Satellite derived impervious surface area as an indicator for water resource impacts in a semi-arid environment, Utah, USA

P. Rieke Arentsen, R. R. Gillies & N. Mesner
Department of Aquatic, Watershed, and Earth Resources, Utah State University, Utah, USA

Abstract

Impervious surface area (*ISA*) has recently emerged as an important ecological indicator of cumulative water resource impacts to urban watersheds. An *ISA* study was conducted in Cache County, Utah, to examine the potential of *ISA* as an indicator of water resource impacts in the region. Two LANDSAT 7 images from the spring of 2000 and, the summer of 2002 were analysed to compute *ISA*. Water chemistry and discharge data were collected from canals during five stormwater runoff events. Variables measured included dissolved metals, nutrients, sediment, oil and grease, fecal coliforms, and field parameters (e.g., water temperature). Percent *ISA* and loading coefficients were calculated for each of the contributing basins for a total of eight sampling locations. Results of linear regressions correlating mean site concentrations and percentage *ISA* were positive and strong ($p<0.03$) for total phosphorus (R^2=0.86), total nitrogen (R^2=0.94), orthophosphate (R^2=0.94), total suspended solids (R^2=0.67), boron (R^2=0.82), copper (R^2=0.98), lead (R^2=0.96), zinc (R^2=0.97), and turbidity (R^2=0.67). Mean site loading coefficients were similarly correlated. Additionally, potential water quality impacts were evaluated by comparing mean site concentrations and percentage *ISA* with Utah and European water quality standards or pollution indicators. Those that exceeded the Utah standards or pollutant indicator values were total phosphorus, total suspended solids, lead, aluminium, and fecal coliform. Concentrations above the European standards were aluminium and iron. The Cache County study indicates that *ISA* is an applicable parameter as an indicator for cumulative water resource impacts and, further, suggests its application as an additional resource tool for the assessment and subsequent planning for water resource protection in urban developments.
Keywords: impervious surface area, water quality, remote sensing, nonpoint source pollution, runoff, urbanisation, planning, watershed management, nutrients, metals.

Management Information Systems, C. A. Brebbia (Editor)

1 Introduction

Water resource planners and managers have recognized impervious surface area (*ISA*) as an important ecological indicator of cumulative impacts to urban aquatic systems. However, cost and technical issues have precluded its widespread use in environmental management. Historically, methods such as mapping from aerial photography have been employed to calculate percent *ISA* (Ragan and Jackson [1]). The cost of gathering and analysing the photos is both time-consuming and expensive. In recent years, remote sensing techniques have been developed to derive *ISA* in a cost and time efficient manner. Moreover, remote sensing data covers a significantly larger temporal and spatial domain over traditional methods (Carlson and Arthur [2]).

ISA is defined as anything that water cannot penetrate including rock outcrops, parking lots, rooftops, and roads (Leopold [3]). During storm events, runoff is often routed from impervious surfaces to storm drains and eventually to receiving water bodies, usually rivers and lakes. The impacts to these water bodies can be physical, chemical and biological in nature (Leopold [3]; Klein [4]; Booth and Jackson [5]). Increases in percent *ISA* have been correlated to increased water quality degradation in urban watersheds (Schueler [6]; Arnold and Gibbons [7]). Schueler [6], for example, undertook a review of multiple studies on the correlation between percent *ISA* and watershed health and developed the following relationship: watersheds with less than 10% *ISA* are healthy, those between 10% and 25% *ISA* indicate impairment to aquatic systems, and those greater than 25% indicate water quality degradation which is potentially irreversible.

Recently, researchers have mapped percent *ISA* using remotely sensed data and have related these measurements of *ISA* to water resource impacts. For example, Gillies *et al* [8] performed a time-series analysis of 3 Landsat images to track changes in percent *ISA* over 18 years in an Atlanta, Georgia, U.S.A. metropolitan watershed. They correlated increases in percent *ISA* with mussel population degradation, and subsequently, a decrease in water quality. A threshold between 50-70% *ISA* was found to correlate with a noticeable decline in water quality. Roy *et al* [9] determined percentage of land cover in another Georgia watershed using Landsat TM data. They were able to relate the percentage of land use at >15-20% urban land cover to a decline in macroinvertebrate assemblages. Clausen *et al* [10] researched the relationship between percent *ISA* and water quality in the state of Connecticut, U.S.A. Landsat TM and ETM data were used to determine percent *ISA*. They found that percent *ISA* was significantly related to all of the water quality variables tested.

Prior research on the relationship between percent *ISA* and watershed functions has been performed in the northwest, midwest, and eastern parts of the United States. However, Schueler's [6] relationship has not yet been applied in a semi-arid climate region (Booth and Jackson [5]). The goal of this research was to examine the relationship between percent *ISA* (as derived from Landsat TM satellite imagery) and water quality in a semi-arid region in northeastern Utah, U.S.A. Of particular concern are the nonpoint source pollution (NPS) impacts on

Management Information Systems, C. A. Brebbia (Editor)

irrigation, aquatic life, and recreational uses of downstream waters. In addition, much of the water that is not allocated for agricultural or municipal use eventually infiltrates to groundwater or flows into the Bear River, where NPS impacts could affect aquatic life and other beneficial uses. Moreover, an established relationship between percent *ISA* and water quality for the western location could be useful in regional planning of water resources. Therefore, the research objectives were to: 1) Calculate percent *ISA* using Landsat TM data, 2) monitor stormwater runoff pollutant concentrations and loads from contributing land areas, and 3) determine if a relationship exists between both mean site loading coefficients and mean site concentrations with percent *ISA*.

2 Methods

2.1 Study area

The Logan urban area (latitude: 41.8° N, longitude: 111.8°W) is the region of interest for this study, located in Cache County in the northeast corner of Utah (ref., Figure 1). The population is approximately 59,000 in an area of approximately 94 square kilometres (km^2).

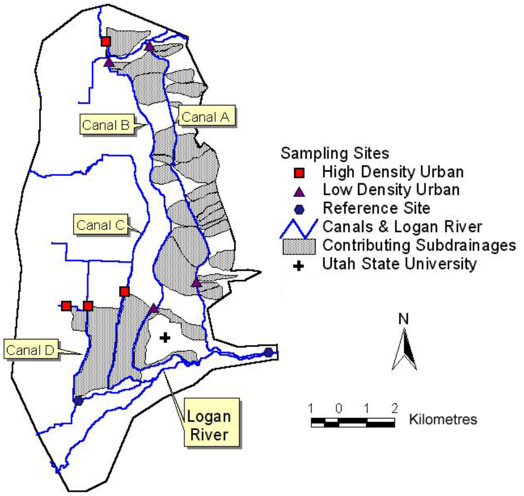

Figure 1: Canal system, sampling sites, and their respective contributing subdrainages within the Logan urban area, as outlined. Note the area designated as Utah State University does not contribute since its drainage is self-contained.

Logan is bordered to the east and west by the Bear River Mountain and the Wellsville Mountain Ranges, respectively. Land uses in the Logan area consist primarily of agricultural and urban and suburban land uses.

Management Information Systems, C. A. Brebbia (Editor)
© 2004 WIT Press, www.witpress.com, ISBN 1-85312-728-0

The Logan River is a tributary to the Bear River, the main-stem tributary in the county, and its watershed drains approximately 65,964 hectares (ha) (UDWQ [11]). Water in the Logan River is diverted at varying locations into four main canals for agricultural and municipal irrigation. The uppermost diversion occurs in Logan Canyon and the subsequent three diversions occur downstream at locations throughout the city of Logan, as noted in Figure 1. In each of the canals, water flows north through the municipalities of Logan, North Logan, Hyde Park and Smithfield, and unincorporated areas. Water is generally diverted into the canals starting the beginning of May until early autumn. The canals run parallel to the hillslope and so provide a unique opportunity to observe stormwater runoff, as they intercept stormwater runoff from up-gradient land areas.

2.2 *ISA* calculation

The following methods describe the steps taken in calculating percent *ISA*. The first step involved classifying the land cover types within the satellite images. Next, the fractional vegetation cover per pixel was calculated, followed by the percent of *ISA* for each pixel.

2.2.1 Classification

Two Landsat 7 TM 30 metre resolution images (from April 26, 2000 and July 5, 2002) were first classified and subsequently utilised in the percent *ISA* computation. The images were georectified using the nearest neighbor technique and referenced to the UTM coordinate system (UTM Zone 12, spheroid GRS 1980, datum NAD 83 North). The Logan urban area was delineated for use in the analysis (ref., Figure 1). A supervised classification was performed on the April 2000 image and an unsupervised classification was carried out on the July 2002 image using ERDAS Imagine 8.5. For the April 2000 image, five land cover classes, based primarily on the Anderson classification system (Anderson *et al* [12]) were identified in the study region: water, cropland/grassland, bare soils, low density urban (LDU), and high density urban (HDU) (Yang and Lo [13]). A forest land cover class was an extra class delineated in the July 2002 classification. The classifications' accuracies were determined using ERDAS Imagine's accuracy assessment program (Erdas [14]). For the accuracy assessments, a stratified random sampling scheme was selected (Yang and Lo [13]). For the April 2000 image, 209 ground control points (GCP) were randomly selected and ground truthed using a Global Positioning System (GPS). A relatively smaller region of the July 2002 Landsat image was assessed for accuracy and, consequently, 43 GCP's were ground truthed.

2.2.2 Fractional vegetation cover

The next step was to establish a relationship between the Normalized Difference Vegetation Index (NDVI) and fractional vegetation cover (Fr), as established by Gillies and Carlson [15]. Calculations were performed using Imagine 8.5's geospatial modeling function. First, the images were converted to apparent reflectance (NASA [16]). The NDVI was then calculated as:

Management Information Systems, C. A. Brebbia (Editor)

$$NDVI = \frac{NIR - RED}{NIR + RED}, \quad (1)$$

where NIR is the near-infrared and RED is the red apparent reflectances, respectively. Following $NDVI$, N^* was computed as:

$$N^* = \frac{NDVI - NDVI_0}{NDVI_S - NDVI_0}, \quad (2)$$

where $NDVI_o$ is the bare soil value and $NDVI_s$ is the dense vegetation value (Gillies and Carlson [15]).

Fr was finally computed as:

$$Fr = N^{*2}. \quad (3)$$

2.2.3 *ISA*

Based on the observation that ISA is inversely related to vegetation cover in an urban setting (Ridd [17]), the assumption is made (Carlson and Arthur [2]) that the percent ISA of the pixel was calculated as:

$$ISA = (1 - Fr)_{HDU / LDU}, \quad (4)$$

where the subscript, HDU / LDU, is included in the equation to indicate that percent ISA is calculated only for HDU / LDU classes Carlson and Arthur [2]. All other classes were assigned zero percent ISA.

2.3 Contributing subdrainage delineation

Contributing subdrainages for each sampling location were determined from USGS topographic (1:24,000 scale) quadrangles (ref., Figure 1). The polygons were then digitized and area computed using ArcView 3.3. The delineated contributing subdrainages were imported into ERDAS Imagine 8.5 and converted to areas of interest (AOI). The AOI's were then used to compute the ISA statistics of the contributing subdrainages. The resulting subset pixels for each contributing subdrainage were then converted to ASCII files. The ASCII files were imported into Microsoft's Excel where mean pixel values, including zero values, were calculated to determine the percent of ISA for each contributing subdrainage. Percent ISA for five of the eight contributing subdrainages was determined from the April 2000 image. The July 2002 image was used to compute percent ISA for the three remaining sites. This was justified since considerable development had occurred between image periods.

2.4 Water quality analysis

As stated previously, the canals originating from the Logan River were the subjects for the water quality analysis. During the spring, summer, and autumn of 2003, five stormwater runoff events were sampled.

Management Information Systems, C. A. Brebbia (Editor)
© 2004 WIT Press, www.witpress.com, ISBN 1-85312-728-0

2.4.1 Sampling design and data collected

A stratified random sampling scheme was used to characterize NPS impacts from *HDU* and *LDU* sites. Ten locations (ref., Figure 1), including four *HDU*, four *LDU* and two reference sites, were sampled during storm events of greater than 2.5 mm total precipitation (Brezonik and Stadelmann [18]).

Water samples were analysed for the following: Dissolved metals (arsenic, barium, boron, copper, lead, iron, zinc, and aluminium), total nitrogen (TN), total phosphorus (TP), nitrate (NO_3-N), orthophosphate (PO_4-P), total suspended solids (TSS), hydrocarbons (HC), and fecal coliforms (FC). Field variables measured include: pH, temperature, dissolved oxygen (DO), specific conductivity, and turbidity. Most samples were collected and analysed according to Standard Methods' [19] guidelines.

2.4.2 Discharge and precipitation data

Flow was measured with the aid of a Flo-Mate portable flowmeter (Model 2000, Marsh-McBirney, Inc.) at each site at varying water stages. A rating curve was subsequently developed for each location to help expedite flow measurements during storm events. Hourly precipitation was collected and, the rainfall intensity was calculated as total precipitation divided by the duration (Hornberger *et al* [20]).

2.4.3 Loading analysis

Loading coefficient calculations were as follows for concentrations [conc] in mg/L as given by eqn 5:

$$\frac{[conc]\left(\frac{mg}{L}\right)\times discharge(cfs)\times 2.4468\ (conversion\ \ factor)}{area(ha)}=\frac{kg}{ha\cdot day} \tag{5}$$

Pollutant concentrations and loads during the five runoff events were subsequently averaged for each site.

3 Results

The following sections detail the results for the elements of *ISA* determination along with those comparisons of pollutant measurements.

3.1 Classifications and percent *ISA*

The accuracy assessment for the April 26, 2000 Landsat image had an overall classification accuracy of 81% and an overall kappa index of agreement of 0.69. Similarly, the July 5, 2002 image's overall classification accuracy was 77% and the overall kappa index of agreement was 0.67.

Computed percent *ISA* for the contributing subdrainages ranged from 9% to 58%. The *ISA* maps for the Logan urban area are shown in Figure 2:

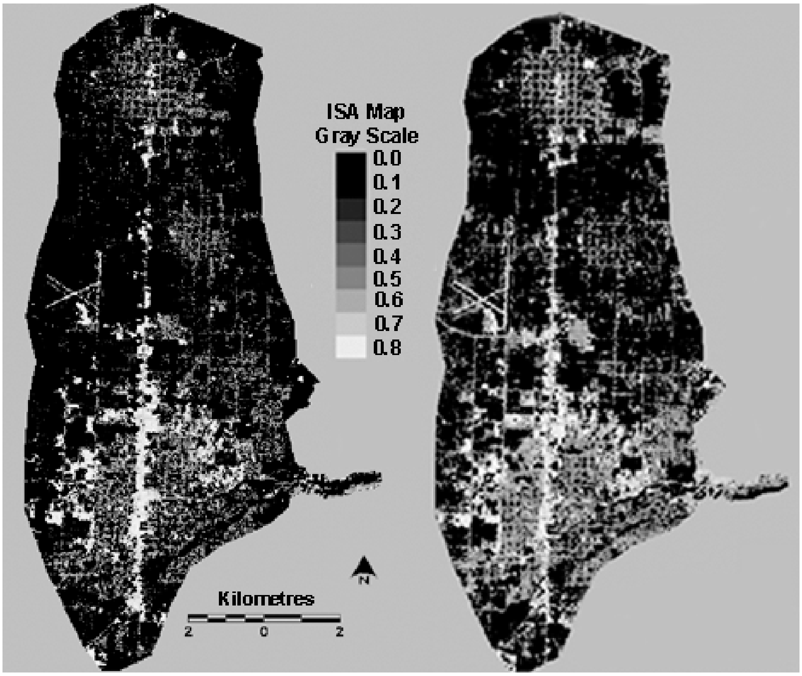

Figure 2: *ISA* maps of the Logan urban area. Left to right: April 2000 and July 2002.

3.2 Stormwater variables and percent *ISA*

Linear regressions were performed using SAS JMP version 4 statistical software (SAS Institute, Inc.) to determine if relationships existed between averaged storm event loading coefficients and concentrations with percent *ISA*.

Table 1: Regression results of both mean site loading coefficients and concentrations with percent *ISA*.

Mean Site Concentrations			*Mean Site Loading Coefficients*		
Variable	*R^2 Value*	*P-Value*	*Variable*	*R^2 Value*	*P-Value*
TN	0.94	<0.0001	*TN*	0.71	0.008
TP	0.86	0.0008	*TP*	0.62	0.021
NO_3-N	0.44	0.073	*PO_4-P*	0.50	0.052
PO_4-P	0.94	0.0001			
TSS	0.67	0.013			
Arsenic	0.71	0.074			
Boron	0.82	0.036			
Copper	0.98	0.001			
Lead	0.96	0.004			
Zinc	0.97	0.002			
Turbidity	0.67	0.013			

Management Information Systems, C. A. Brebbia (Editor)

3.2.1 Mean site concentrations and loading coefficients

Results of the regression analysis for loading coefficients and concentrations are shown in Table 1.

Regression results for TP, TN, PO_4-P, show strong positive correlations with percent *ISA* and both mean site concentrations and loading coefficients ($p<0.05$) (ref., Table 1). TSS, NO_3-N, boron, copper, lead, zinc, and turbidity also reveal positive correlations with percent *ISA* and mean site concentrations ($p<0.07$). As expected, the graphed results of the regressions (not shown) for TSS coincide with those of turbidity ($p<0.01$).

3.2.2 Water quality and Utah and European water quality standards

Mean site concentrations were compared with Utah water quality (UWQ) standards or pollutant indicators to determine the degree of potential water quality impact. Findings revealed that TP mean site concentrations exceeded the UWQ pollution indicator level of 0.05 mg/L at 12% *ISA*, lead mean site concentrations exceeded 0.0032 mg/L at 42% *ISA*, and TSS mean site concentrations exceeded 90 mg/L at 48% *ISA* (UDAR [21]). Aluminium and FC mean site concentrations exceeded UWQ standards (0.087 mg/L and 200 conc/100ml, respectively) in all cases. All other pollutants that have specified standards or pollution indicators did not exceed UWQ standards. These thresholds of 12% *ISA*, 42% *ISA*, and 48% *ISA* correlate reasonably well with Schueler's proposed thresholds. This suggests that the Schueler thresholds for percent *ISA* in relation to water resource degradation are applicable for some water quality variables in this semi-arid region.

European water quality standards (EWQS) (European Commission Water Quality Legislation [22]) were also compared to mean site concentrations. Aluminium was found to exceed the EWQS of 0.2 mg/L at 23% *ISA* and iron exceeds 0.2 mg/L in all cases. All other pollutants that have specified standards did not exceed the EWQS.

4 Discussion and conclusions

The main goal of this study was to examine the nature of the relationship between percent *ISA* (as computed from a remote sensing technique) and water quality (as indicated by water quality variables) in a semi-arid climate. The regression statistics indicate that *ISA* is a useful measure for assessing cumulative water resource impacts in such a climatic regime. In particular, high correlation coefficients are shown to exist between certain dependant variables and percent *ISA* (the independent variable) for such a region/regime. This suggests that *ISA* as derived, may be used as a surrogate to infer the potential loadings to be expected and, moreover those concentrations likely to exceed water quality standards in such rural-urban regions, such as those examined here. Furthermore, given the relative ease of determining *ISA* from remotely sensed sources coupled with the advantages of the spatial and temporal extent of such data are persuasive arguments that *ISA*, as computed, can serve as an important planning tool for protecting current and potential impacts to sensitive waters.

Management Information Systems, C. A. Brebbia (Editor)

An important aspect of this analysis lies in the reliance of classifying the image into land cover types. While there exist multiple methods, with increasing complexity, to perform classifications to arguably better levels of accuracy, their implementation precludes their use for planners and natural resource managers. The method used here to classify land cover types and subsequently compute *ISA* is a relatively straightforward methodology that may be implemented effectively by planners and natural resource managers (Carlson *et al* [23]).

References

[1] Ragan, Robert M., M.ASCE and Jackson, Thomas J., A.M. ASCE, Use of satellite data in urban hydrologic models. *Journal of the Hydraulics Division*, pp. 1469-1475, 1975.

[2] Carlson, Toby N. and Arthur, S. Traci, The impact of land use-land cover changes due to urbanization on surface microclimate and hydrology: a satellite perspective. *Global and Planetary Change*, **25**, pp. 49-65, 2000.

[3] Leopold, L.B, *Hydrology for Urban Land Use Planning: A Guidebook on the Hydrologic Effects of Urban Land Use*, US Geological Survey Circular 554, 1968.

[4] Klein, Richard D., Urbanization and stream quality impairment. *Water Resources Bulletin: American Water Resources Association*, **15(4)**, pp. 948-963, 1979.

[5] Booth, Derek B. and Jackson, C. Rhett, Urbanization of aquatic systems-degradation thresholds, stormwater detention, and the limits of mitigation. *Journal of the American Water Resources Association*, **22(5)**, pp. 1-19, 1997.

[6] Schueler, Thomas, The importance of imperviousness. *Watershed Protection Techniques*, **1(3)**, pp. 1-12, 1994.

[7] Arnold, Chester L., and Gibbons, C. James, Impervious surface coverage: the emergence of a key environmental indicator. *Journal of American Planning Association*, **62(2)**, pp. 243-258, 1996.

[8] Gillies, Robert R., Brim-Box, Jayne, Symanzik, Jurgen, and Rodemaker, Eli J., Effects of urbanization on the aquatic fauna of the Line Creek Watershed, Atlanta- a satellite perspective. *Remote Sensing of the Environment*, **86**, pp. 411-422, 2003.

[9] Roy, A.H., Rosemond, A.D., Paul M.J., Leigh, D.S., and Wallace, J.B., Stream macroinvertebrate response to catchment urbanization (Georgia, U.S.A.). *Freshwater Biology*, **48**, pp. 329-346, 2003.

[10] Clausen, John C., Warner, Glenn, Civco, Dan, and Hood, Mark. Nonpoint education for municipal officials impervious surface research. www.nemo.uconn.edu/publications/research_reports/clausen_is-wq.pdf

[11] Bear River Watershed Description; Utah Division of Water Quality (UDWQ).www.eq.state.ut.us/EQWQ/watersheds/bear/watershed_description.htm#Physiography_20_20Geology

Management Information Systems, C. A. Brebbia (Editor)

[12] Anderson, R.J., Hardy, E.E., Roach, J.T., and Witmer, R.E., *A Land Use and Land Cover Classification System for Use with Remote Sensor Data*, US Geological Survey Professional Paper 964, 1976.

[13] Yang, X. and Lo, C.P., Using a time series of satellite imagery to detect land use and land cover changes in the Atlanta, Georgia metropolitan area. *International Journal of Remote Sensing*, **23(9)**, pp. 1775-1798, 2002.

[14] Erdas Imagine 8.4 *Tour Guides*. Erdas, Inc. Atlanta, GA., pp. 429-477, 1999.

[15] Gillies, R.R. and Carlson, Toby N., Thermal remote sensing of surface soil water content with partial vegetation cover for incorporation into climate models. *Journal of Applied Meteorology*, **34**, pp. 745-756, 1995.

[16] Science Data User's Handbook; NASA. ltpwww.gsfc.nasa.gov/IAS/handbook/handbook_toc.html

[17] Ridd, M.K., Exploring a v-i-s (vegetation-impervious surface-soil) model for urban ecosystem analysis through remote sensing: comparative anatomy for cities. *International Journal of Remote Sensing*, **16**, pp. 2165-2185, 1995.

[18] Brezonik, Patrick L. and Stadelmann, Teresa H., Analysis and predictive models of stormwater runoff volumes, loads, and pollutant concentrations from watersheds in the Twin Cities Metropolitan Area, Minnesota, USA. *Water Research*, **36**, pp. 1743-1757, 2002.

[19] Greenburg, Arnold E., Trussell, R. Rhodes, and Clesceri, Lenore S., (eds). *Standard Methods for the Examination of Water and Wastewater, 16th Ed.*, American Public Health Association: Washington, D.C., 1985.

[20] Hornberger, George M., Raffensperger, Jeffrey P., Wiberg, Patricia L., and Eshleman Keith N., *Elements of Physical Hydrology*, The John Hopkins University Press: Baltimore and London, pp. 25 & 102, 1998.

[21] Utah Division of Administrative Rules (UDAR), 2004. Rule R317-2 Standards of Quality for Waters of the State, www.rules.utah.gov/publicat/ code/ r317/r317-002.htm

[22] European Commission Water Quality Legislation (ECWQ), www.italocorotondo.it/tequila/module4/legislation/drink_water_directive_98.htm#ANNEX%20I

[23] Carlson, Toby N., Arthur, Traci, Ripley, David A., and Lembeck, Stanford, *Urban Planning and Satellite Remote Sensing: A Pilot Training Program for Planners*. The Pennsylvania State University: University Park, PA, 1999.

Management Information Systems, C. A. Brebbia (Editor)