

Impact of residential development on storm water runoff and Edwards Aquifer recharge in Helotes

Sylvie Shurgot* and Angie Gruber, Department of Earth and Environmental Sciences, The University of Texas at San Antonio

Abstract

Increased rate of development has made the use of remote sensing necessary to the production of current Land Use Land Cover data. Two major players in the modeling of urban storm-water runoff are accurate hydrological soil groups and land use data. In this study runoff depth was calculated using the US Department of Agriculture, Natural Resources Conservation Service Curve Number method. Remote sensing, in the form of 1m orthophotos, and GIS were the tools employed to delineate two classes of land cover appropriate for the study region – vegetated areas and residential development – in a 414-acre section of Helotes, a small municipality located northwest of San Antonio, Texas. Images of the region from 1995 (pre-development) and 2004 (post-development) were processed with the Spectral Angle Mapper (SAM) and areas of coverage compared. The loss of vegetation cover to residential development was 13.86%. Spatially distributed curve numbers (CN) and average annual runoff depths were calculated for 1995 and 2004 based on the land use analysis results from the SAM process. Comparison of the results from those two years shows that average annual runoff depth has increased by 1.1%. Furthermore, maximum recharge capacity and runoff depth were calculated for a hypothetical 24-hour rain event of 11.26in and a hypothetical 7-day rain event of 33.75in. Those rain events were chosen because they actually occurred in the study area in October 1998 and July 2002 respectively, that is to say before development. Should those rain events occur again, the 24-hour event would create almost 2.5 million gallons of additional runoff; the 7-day event would create almost 3.5 million gallons of additional runoff. Even though the percentage of change in runoff may seem small, in terms of prevention and damage costs, the number of millions of gallons cannot be considered so.

Introduction

The Edwards Aquifer is one of the largest karst limestone aquifers in the United States and the sole source of drinking water for the residents of San Antonio and surrounding municipalities. The relatively recent and on-going growth spurt in population and development in the northerly direction has led to clearing of trees followed by high density construction over the Edwards Aquifer Recharge Zone (EARZ). In an undeveloped region, storm water is intercepted by the leaves of

* Email address: sshurgot@smhall.org

trees (from which it can evaporate) or soaks in the soil where some is absorbed by the vegetation and the rest is allowed to replenish the Edwards Aquifer through infiltration (French, 2005). In recent years, thanks to favorable legislation, developers have become much more likely to scrape the land, removing native trees, shrubs, grasses, and soils, leaving exposed limestone during construction and later replacing some of the native landscape with non-native soil, grasses, and vegetation; and the rest with impervious cover. Trees help improve air quality and lower energy usage. They also play an important role in storm water flow reduction (American Forests, 2003), which is the focus of this study.

One important concern in the San Antonio area is increased runoff; impervious cover keeps the water from infiltrating into the ground and can lead to flash flooding. Decreased infiltration leads to less recharge of the water supply, and the rainwater that does enter the aquifer may be carrying pollution from parking lots, roads, etc. Poor water quality in the aquifer, in turn, could cause health problems for residents or the extinction of several endangered creatures living in the Edwards Aquifer.

Because the rate of development is increasing so rapidly, remote sensing is necessary if one is to produce an accurate up-to-date analysis of the consequences of development on local hydrology (Dougherty, 2004). Aerial imagery clearly shows that the area has been developed, but those changes are not reflected on land use maps, where few areas are reported to be residential (Map b). Land use is an important factor that affects infiltration, runoff, soil erosion, and evapotranspiration. The main goal of this project was to determine how residential development has affected storm water flow and infiltration in the study region by analyzing and comparing the change in land use and land cover (LULC) in the study area as a function of time, and by quantifying the changes in storm water flow through calculations of the maximum recharge capacity (S) and the effective uniform depth of runoff (Q), using the Curve Number method from the Natural Resources Conservation Service (NRCS). The change in runoff was



also calculated for two plausible catastrophic storm events.

Study area and data

The study region, an area of about 1.676645km² (414 acres) in the Leon Creek watershed, consists of the Iron Horse Canyon and Adobe Ranch Acres subdivisions where the

average lot sizes are 0.25 acre and one acre, respectively. Both are in Helotes, northwest of San Antonio, on the edge of the Hill Country. Most of the study region lies over the Edwards Aquifer Recharge Zone in soil TX371. Average annual precipitation is 30 to 32 inches/year. Live oak and Ashe juniper are the dominant vegetation, though sumac, hackberry, kidneywood, cedar elm are also frequently observed.

Color-infrared aerial photography 1-meter orthophoto from 1995 (TNRIS) and 2004 (City of San Antonio), and ENVI software (RSI) were used to analyze the change in land cover (tree canopy, residential development) in the study area. Since Level III of the USGS land-cover classification system urban class data is necessary to identify buildings and roads, images of spatial resolution no less than 5m were chosen (Jensen, 2000). Both the 1995 and the 2004 images were resized to accommodate the study area; they were clipped to 528498.6588 Easting and 3271702.7472 Northing for the upper left corner. The lower right corner was clipped at 529738.6588 Easting and 3270353.7472 Northing. The area under consideration was delineated manually because the Leon Creek watershed is much larger than the specific area affected by the development; for a study of larger scope, a watershed could be delineated from pourpoints.

Political and natural boundaries were downloaded into ESRI's ArcInfo 9.1 from the General Land Office (GLO), Edwards Aquifer and Texas precipitation data were downloaded from the Texas Water Development Board (TWDB), soil data were downloaded from The Texas Natural Resources Information System (TNRIS), and Land Use Land Cover data came from the Texas Commission on Environmental Quality (TCEQ).

Methods

Supervised classification was performed on both images using the Spectral Angle Mapper (SAM) method. SAM uses a comparison of the spectral angle between the reference spectra (endmembers) of a Region of Interest (ROI) and the reflectance spectra of the image being classified. The angular distance between each spectrum in the image and the reference spectrum is calculated. A spectral angles map is created, in which small angular distances (represented as darker colors) indicate greater similarity between reference and image spectra. The spectra are treated as vectors in an n-dimensional space, where n is the number of bands. The lengths of the vectors, which depend on illumination, are not taken into account so the procedure treats all levels of brightness equally. Since only the directions of the spectra are used, the colors of the various materials are defined by the direction, not the length (Kruse, 1993).

To create reference spectra, several Regions of Interest must first be selected to represent the various image classes and obtain a representative sampling of the data. In this case a class of tree and vegetation cover and another class of non-vegetation cover (roads, houses, bare ground, etc.) were chosen. Next, those

ROI's were entered as endmembers in the SAM process. ENVI calculated the angular distance between each spectrum in the image and the reference spectra. Endmember values thresholds (angles) were adjusted to determine which pixels would be included in the classification image, and the SAM was re-applied until a good representation of the study area was achieved. The processed data was then exported as ENVI vector files (.evf). Finally, the vector files were exported as shape files (.shp) and image (.img) files ready to open in ArcMap for further analysis (Appendix C).

In ArcCatalog, projections were defined for all GIS datasets and feature classes were created for each in a personal geodatabase. The polygon datasets were then clipped with the study region. Subsections of area A_i , which were used in calculations of runoff and recharge, were obtained from the results of the SAM process. The effective uniform depth of runoff (Q) was calculated using the

Curve Number method: $Q = \frac{(P - 0.2S)^2}{(P + 0.8S)}$, where P is rainfall (in mm),

$S = \frac{25,400}{CN} - 254$ is the maximum recharge capacity, and $CN = \frac{\sum_{i=1}^n CN_i A_i}{A}$ is the

weighted curve number (a dimensionless index) for the total area A under consideration. Curve numbers range from 1 to 100; the higher the CN, the higher the expected runoff. 0.2s is the initial abstraction: all losses before runoff begins including water retained in surface depressions, water intercepted by vegetation, evaporation, and infiltration. It is correlated with soil type and land cover. The USDA curve numbers table (Appendix B) used in the calculations assumes a normal Antecedent Moisture Condition (AMC II), an assumption that was maintained in this study. The CN's are smaller for AMC I (dry) and larger for AMC III (wet). Antecedent Moisture Condition can greatly affect runoff so they are an important factor in the calculations. (An adjustment guide for curve numbers based on AMC is available through the Natural Resources Conservation Service.)

The process of determining soil type is rather lengthy and requires some manipulation of the data. First the Decimal Degree STATSGO soil data was downloaded from TNRS. The folder contains several files, and the interchange file comp.e00 must be chosen in order to find the necessary data. Columns MUID, SEQNUM, COMPNAME, and HYDGRP are an excerpt from that table (Appendix A). The entire table was exported to a .csv file in Microsoft Excel, where extraneous columns were removed. COMPPCT values were divided by 100. A number (HGNUM) was assigned for each of the four Hydrological Group letter (HYDGRP): 1 for D, 2 for C, 3 for B, and 4 for A; that step is necessary for the computations of average curve numbers, for which each COMPPCT value is multiplied by the HGNUM assigned for that particular sequence (SEQNUM). The values obtained are added, resulting in an average value between 1 and 4, which can be assigned an appropriate letter A, B, C, or D. The resulting average

numbers were 1.68 for soil type TX536 and 2.48 for soil type TX371. Since those numbers are not integers, they were both rounded to the nearest integer and resulted in an “average” hydrological soil group of C.

HSG	A	B	C	D
Infiltration rate (after prolonged wetting)	High (low runoff potential)	Moderate	Slow	Very slow
Description	Deep	Deep and moderately deep	Shallow soils, soils containing considerable clay and colloids	- High water table or - Shallow to an impervious layer or - Permanent high water table or
Drainage	Well to excessively well drained	Moderately well and well drained	Soil layers impeding downward movement of water	- Have a claypan or clay layer at or near the surface or - Shallow over nearly impervious material
Texture	sands	Moderately fine to moderately coarse	Moderately fine or fine	Clay with high swelling potential
Water transmission rate	Fast: >0.30in/hr	Moderate: 0.15 to 0.30in/hr	Slow: 0.05 to 0.15in/hr	Very slow: 0 to 0.05in/hr

Adapted from <http://www.bsyse.wsu.edu/cropsyst/manual/parameters/soil/runoff.htm>

A curve number (CN) was assigned to each land use class (veg_95, veg_04, dev_04, bare_95), based on soil type and the land use classes obtained from ENVI, according to TR-55 from United States Department of Agriculture (Appendix B). Then each table was exported to a .txt file, opened and saved as a .xls file. All the data was combined in a single .xls file. The mean annual rainfall of 787.4mm was used in the calculations of maximum recharge capacity, average annual effective uniform depth of runoff, and the average annual volume of runoff.

Results and discussion

Supervised classification allowed for adjustment of the parameters to a close fit. The vegetation coverage was calculated at 77.0 % in the 1995 image and 46.9 % in the 2004 image; however ENVI reported some of the vegetation from the 1995 and 2004 images as unclassified. Once the resized images and .shp files had been loaded and processed in ArcMap, a study region polygon was created along the sides of the resized images. By subtracting the area of development from the area of the whole study region in ArcMap, 19% of the 2004 and 2.86% of the 1995 vegetation were found to have been reported as unclassified. Those areas were visually determined to be vegetation. The areas created in ENVI

were verified in the GIS and, with the unclassified areas added to the classified vegetation areas, the numbers match very well.

Study area curve number calculations for 1995 and 2004

	Area	CN	(A) X (CN)	Weighted curve number
Bare_95	337730.330	79.000	26680696.070	
Veg_95	1300490.710	70.000	91034349.700	
	38424.312	70.000	2689701.840	
Sum	1676645.352		120404747.610	71.81289
Dev_04	567803.877	80.000	45424310.160	
Veg_04	786467.148	70.000	55052700.360	
	322374.327	70.000	22566202.890	
Sum	1676645.352		123043213.410	73.38655

Overall, a loss of vegetation of 13.86% was calculated, along with a decrease in maximum recharge capacity of 7.6% and an increase in effective uniform depth of runoff : 1.1%.

	1995	2004	Difference (2004 – 1995)
Max recharge capacity (S)	99.69695	92.11248	- 7.58447
Avg annual precipitation	787.4mm (31 in)	787.4mm (31 in)	N/A
Avg annual volume of precipitation	1,320,190.55m ³	1,320,190.55m ³	N/A
Effective uniform depth of runoff (Q)	679.2258mm (26.74in)	686.7185mm (27.036in)	+ 7.4927mm (0.295in)
Volume of runoff	1,138,820.781m ³ (300,844,621.71gal)	1,151,383.381m ³ (304,163,309.52gal)	12,562.6m ³ (3,318,687.81gal)
% of rainwater runoff	86.26	87.21	0.95

The expected result was a greater difference between 1995 and 2004. Possible reasons for the discrepancy involve soil. The hydrological soil group of the area is one for which the infiltration and water transmission rates are low; it is a soil with layers impeding downward movement of water. Even the vegetated areas have a curve number of 70, which is relatively high. Development has a greater effect on soils that have higher infiltration rates (USDA). In addition, residential development is only partly made of impervious cover so the soil is still an important factor in estimates of runoff. Finally, the soil type may no longer be

what TNRIS reported; native soil was removed and replaced by other soils and materials that may have different hydrological characteristics.

One interesting question remains. On October 17, 1998 San Antonio saw the beginning of a three-day long record-breaking rain event that caused tremendous flooding. How much more runoff would there have been in the study region had it been developed on October 17th, 1998? Assuming Helotes received the same 11.26in of precipitation San Antonio received, 2,444,912.334 additional gallons of water would have run off.

17 October 1998	Undeveloped	Developed
Effective depth of runoff (Q)	193.54mm	199.058mm
Total volume of runoff for the 414 acres	85,723,286.81gal	88,167,335.05gal

The week of June 30th to July 6th, 2002 also brought an unusual precipitation event. How much more runoff would there have been in the study region had it been developed in June 2002? Helotes Precipitation for that week was 33.75 inches, and 3,468,085.85 additional gallons of water would have run off.

30 June – 6 July 2002	Undeveloped	Developed
Effective depth of runoff (Q)	748mm	755.83mm
Total volume of runoff for the 414 acres	331,306,285.7gal	334,774,371.5gal

Conclusion

Residential development has changed the maximum recharge capacity and effective uniform depth of runoff in Iron Horse Canyon and Adobe Ranch Acres but not as much as expected based on the percentage of vegetation lost. In this era of rapid land use changes, remote sensing is a necessary tool to obtain accurate results based on the latest data available. The weighted curve number

calculations require land cover analysis to be performed in order to determine curve numbers (CN_i) for each separate section of land of area A_i under consideration. Up-to-date soil type and land use information are required for the determination of curve numbers.

In larger cities, recent high resolution aerial imagery is quite readily available through local government agencies. The Spectral Angle Mapper performed the analysis adequately and, in conjunction with ArcGIS and the Curve Number method, allows researcher to calculate change in runoff more accurately than with outdated land use maps. In terms of percentages, the increased runoff may seem insignificant, but with a rain even of catastrophic magnitude the number of gallons of water lost to the Edwards Aquifer reaches the millions.

Future research will need to account for the difference in tree species. Live oaks and Ashe Juniper are the dominant types of vegetation in the area, and the two absorb different quantities of water at different rates. Antecedent Moisture Conditions should be adjusted to fit the soil condition as it changes during the storm. In situ data collection of recharge features would be very helpful as well. A more detailed study is necessary in order to obtain accurate data, but it is beyond the scope of this paper.

Acknowledgments

The authors thank Dr. Hongjie Xie for his detailed and informative lectures, Dr. Richard French for his lecture on the curve number method and Dr. Kyle Murray for his directions on how to process the soil data. All three are members of the Department of Earth and Environmental Sciences and/or of the Department of Civil and Environmental Engineering at the University of Texas at San Antonio. The authors also thank Dr. Jon Allan, Mayor of the city of Helotes, for answering questions about the subdivisions under consideration, and Mr. Gregg Eckhardt whose website <http://www.edwardsaquifer.net> provides a wealth of information about the Edwards Aquifer.

References

American Forests. 2003. Urban Ecosystems Analysis Phase 2: Data for Decision Making San Antonio, TX. Available on the World Wide Web at http://www.americanforests.org/downloads/rea/AF_SanAntonio2.pdf

City of San Antonio <http://imageserver.sanantonio.gov>

Dougherty, M., Dymond, R.L., Goetz, S.J., Jantz, C.A., and Goulet, N. 2004 Evaluation of Impervious Surface Estimates in a Rapidly Urbanizing Watershed

Photogrammetric Engineering & Remote Sensing Vol. 70, No. 11, November 2004, pp. 1275–1284.

Environmental Systems Research Institute (ESRI), 2005. ArcInfo v9.1. 2005. Redlands, CA.

French, R. 2005. Lecture at the University of Texas at San Antonio.

General Land Office (GLO) <http://www.glo.state.tx.us/gisdata/gisdata.html>

Jensen, J. 2000. Remote Sensing of the Environment: An Earth Resource Perspective. Prentice Hall, New Jersey.

Kruse, F., Lefkoff, A., Boardman, J., Heidebrecht, K., Shapiro, A., Barloon, P. & Goetz, A. 1993. The spectral image processing system (SIPS) - interactive visualization and analysis of imaging spectrometer data. *Remote Sensing of Environment*, 44(2-3), pp. 145-163.

Melesse, A. and Shih, S. 2002 Spatially Distributed Storm Runoff Depth Estimation Using Landsat Images and GIS. *Computers and Electronics in Agriculture* 37. 173-183

Melesse, A., Graham, W., Jordan, J. 2003. Spatially Distributed Watershed Mapping and Modeling: GIS-based Storm Runoff Response and Hydrograph Analysis: part 2. *Journal of Spatial Hydrology*. Vol. 3, No.2

Pandey, A. and Dabral, P. 2003. Estimation of Runoff for Agricultural Watershed Using SCS Curve Number and Geographic Information System.

RSI. ENvironment for Visualising Images v4.1

Texas Comission on Environmental Quality (TCEQ). <http://www.tnris.state.tx.us/>

Texas Natural Resources Information System <http://www.tnris.state.tx.us/digital.htm>

The Texas Water Development Board (TWDB):
<http://www.twdb.state.tx.us/mapping/gisdata.asp>

Urban Hydrology for Small Watersheds, United States Department of Agriculture Technical Release 55 – 1986. 2nd ed. Available on the World Wide Web: www.hydrocad.net/pdf/TR-55%20Appendix%20B.pdf

Runoff parameters
<http://www.bsyse.wsu.edu/cropsyst/manual/parameters/soil/runoff.htm>

Appendix A

Soil Table

MUID	SEQNUM	COMPNAME	COMPPCT	HYDGRP	HGNUM	C_X_H	C_X_H_SUM
TX371	1	NUVALDE	0.07	B	3	0.21	
TX371	2	NUVALDE	0.16	B	3	0.48	
TX371	3	OAKALLA	0.24	B	3	0.72	
TX371	4	BOERNE	0.10	B	3	0.30	
TX371	5	BOERNE	0.06	B	3	0.18	
TX371	6	BARBAROSA	0.03	D	1	0.03	
TX371	7	DENTON	0.09	D	1	0.09	
TX371	8	DENTON	0.01	D	1	0.01	
TX371	9	KRUM	0.04	D	1	0.04	
TX371	10	KRUM	0.08	D	1	0.08	
TX371	11	ORIF	0.06	A	4	0.24	
TX371	12	DEPALT	0.04	D	1	0.04	
TX371	13	SUNEV	0.02	B	3	0.06	2.48
TX536	1	STRABER	0.23	C	2	0.46	
TX536	2	STRABER	0.01	C	2	0.02	
TX536	3	TREMONA	0.17	C	2	0.34	
TX536	4	TREMONA	0.01	C	2	0.02	
TX536	5	TABOR	0.17	D	1	0.17	
TX536	6	CROCKETT	0.12	D	1	0.12	
TX536	7	CROCKETT	0.01	D	1	0.01	
TX536	8	FRELSBURG	0.04	D	1	0.04	
TX536	9	FRELSBURG	0.01	D	1	0.01	
TX536	10	CATILLA	0.03	B	3	0.09	
TX536	11	LATIUM	0.03	D	1	0.03	
TX536	12	KNOLLE	0.03	B	3	0.09	
TX536	13	SILAWA	0.03	B	3	0.09	
TX536	14	AXTELL	0.03	D	1	0.03	
TX536	15	FALBA	0.02	D	1	0.02	
TX536	16	PADINA	0.02	B	3	0.06	
TX536	17	BLEIBLERVILLE	0.02	D	1	0.02	
TX536	18	BOSQUE	0.02	B	3	0.06	1.68

Appendix B

Urban Hydrology for Small Watersheds, United States Department of Agriculture Technical Release 55 - 1986

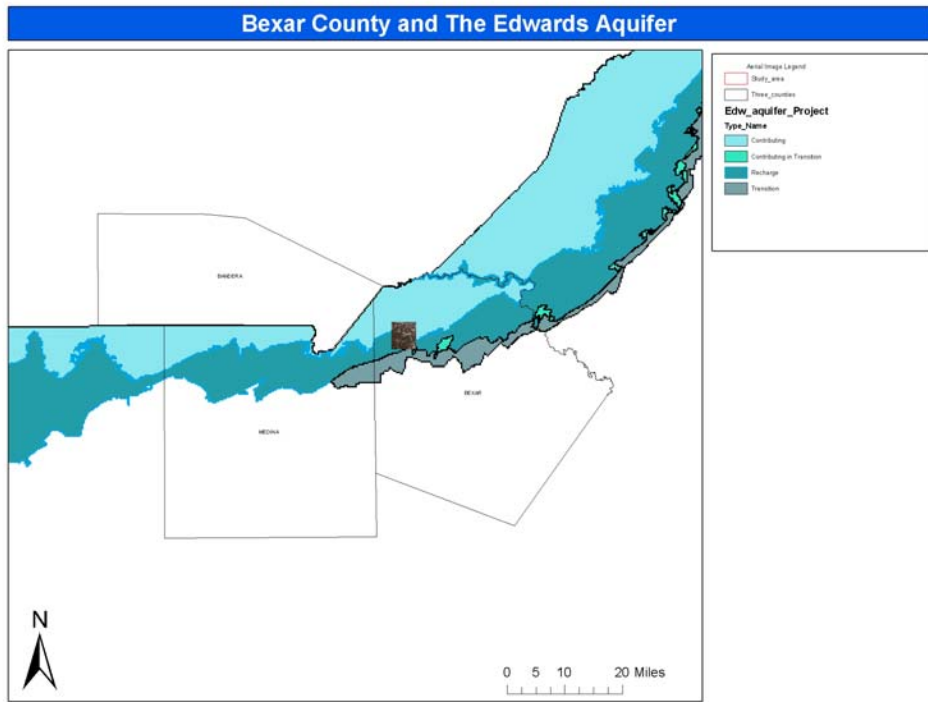
These CN's represent average runoff condition for urban, cultivated agricultural, other agricultural, and arid and semiarid rangeland uses.

Table 2-2a Runoff curve numbers for urban areas ^{1/}

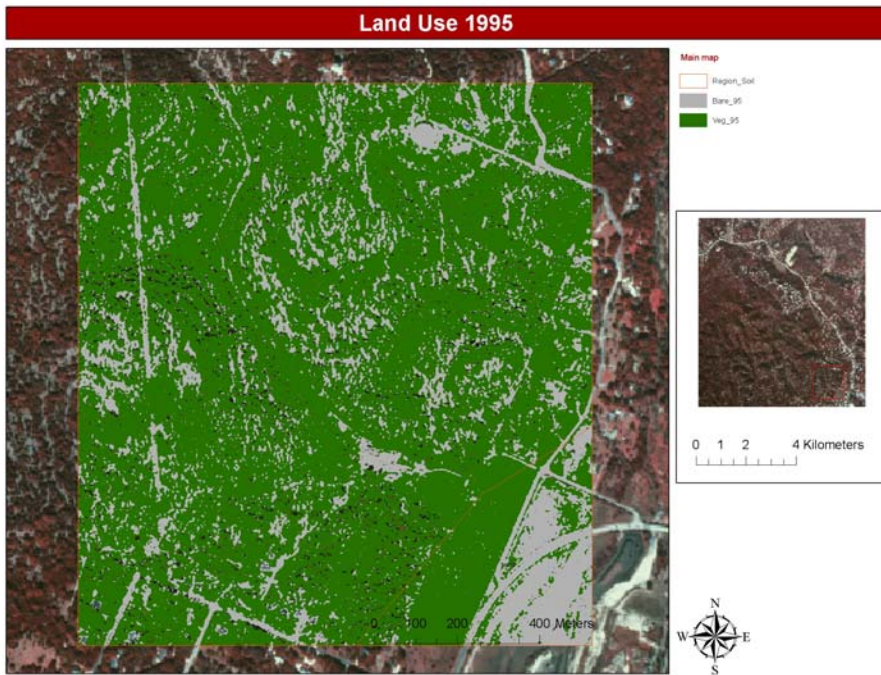
Cover description	Average percent impervious area ^{2/}	Curve numbers for hydrologic soil group			
		A	B	C	D
<i>Fully developed urban areas (vegetation established)</i>					
Open space (lawns, parks, golf courses, cemeteries, etc.) ^{3/} :					
Poor condition (grass cover < 50%)		68	79	86	89
Fair condition (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
<i>Developing urban areas</i>					
Newly graded areas (pervious areas only, no vegetation) ^{5/}					
		77	86	91	94

Appendix C – Maps

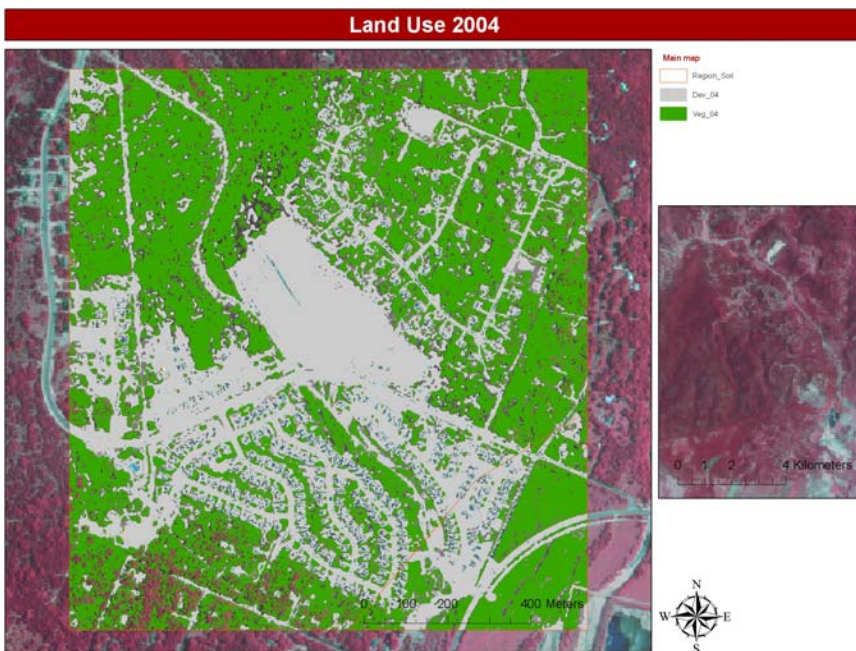
Map a: study area



Map b: outdated LULC data



Map c: result of the SAM process for 1995



Map d: result of the SAM process for 2004