Using Remote Sensing and GIS to Improve Runoff Index Determination for Urban Hydrologic Modeling

Presenter

Eric Warmath, NDOT

GIS-T 2006
Taking Flight
Columbus, Ohio - March 27 - 29

SDSU

Acknowledgments

- South Dakota State Univ. Brookings, SD
  - ***Ms. Pravara Thanapura***, Principal Investigator, and Research Associate, Engineering Resource Center (ERC), Ph.D. Student in the Geospatial Science and Engineering Program, and owner of GeoTech Consulting, LLC.
  - ***Dr. Dennis Helder***, Director of Engineering Research, Department Head, Department of Electrical Engineering and Computer Science *
  - ***Mr. Kevin Dalsted***, Director, ERC
  - ***Dr. Suzette Burckhard***, Hydrologist, College of Engineering*
  - ***Dr. Dwight Galster***, Statistician, Department of Mathematics*
  - ***Ms. Mary O'Neill***, Program Manager, Office of Remote Sensing, ERC*
- City of Sioux Falls, SD
  - *Steve Van Aartsen*, GIS Supervisor, *Thanks for all the data*!
  - ***Jeff Dunn***, City Drainage Engineer, for reviews and information
  - ***Sam Trebilcock***, Transportation Planner, for input and information

** Denotes co-author*

Topics

- Presentation Objective
- Research Contributions & DOT End User Benefits
- Hydrologic Model Background
- Runoff Methods & Runoff Index for Urban Drainage Design and Analysis
- Composite Runoff Index Geographic Model for Industry Standard Runoff Index Calculations
- Mapping Impervious Area and Open Space
- GIS Spatial Modeling
- Results
- Conclusions

Presentation Objectives

- Show the potential value of the research, in urban areas, for hydrologic engineers at DOT's nationally.
- Briefly describe the 2 most common runoff methods and associated Runoff Index
- Describe the research: *Integration of remote sensing and GIS for determining industry standard values of NRCS CN & C using the composite runoff index geographic model developed by Thanapura in 2005-6.*

Benefits

- Lead to an improved scheme for determining the standard runoff index used in urban watershed runoff assessment methods - the NRCS curve number and rational methods.
- Demonstrate a more precise, simpler, and efficient approach of calculating runoff index.
- Allow repeatability and consistency of the results by removing human error factors while increasing speed and potentially reducing costs of analysis and mapping for both methods.
- Lead to an improved scheme of urban impervious surface detection – a key indicator of the effects of non-point source pollution runoff and of future water and ecosystem quality.

DOT End User Benefits

- Beneficial to engineers involved drainage analyses and designs in urban areas.
- Allow for identification of structures nearing design capacity and needing replacement due to the effects of increased urbanization on a drainage basin.
- *Identify sites for potential property damage or loss of life.*

Table. Minor Structure Design Frequencies (Viessman and Lewis, 2003).

Type of minor structure			Return period, *Tr*	Frequency = 1/*Tr*
Highway crossroad drainage*				
	0-400	ADT*	10 yr	0.10
	400-1700	ADT	10-25 yr	0.10-0.04
	1700-5000	ADT	25 yr	0.04
	5000+	ADT	50 yr	0.02
Airfields			5 yr	0.20
Railroads			25-50 yr	0.04-0.02
Storm drainage			2-10 yr	0.50-0.10
Levees			2-50 yr	0.50-0.02
Drainage ditches			5-50 yr	0.20-0.02

* ADT = average daily traffic

Why NDOT & SDSU ?

- One of the conference discussions at GIS-T 2004 in Rapid City, SD, was getting more use out of imagery and remote sensing at DOT's.
- I met the principal investigator, was impressed with the research, and saw the potential benefits for NDOT.
- Since Nevada is the fastest growing state and urban drainage problems sometimes occur, the research is very relevant to NDOT issues .
- We have tentative plans to work in the Las Vegas area this year as part of the study.

Hydrologic Models Background

- There are 2 main hydrologic modeling methods used by the majority of practicing engineers. These models were developed for storm water calculation in engineering storm drainage design and water resource planning and analysis.

1. *Natural Resource Conservation Service (NRCS), NRCS-CN Method.*
2. *The Rational Method.*

- According to an EPA study *~86%* of private engineering firms, water boards, and other government entities are using one or both methods in their hydraulic engineering.
- NDOT and the City of Sioux Falls, SD use both.

Runoff Curve Number Method

- The NRCS Runoff Curve Number (NRCS-CN) method:
  - Used to estimate runoff from storm rainfall.
  - Well established in hydrologic engineering and environmental impact analysis.
  - Widely used by practicing engineers and hydrologists nationally and internationally.

Curve Number (CN) Industry Standard Table

Cover description: Cover type and hydrologic condition	Average percent impervious area 2/	Curve numbers for hydrologic soil group: A	B	C	D
Fully developed urban areas (vegetation established)					
Open space (lawns, parks, golf courses, cemeteries, etc.) 3/:					
Poor condition (grass cover < 50%)		68	79	86	89
Fair condition (grass cover 50% to 75%)		49	69	79	84
Good condition (grass cover > 75%)		39	61	74	80
Impervious areas:					
Paved parking lots, roofs, driveways, etc. (excluding right-of-way)		98	98	98	98
Streets and roads:					
Paved; curbs and storm sewers (excluding right-of-way)		98	98	98	98
Paved; open ditches (including right-of-way)		83	89	92	93
Gravel (including right-of-way)		76	85	89	91
Dirt (including right-of-way)		72	82	87	89
Western desert urban areas:					
Natural desert landscaping (pervious areas only) 4/		63	77	85	88
Artificial desert landscaping (impervious weed barrier, desert shrub with 1- to 2-inch sand or gravel mulch and basin borders)		96	96	96	96
Urban districts:					
Commercial and business	85	89	92	94	95
Industrial	72	81	88	91	93
Residential districts by average lot size:					
1/8 acre or less (town houses)	65	77	85	90	92
1/4 acre	38	61	75	83	87
1/3 acre	30	57	72	81	86
1/2 acre	25	54	70	80	85
1 acre	20	51	68	79	84
2 acres	12	46	65	77	82
Developing urban areas					
Newly graded areas (pervious areas only, no vegetation) 5/		77	86	91	94
Idle lands (CN's are determined using cover types similar to those in table 2-2c).					

- CN is an runoff index described in detail in the TR-55 *(NRCS 1986).*
- CN is a function of 3 factors:
  - Hydrologic soil group
  - Cover complex (Land Cover / Land Use)
  - Antecedent moisture

Curve Number (CN)

- Proposed runoff coefficients for the composite runoff calculation for urban land use recommended by McCuen in 2005 (Thanapura, 2006).

Land Cover	**Curve Number (CN) for SCS Hydrologic Soil Group**			
Character of Surface[1]:	**A**	**B**	**C**	**D**
Impervious Areas	98	98	98	98
Open Spaces - Good Condition	39	61	74	80

Rational Method

- Developed by Mulvaney in 1851 and refined by Kuichling and others in the late 19th century.
- Is the preferred method for use in smaller drainage basins (<= ~200 acres).
- A constant in American Hydrologic practice since its development.
- Widely used due to its simplicity.

Runoff Coefficients (C) Industry Standard Table

Description of Area	Range of Runoff Coefficients	Recommended Value*
Business		
Downtown	0.70–0.95	0.85
Neighborhood	0.50–0.70	0.60
Residential		
Single-family	0.30–0.50	0.40
Multiunits, detached	0.40–0.60	0.50
Multiunits, attached	0.60–0.75	0.70
Residential (suburban)	0.25–0.40	0.35
Apartment	0.50–0.70	0.60
Industrial		
Light	0.50–0.80	0.65
Heavy	0.60–0.90	0.75
Parks, cemeteries	0.10–0.25	0.20
Playgrounds	0.20–0.35	0.30
Railroad yard	0.20–0.35	0.30
Unimproved	0.10–0.30	0.20

It is often desirable to develop a composite runoff coefficient based on the percentage of different types of surface in the drainage area. This procedure often is applied to a typical sample block as a guide to the selection of reasonable values of the coefficient for an entire area. Coefficients with respect to surface type currently in use are listed below.

Character of Surface	Range of Runoff Coefficients	Recommended Value*
Pavement		
Asphaltic and concrete	0.70–0.95	0.85
Brick	0.75–0.85	0.80
Roofs	0.75–0.95	0.85
Lawns, sandy soil		
Flat, 2%	0.05–0.10	0.08
Average, 2 to 7%	0.10–0.15	0.13
Steep, 7%	0.15–0.20	0.18
Lawns, heavy soil		
Flat, 2%	0.13–0.17	0.15
Average, 2 to 7%	0.18–0.22	0.20
Steep, 7%	0.25–0.35	0.30

The coefficients in these two tabulations are applicable for storms of 5- to 10-year frequencies. Less frequent, higher intensity storms will require the use of higher coefficients because infiltration and other losses have a proportionally smaller effect on runoff. The coefficients are based on the assumption that the design storm does not occur when the ground surface is frozen.

* Recommended value not included in original source.
Source: American Society of Civil Engineers. *Design and Construction of Sanitary and Storm Sewers*. New York, 1969: 332.

- C is a function of 3 factors:
  - Land cover (Impervious and Open space)
  - Hydrologic Soil Group
  - Slope

Runoff Coefficient (C)

- Proposed runoff coefficients for the composite runoff calculation defined from the runoff coefficient, C recommended by the American Society of Civil Engineers (ASCE), the Water Pollution Control Federation (WPCF) in 1969, and McCuen in 2005

Land Cover	Runoff Coefficients (C)[2] for Hydrologic Soil Group			
Character of Surface[1]:	A[3]	B[4]	C[5]	D[6]
	Sandy Soil		Heavy Soil	
Impervious Areas (e.g. Pavement, roofs, etc.)	0.85	0.85	0.85	0.85
Open Spaces (e.g. Lawns, etc.)				
Flat, 2 percent	0.08	0.08	0.15	0.15
Average, 2-7 percent	0.13	0.13	0.20	0.20
Steep, 7 percent	0.18	0.18	0.30	0.30

SDSU

Runoff Index Limitations

- Conventional ground-based methods for determining index values are time-consuming and labor-intensive. A problem exists in quantifying the detailed spatial extent and distribution of various land cover classes, soil, and/or slope data.
- Utilization of satellite remote sensing and GIS technologies can provide spatially and temporally distributed input parameters for runoff index determination but have been hampered traditionally by data resolution.

Research Objective

The objective of this study was to demonstrate and evaluate Normalized Difference Vegetation Index (NDVI) data derived from QuickBird (QB) high resolution satellite imagery to map land cover surface characteristics such as impervious area and open space for runoff index number determination in urban watersheds.

Study Method

Composite Runoff Index Spatial Model

↓

Digital Data & Pre-Processing

Data Merging and Integration

QuickBird NDVI Imagery & GIS Layers

↓

Decision and Classification

↓

Image Classification

Unsupervised – ISODATA Algorithm & QuickBird NDVI

↓

Classification Output

↓

Accuracy Assessment

Reference Data – Ortho Photo

↓

Reports and GIS Data

↓

GIS Spatial Modeling

The Composite of Runoff Index CN & C calculations and comparisons

↓

Reject / Accept Hypothesis

Composite Runoff Index Geographic Model

Model 1. The composite runoff index geographic model (© 2005-2006 Pravara Thanapura. Use with permission) [Thanapura et al., 2005; 2006]:

$$RI_c = \Sigma\,[f_{(j/i)} \times RI_{(j)}]$$

Where:

RI_c or Runoff $Index_{composite}$ is the sum of the component runoff index within an area (i) delineated by the description of the area;

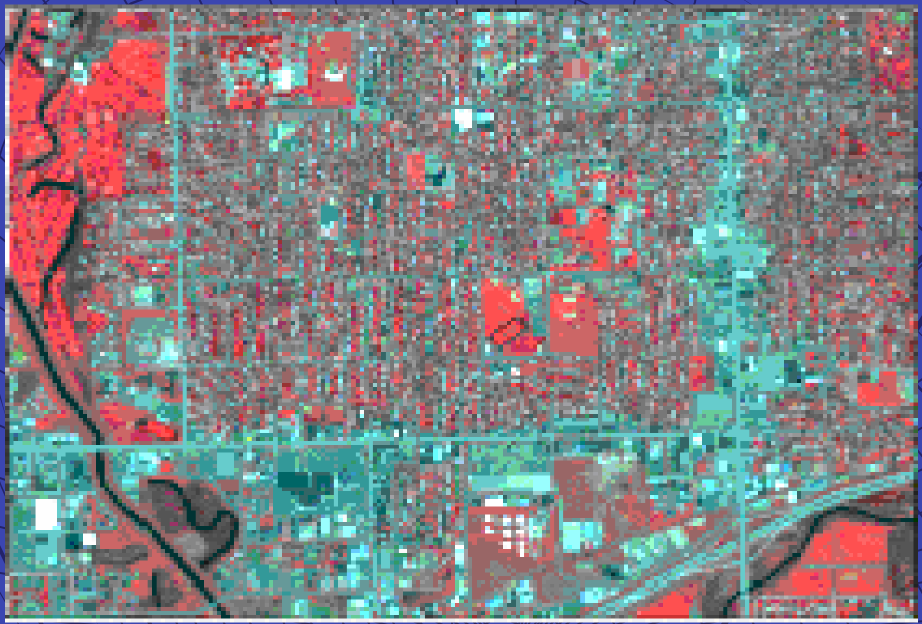
f or the fraction of area covered $_{(j/i)}$ is the component (j) of the area (i) divided by the total area (i). Note that the component of the area is delineated by surface characteristics of land cover, hydrologic soil group, and/or slope;

RI(j) or Runoff Index (j) is a runoff index of the component (j) of the area (i) determined by the surface characteristics and/or its hydrologic soil groups.

In this study, the composite runoff index geographic model was applied to develop a GIS spatial model for the composite runoff index calculation of both the NRCS CN and C for the NRCS CN method and the rational method.

SDSU

Study Area



The QB multi spectral image (4-3-2)

The QB NDVI Image

(Band 4 – Band 3 / Band 4 + Band 3)

This is ~2900 acres in the southwest portion of the City of Sioux Falls, SD representing almost all potential land use types.

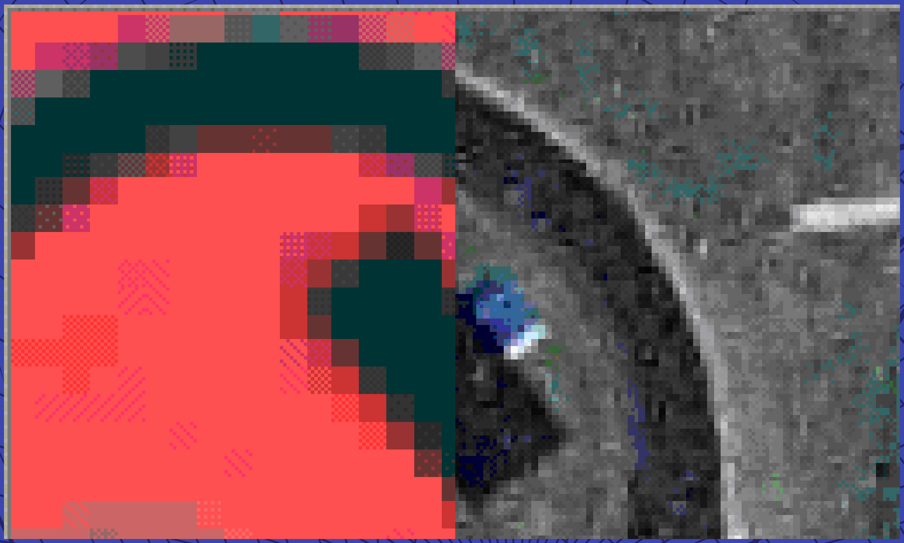
Digital Data

- QuickBird
  - ~8 ft (~2.4 m) [April 26, 2004]
  - Blue, Green, Red, and NIR bands
- Orthophotos
  - 2 ft color (0.6 m)[April 23, 2004]
  - 0.5 ft color (0.15 m)[May 20, 2002]
- *QB NDVI (band4-band3/band4+band3)*

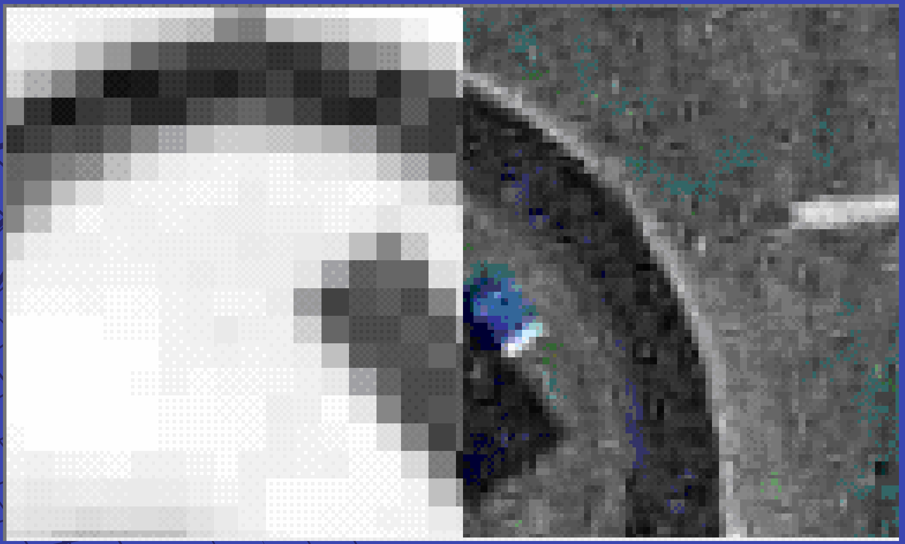
  (created using Erdas Imagine 8.7)
- GIS Layers
  - Parcel, hydro, and street layers.
  - NRCS SSURGO (1:24K) soil data

SDSU

Pre-Processing
QB Registration (2.39m/ 8ft)
A Root Mean Square of 0.42m/1.38ft (0.69pixel)



The QuickBird multi image (4-3-2) on the left with the 2004 Ortho-image (1-2-3) on the right.



The QuickBird NDVI image on the left with the 2004 Ortho-image (1-2-3) on the right.

The registered 2004 images displayed at same scale and location.

SDSU

Classification Approach
Why High Resolution NDVI?

- Reduce heterogeneous spectral-radiometric characteristics within land use land cover surfaces in the QB image.
- Normalize potential atmospheric effects within the image.
- Improve accuracy of mapping impervious surface and open space as used in the proposed runoff index calculation.

Classification Approach

Why Unsupervised Classification?

- To maximize control over the menu of informational classes.
- Minimize human involvement and error while expediting the process.
- To maximize correlation between spectral homogeneous classes and the informational categories (i.e., impervious area and open space).

Classification Approach

QB multi spectral image (4-3-2)

QB NDVI Image

Orthophoto (1-2-3)

Sample Design
Random Sampling Method

- The conservative sample size equation is expressed as follows (Congalton and Green, 1999):

  $n = B / 4b^2$

  Where: n = the total samples of all classes
  B = the upper (α/k) x 100th percentile of the Chi-squared distribution with 1 degree of freedom (α)
  k = number of classes
  b = Significance level = ***+/- 5%** accuracy*

- To ensure unbiased sample selection.
- To provide a statistically sound assessment of accuracy.
- Over 500 points were used.

Classification Scheme

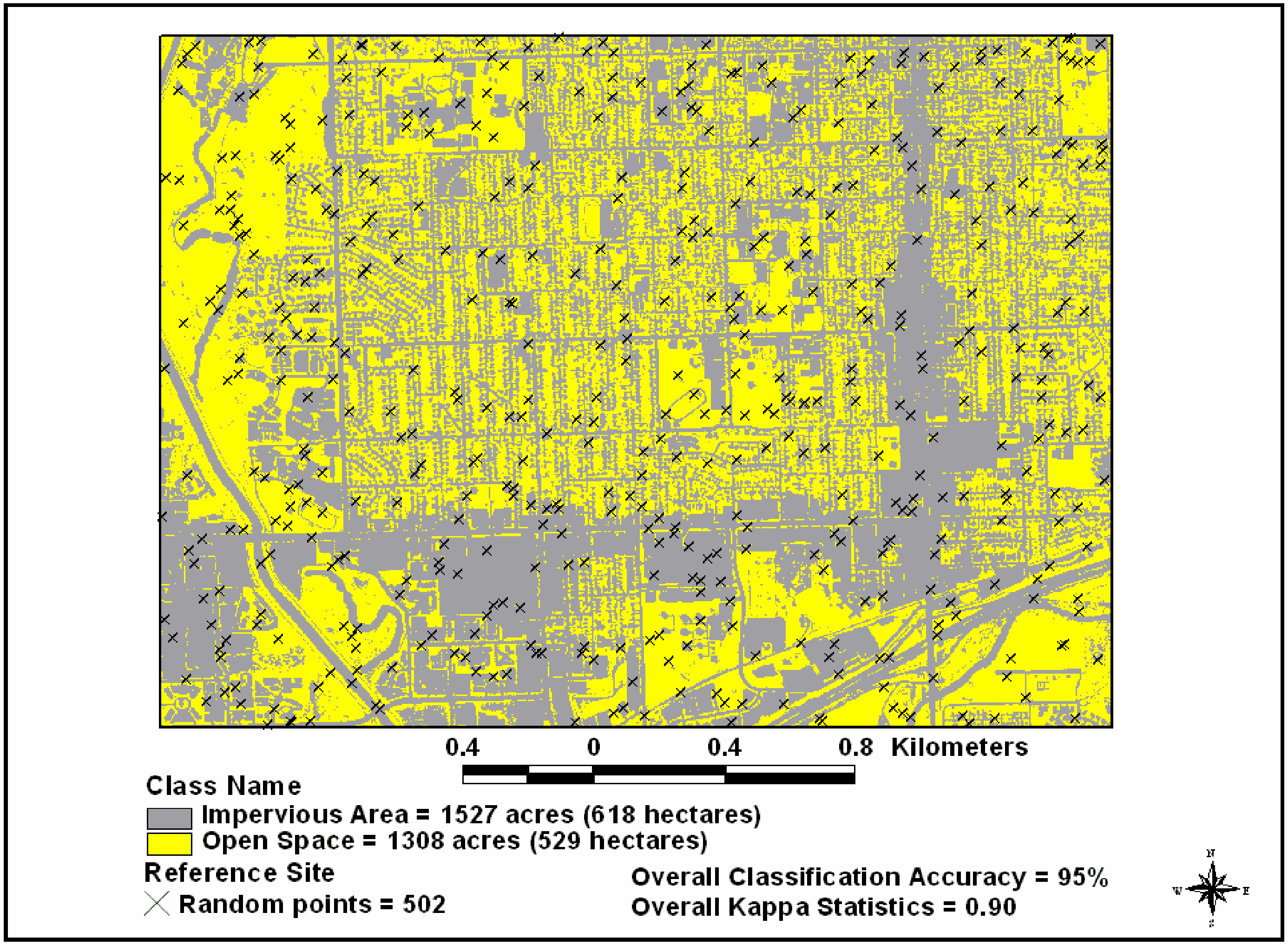
Labels	Rules
Land Use / Land Cover	
Character of Surface:	
Impervious Areas	If land area has < 25% covered with areas characterized by vegetative open spaces then **Impervious Area (1)** If land area > or = 75% characterized by impervious surfaces (e.g., asphalt, concrete, and buildings.) then **Impervious Area (1)** If land area > or = 75% covered by bare land (e.g., bare rock, gravel, silt, clay, dirt, and sand or any other earthen materials.) then **Impervious Area (1)**
Open Spaces	Else if land area < 25% covered with areas characterized by impervious surfaces then **Open Space (2)** If land area > 75% covered with vegetation naturally existing or planted (e.g., grass, plants, trees (leaf-on /leaf-off), forest, shrub, and scrub.) then **Open Space (2)** Else **Impervious Area (1)**

Accuracy Assessment

Accuracy Assessment - Unsupervised Thematic Map#1(100 spectral clusters)										
Map ID	Class Name	Labeling Criteria*	Areas (Acres)	Areas (%)	Reference Totals	Classified Totals	Number Correct	Producers Accuracy	Users Accuracy	Kappa Statistics
11	Impervious area	1-40	1270.98	43.72	258	216	210	81.40	97.22	0.9429
	Open space	41-100	1635.81	56.28	244	286	238	97.54	83.22	0.6734
		Overall Classification Accuracy = 89.24 %					Overall Kappa Statistics = 0.7857			
12	Impervious area	1-45	1392.27	47.90	258	241	229	88.76	95.02	0.8976
	Open space	46-100	1514.53	52.10	244	261	232	95.08	88.89	0.7838
		Overall Classification Accuracy = 91.83 %					Overall Kappa Statistics = 0.8368			
13	Impervious area	**1-50**	1526.54	52.52	258	261	247	**95.74**	**94.64**	**0.8896**
	Open space	**51-100**	1380.25	47.48	244	241	230	**94.26**	**95.44**	**0.9112**
		Overall Classification Accuracy = 95.02 %					**Overall Kappa Statistics = 0.9003**			
14	Impervious area	1-55	1677.57	57.71	258	285	250	96.90	87.72	0.7473
	Open space	56-100	1229.22	42.29	244	217	209	85.66	96.31	0.9283
		Overall Classification Accuracy = 91.43 %					Overall Kappa Statistics = 0.828			
15	Impervious area	1-60	1842.09	63.37	258	306	251	97.29	82.03	0.6302
	Open space	61-100	1064.70	36.63	244	196	189	77.46	96.43	0.9305
		Overall Classification Accuracy = 87.65 %					Overall Kappa Statistics = 0.7515			

- Comparing the maps generated using five different labeling criteria showed slight differences in overall accuracy results, with accuracy improvement increasing toward the mid DNs of the unsupervised QB NDVI. *No major difference was found between 8 and 16 bit imagery.*
- This pattern of change in classification accuracy showed the potential correlations between increasing and decreasing of the DN values and amounts of open space and impervious area.

Accuracy Assessment
QB NDVI Thematic Map



Geographic Modeling

- ArcView 3.3 geoprocessing was used to generate new polygons showing the relationship between impervious area, open space, hydrologic soil groups, and slope with the index values (NRCS CN or C).
- The composite runoff index spatial model was used to develop spatial modeling for the runoff index calculation in the study area.
- The results were compared to industry standard values of NRCS CN and C in order to validate the utility of the QB NDVI image.

CN Results and Comparison

Table. The Runoff Curve Number (CN) Results and Comparisons.

GIS ID[1]	GIS Vector Layer Descriptions[2]: Activity Code and Description	GIS Model CN Results: CN (avg.)	GIS Model CN Results: Impervious (%)	Industry Standard Values of NRCS CN (McCuen, 2005): Hydrologic Soil Group B	The Standard CN of Sioux Falls in 2005 by Storm Frequency, Years and Impervious Areas (%): 5	10	100	Impervious (%)
1	11 Single family - Residential 1/8 acre (0.13 acres or 506 sq.m)	***80***	50	85	45	50	***70***	40
2	11 Single family - Residential 1/4 acre (0.25 acres 1012 sq.m)	***76***	41	75	45	50	***70***	40
3	11 Single family - Residential 1/3 acre (0.33 acres 1348 sq.m)	***74***	35	72	45	50	***70***	40
4	11 Single family - Residential 1/2 acre (0.5 acres 2023 sq.m)	***74***	34	70	45	50	***70***	40
5	11 Single family - Residential 1 acre (4047 sq.m)	***68***	29	68	40	45	***65***	30
6	11 Single family - Residential 2 acres (8094 sq.m)	***76***	31	65	40	45	***65***	30
7	31 Banks and Financial Institutions	***92***	82	92	88	90	***93***	95
8	33 Other offices	***90***	73	92	88	90	***93***	95
9	64 Warehousing, Distribution, and Wholesale	***76***	81	88	80	80	***85***	80
	Total (avg.)	***78***	51	79	57.33	61.11	***75.67***	54.44

CN results compared to published values: NRCS/McCuen and City of Sioux Falls

Reference—The City of Sioux Falls' s Standard CN:

The City of Sioux Falls, 2005. The City's design standards, Chapter 11. Drainage improvements, Sioux Falls, South Dakota. *Available at* http://www.siouxfalls.org/upload/documents/publicworks/designstandards/ch11.pdf. Keyword: U30011. *Accessed on* February 3, 2006.

C Results and Comparison

GIS ID[1]	GIS Vector Layer Descriptions[2]	C Results (avg.)	C Standards		
	Activity Code and Description	Using C Criteria from Table 5	Table in Figure 2.5 (McCuen, 2005)		
			Description of Area	Recommeded C by ASCE &WPCF in 1969	Recommeded C by McCuen in 2005
1	11 Single family - Residential 1/8 acre (0.13 acres or 506 sq.m)	0.49	Residential: Single Family	0.30-0.50	0.40
2	11 Single family - Residential 1/4 acre (0.25 acres 1012 sq.m)	0.43	Residential: Single Family	0.30-0.50	0.40
3	11 Single family - Residential 1/3 acre (0.33 acres 1348 sq.m)	0.40	Residential: Single Family	0.30-0.50	0.40
4	11 Single family - Residential 1/2 acre (0.50 acres 2023 sq.m)	0.39	Residential: Single Family	0.30-0.50	0.40
5	11 Single family - Residential 1 acre (4047 sq.m)	0.34	Residential: Single Family	0.30-0.50	0.40
6	11 Single family - Residential 2 acres (8094 sq.m)	0.39	Residential: Single Family	0.30-0.50	0.40
7	31 Banks and Financial Institutions	0.72	Business: Downtown Neighborhood	 0.70-0.95 0.50-0.70	 0.85 0.60
8	33 Other offices	0.69	Business: Downtown Neighborhood	 0.70-0.95 0.50-0.70	 0.85 0.60
9	64 Warehousing, Distribution, and Wholesale	0.68	Industrial: Light	0.50-0.80	0.65
	Total (avg.)	0.50		0.43-0.65	0.54

C results compared to the industry standard published values of C

Conclusions

- The composite runoff index geographic model (Thanapura 2005/6) demonstrated that mapping techniques using high spatial resolution satellite imagery, and GIS spatial modeling were successful in determining a more precise, spatially representative runoff index (CN or C) in urban watersheds.
- Mapping impervious area and open space, using QuickBird NDVI satellite imagery generated with traditional unsupervised classification using the ISODATA algorithm, is a more precise, simpler, consistent, and efficient data extraction approach. This is reflected in the fact that overall accuracy for the QB NDVI thematic map produced was *95%*.
- The finer resolution image and the mapping approach used in this study allowed for better discrimination in land cover/land use and more accurate spatially representative runoff index estimation compare to previous studies that utilized medium resolution remotely sensed data (Bondelid et al., 1981; Singh, 1982; Slonecker et al., 2001).
- Previous studies using medium resolution data demonstrated a significant time savings in the ability to produce land cover but with accuracies only in the *70-80%* range. That was not sufficient for urban areas.

Thank you! & Questions???

For more information, see publications and presentation schedules below:

- Thanapura, P*., et all, 2005. Mapping Urban Land Use/Land Cover Using QuickBird NDVI Imagery for Runoff Curve Number Determination. *In:* Proceedings of the PECORA16 Symposium Global Priorities in Land Remote Sensing, The American Society for Photogrammetry and Remote Sensing (ASPRS), 23-27 October, Sioux Falls, South Dakota. Unpaginated CD-ROM.
- Thanapura, P.*, et all, 2006. Mapping Urban Land Cover Using QuickBird NDVI Image and GIS Spatial Modeling for Runoff Coefficient Determination. *In:* Proceedings of the ASPRS 2006 Annual Conference – Prospecting for Geospatial Information Integration, The American Society for Photogrammetry and Remote Sensing (ASPRS): The Imaging and Geospatial Information Society, 1-5 May, Reno, Nevada. Unpaginated CD-ROM (Upcoming Presentation).
- Thanapura, P.*, et all, 2006. Integration of Remote Sensing and GIS: Urban Runoff Index Determination, *In: Proceedings of the 2006 Spring Specialty Conference – Geographic Information Systems (GIS) and Water Resources IV*, American Water Resources Association, 8-10 May, Houston Texas, Unpaginated CD-ROM. (Upcoming Presentation)

Contact information:

- **Principal Investigator: pravara.thanapura@sdstate.edu or geotechconsulting@gmail.com**
- **Eric Warmath: ewarmath@dot.state.nv.us**