal relative to flatness, accessibility, obstructions, and land type. However, the process of locating the site within the
10-km ring of acceptability (section 5) was time-consuming, as many sites were on private property or land otherwise unavailable to NCURN scientists. In the end, it was learned that public school locations and community colleges were very receptive to NASA and Clark Atlanta University's gauge sitting on their property. Therefore, a future criterion for the analysis might be school locations. It would also be valuable for the analysis system to integrate representation of private land ownership classes (residential, business, farmland). This criterion might serve to further discriminate lands that may be available for gauge sitting. Furthermore, it may be beneficial to develop some type of criterion to reflect the climatological spatial distribution of rainfall or its areal uncertainty. It is anticipated that various components of the procedure will need to be adjusted to further optimize the network and provide applicability for other sitting requirements.

Acknowledgments. The authors would like to acknowledge Dr. Ming-Ying Wei and the NASA New Investigator Program for their support. The authors would also like to thank Dr. Kofi Bota and Dr. Randal Mandock of Clark Atlanta University.

APPENDIX

Optimized Siting Locations

<table>
<thead>
<tr>
<th>Points</th>
<th>X</th>
<th>Y</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>85°09'36.18&quot;W</td>
<td>34°18'40.94&quot;N</td>
</tr>
<tr>
<td>2</td>
<td>84°20'58.68&quot;W</td>
<td>34°19'22.18&quot;N</td>
</tr>
<tr>
<td>3</td>
<td>83°31'49.13&quot;W</td>
<td>34°19'56.41&quot;N</td>
</tr>
<tr>
<td>4</td>
<td>84°53'23.68&quot;W</td>
<td>34°05'34.06&quot;N</td>
</tr>
<tr>
<td>5</td>
<td>84°37'03.49&quot;W</td>
<td>34°05'44.66&quot;N</td>
</tr>
<tr>
<td>6</td>
<td>82°21'06.96&quot;W</td>
<td>34°06'02.46&quot;N</td>
</tr>
<tr>
<td>7</td>
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