A Place-based Tool for Assessing Cumulative Impervious Surface Outcomes of Proposed Development Scenarios

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Abstract: *Impervious surface cover is commonly used as an environmental indicator for land-use and watershed planning. Tools for predicting the net increase in impervious surface area that will result from future land-use or development scenarios can aid planners in assessing the relative impacts on water quality, flood-control infrastructure, stream erosion, groundwater recharge, and habitat. While methodologies currently exist for estimating impervious surface cover, each has drawbacks when applied to support prospective analysis. Existing methodologies also are limited in their ability to differentiate the impacts of infill and greenfield development. To attempt to address these limitations and to fill unmet needs, a remote-sensing and regression analysis was undertaken using sample data from the U.S. National Land Cover Database (2006). The result is an impervious surface growth model capable of predicting the net increase in impervious cover at the census block group scale as a function of quantities of residential and commercial development added and relative centrality of the block group within a metropolitan regional context.*

INTRODUCTION

The environmental impacts of storm-water runoff from impervious surfaces are well documented in the research literature (EPA 1992, EPA 1998, Schueler 1994, Brabec et al. 2002). Heightened concerns about these impacts have led scholars to propose impervious surface cover as a key environmental indicator for land-use and watershed planning (Arnold and Gibbons 1996). Planners seeking to take into consideration the likely storm-water runoff impacts of alternative development or land-use scenarios require tools for assessing cumulative impervious surface outcomes.

The ability to account for off-site impacts of proposed land uses is particularly important when comparing alternative development or land-use scenarios. For instance, when considered at the parcel scale, lower-density residential development often creates less impervious surface per acre than a higher-density alternative. However, compact neighborhood development creates less new impervious surface area per home because it significantly requires less miles of roadway per home (Brabec et al. 2002; EPA 2003). Better yet, infill development[1]—or building new homes within previously developed areas—takes advantage of existing services and infrastructure, further reducing the net increase in impervious area per home. Any tool that fails to account for these cumulative impacts of alternative development scenarios is at risk of providing an incomplete and misleading representation of the full environmental implications of land-use decisions.

The ability to compare the likely outcomes of alternative land-use scenarios is a topic of growing interest among planning practitioners. During the past few decades, an increasing number of metropolitan regions have engaged in visioning exercises that allocate forecasted growth to specific locations (Bartholomew 2005).[2] These projects often involve comparing a preferred vision scenario to "business as usual" in which development patterns conform to prevailing trends. Proponents of "smart growth"[3] and compact infill development also are seeking new ways to measure the environmental benefits of specific development proposals. One way to do this is to compare the impacts of the proposed infill development to the impacts of an equivalent amount of development (on a per-unit basis) occurring in conformance with prevailing development patterns (EPA 2001).[4]

There are several methods for estimating impervious surface cover based on land-use class or gross density of activity. This paper explains why each has important limitations with regard to estimating the net increase in impervious cover associated with new development. We then report on the development of a new model, dataset, and spreadsheet tool for use in assessing impervious surface impacts of proposed growth and development scenarios. This tool is designed to be practical for routine use by local planners as well as sensitive to differences in cumulative and off-site impacts associated with the location of a proposed development. We discuss tool applications as well as potential

[1] The term infill refers to new development that occurs within areas that are already urbanized. Infill may come in the form of building on an empty lot in an existing neighborhood or redeveloping an underutilized parcel.

[2] For a list of examples, see Urban Land Institutes "Reality Check" program, http://www.uli.org/programs/local-programs/reality-check-regional-planning-sustainable-development/.

[3] The term smart growth refers to community development and conservation strategies that promote vibrant, compact, and walkable neighborhoods while preserving natural lands and critical environmental areas, protecting water and air quality, and reusing already-developed land. See www.epa.gov/smartgrowth/about_sg.htm for more information.

[4] An example of this kind of analysis was conducted to support the Atlantic Steel Site Redevelopment Project. Read more at http://www.epa.gov/smartgrowth/topics/atlantic_steel.htm.

enhancements that could facilitate ease of integration with existing scenario planning and GIS tools.

EVALUATION OF EXISTING METHODOLOGIES

Several methodologies exist for estimating impervious surface cover based on analysis of remote-sensing imagery (Slonecker et al. 2001, Dougherty et al. 2004, Chabaeva et al. 2009). Fewer options, however, are available for predicting the impervious surface outcomes of proposed land-use or development scenarios. These options fall into two main categories. The first applies predefined impervious surface coefficients associated with individual land-use types. The second estimates impervious surface cover for census-defined areas based on activity density. Here we review this previous work and assess its suitability for supporting local and regional planning initiatives.

The most common approach used to assess the impervious surface impacts of proposed land-use scenarios is applying standardized impervious surface coefficients for designated land-use types (Brabec et al. 2002).[5] For instance, a detailed analysis of current land cover in three California metropolitan regions determined that retail land uses result in an average of 86 percent impervious land cover (Washburn et al. 2010). Using this information, California land-use planners could assume that areas zoned for retail will have approximately 86 percent impervious land cover after full build-out. This approach provides a straightforward methodology for roughly assessing future impervious surface cover based on full implementation (or build-out) of a master plan or land-use scenario. A number of planning analysis tools have adopted established coefficients to estimate the impervious surface outcomes of land-use scenarios. Examples include CommunityViz (Placeways 2013) and the Long Term Hydrologic Impact Analysis (L-THIA) spreadsheet model (Purdue University 2013).

A key limitation of this approach is that it can only be used to evaluate the outcomes of a fully implemented land-use plan. This makes it difficult to compare alternative land-use scenarios that include the same quantity of development. For instance, regional planning studies typically seek to evaluate the outcomes of growth that are expected to occur during a defined period of time (usually 20 to 40 years). To do this, planners typically allocate units of forecasted growth based on where it is anticipated or desired to occur. Local zoning or land-use plans can be used to limit the quantity of growth allocated to a specific area. But build-out is not a foregone conclusion. Therefore, land-use coefficients often prove to be impractical tools for translating forecasted growth into impervious surface outcomes.

To be comparable, alternative land-use scenarios must accommodate an equivalent amount of population, housing, and/or employment growth. This requires an impervious surface model that takes units of development as inputs (rather than land-use classes). The second category of impervious surface models fits this description. These models estimate impervious surface cover as a function of gross population, housing, and/or employment density. Such models have been developed to estimate impervious surface cover at the scale of municipality (Stankowski 1972, Reilly et al. 2004) and census tract (Chabaeva et al. 2004).

Activity density models address the limitations of the land-use coefficient approach and therefore are more appropriate for scenario-planning studies. However, models developed to date also present some important limitations. First, municipalities and even census tracts are a fairly coarse unit of geography. Operating at as fine a geographic scale as possible is essential in scenario-planning exercises that seek to differentiate the impacts of new greenfield development at the periphery of an urbanized area from infill development. This is partly because the development density estimates become less accurate as the scale of analysis grows. Secondly, models developed to date are insensitive to location. A high-density housing development at the periphery of a metropolitan region would be expected to result in a greater net impervious surface impact than one of equal density closer to the region's core. This is because peripheral development often requires new or expanded roadways and larger parking areas due to the much higher likelihood that residents require a vehicle for daily transportation. Development closer to the core, on the other hand, would be expected to take greater advantage of existing roadways and infrastructure.

MODEL REQUIREMENTS

This study set out to develop a model, user interface, and dataset that can be used to roughly assess the net impervious surface impacts of proposed development projects. More specifically, we wanted to be able to assess the cumulative additional impervious surface cover (both on-site and off-site) that could be expected to result from a proposed development, based on the development location. Furthermore, we sought to create a tool that is both practical for routine use and can be applied anywhere in the contiguous United States. The model requirements are described in greater detail in the following section.

1. **Relevant for application throughout the United States**
   The majority of models that estimate impervious surface cover focus exclusively on a single region or state. For this study, we sought to create a model based on nationally available data that can be applied in any location within the contiguous United States. Creating a single model with nationwide scope makes it possible to execute national studies of development scenario impacts. We also sought to create a model that could be adopted for use in localities that lack the resources to create customized models based on local data and conditions.
2. **Assesses net impervious surface impacts per unit of new development**
   Assessing impervious surface impacts per unit of new development facilitates the ability to compare the relative impacts of alternative development scenarios. This interest

[5] For examples, see USDA 1986, Washburn et al. 2010, SCAG 2009.

in scenario comparison grew out of work at the EPA to better understand the indirect environmental benefits of brownfield cleanup and reuse (EPA 2001, EPA 2011). This work begins with the assumption that aggregate population and job-growth projections for a given metropolitan region are independent of particular land-use policies and decisions. From this perspective, redeveloping a brownfield can be thought to displace an equivalent amount of development (in terms of housing units, commercial floor space, etc.) elsewhere in the same metropolitan region. Based on this assumption, the indirect environmental benefits (or impacts) of brownfield redevelopment can be assessed in part by comparing anticipated impervious surface growth associated with redeveloping the brownfield location to the anticipating impervious surface growth associated with an equivalent amount of development located in the fastest-growing part of the metropolitan region.[6] Crucial to this kind of analysis is the ability to measure incremental growth in impervious surface area (growth beyond current conditions). Modeling net impervious surface impact per unit of new development facilitates this kind of study.

3. **Assesses impervious surface cover as a function of development density and regional centrality**
As noted above, previous studies have shown that density of population, housing, and/or jobs can serve as reasonable predictors of existing impervious surface cover.[7] This study will take a similar approach, but with two important refinements. First, it will seek to develop a model calibrated at the smallest geographic unit possible that is supported by nationally available data—the census block group (block group). Block groups are contained within census tracts and generally contain between 600 and 3,000 people, with an optimum size of 1,500 people. Secondly, this study is interested in where proposed development sites are located within a metropolitan region. As noted in the introduction, a development site located near the center of a metropolitan region may require less new impervious surface than one at the periphery of the metropolitan region in part because peripheral locations often necessitate more driving. This is because peripheral locations often lack transportation choices and require further travel distances to reach everyday destinations. More driving means more need for pavement (per unit of development) both on-site and off-site. Therefore, this study tested additional variables representing regional centrality as well as the overall size (in terms of population and jobs) of the surrounding metropolitan region.
4. **Accounts for off-site impervious surface growth**
For reasons already stated, the ability to at least partially account for off-site impervious surface growth is an essential feature of this model. Structuring the model to assess impacts per unit of development within a geographic area (e.g., census tract or census block group) provides nearby off-site impacts of development. (The implications of selecting a census block group level model on its ability to capture off-site impervious surface growth are discussed later in the report.)
5. **Practical for routine use**
We sought to develop a model and dataset that is ready for use in regions across the United States, without the need for additional baseline data or calibration from the local area of analysis. We also sought to develop a tool that requires only the site location and units of development as inputs, rather than fully formed land-use scenarios.

DATA SOURCES AND MODEL SELECTION

The Impervious Surface Growth Model (ISGM) that was developed from this study is a regression-based model developed to meet the needs introduced above. The selection of the form of model was based primarily on the datasets that are available to support this study and their reliability for this application. A preliminary analysis of available datasets was conducted, including correlation analyses and inspection (analytical and visual) of datasets related to their completeness and reliability. Key sources of data that were considered for this analysis are identified in Table 1, including a brief summary of their eventual use in development of the ISGM.

These datasets were reviewed and preliminary data analyses were conducted to guide interim decision making related to development of the ISGM. A summary[8] of the key practical findings of these analyses are as follows:

- ***Is it more reliable for the ISGM regression model to be based on estimates of change in input parameters over a given period (i.e., change in imperviousness from 2001 to 2006) or based on static estimates of these parameters at a "snapshot" (i.e., total imperviousness in 2006)?*** A regression based on change metrics would more directly support the estimation of net impervious surface growth (net ISG)—the net of amount of impervious surface added per incremental unit of development. However, based on findings of preliminary data analyses, a model based on static estimates was considered more reliable for the ISGM. This preference was primarily based on the observation that static estimates appear to have lower levels of relative error and "noise" than change estimates do, which, in available datasets, are based on a relatively short period of change. The result of this decision is that the model may be more reliable for estimating impervious growth in areas that have already undergone some development, as discussed further in

[6] A more detailed discussion of this methodological approach to assessing the impacts of brownfield redevelopment is available in EPA 2001.

[7] In addition to Chabaeva et al. 2004, Washburn et al. 2010 estimate percent impervious surface cover at the submunicipality level based on residential density.

[8] A more detailed account of the preliminary data analysis is available in Geosyntec 2011, https://edg.epa.gov/data/public/op/ISGM/ISGM_finalreport.pdf.

Table 1. Datasets identified and evaluated for use

Category	Description	Source(s)	Use in ISGM Development
Nationwide Land Cover and Impervious Cover Datasets	Raster datasets (30-m resolution) containing estimates of composite imperviousness, land cover, impervious cover, and changes in land cover and imperviousness from 2001 to 2006	National Land Cover Databases 2001, 2006 Multi-Resolution Land Characteristics Consortium (MRLC) (USGS, NOAA, and EPA)	Used to calculate impervious cover in each block group via spatial analysis methods in GIS
State and Local Impervious Cover Datasets	Raster datasets with various resolution and spatial extent; available from various state and local agencies	State of Massachusetts, State of Maine, State of Hawaii, State of Delaware, City of Atlanta, Oregon Metro, City of Durham, NC, King County, WA, Santa Barbara County, CA	Oregon and Massachusetts data were used to evaluate reliability of NLCD impervious cover datasets; datasets were not used directly in the ISGM
High-resolution Aerial Photography	Various datasets available at nationwide or custom extents, some with multispectral bands, circa 2009 to 2011; some sources with historical data as well	Various agencies and companies	Used to evaluate reliability of NLCD impervious cover datasets; not used directly in the ISGM
Census Block Groups	Geographic dataset of block group boundaries defined by political boundaries and population; shapefile format for geospatial analysis with other layers or tabular relationships with related datasets	U.S. Census Bureau (obtained directly from the Smart Location Database, Ramsey et al. 2012)	Used as base unit of geography for spatial analyses and regression analyses
EPA Smart Location Database[9]	A nationwide collection of population, housing, employment, transportation, and other metrics at the block group scale (e.g., population density), as well as modeled data and indices (e.g., gravity model of destination accessibility); the 2012 version of this dataset provided density metrics based on only the "unprotected" areas of each block group. See "protected areas datasets" below	EPA (Ramsey et al. 2012)	Various metrics and model results/indices from the SLI were considered in preliminary regression analyses. Certain metrics and model results from the SLI were used in the final regression model and associated user interface (See Table 2.)
Local Employment Dynamics Dataset (LED) and Longitudinal Employer-Household Dynamics Dataset (LEHD)	Information about locations of employment and residence at the census block scale (one degree finer than block group)	U.S. Census Bureau (accessed May, 2011)	Used as a source of data for estimating the number of employees in each block group
Protected Areas Datasets	Various datasets identifying locations that are restricted from development in some way, either via land cover (i.e., water) or local, state, or national planning designations (i.e., parks, national forest, military reserves, etc.)	Protected Areas Database—US (PADUS) v1.2 (USGS) (2011) Navteq land-use and water features (Navteq, 2011) NLCD 2006 (MRLC, 2011)—water land cover	Used in spatial analysis to categorize "unprotected" and "protected" portions of block groups, incorporated into 2012 SLI Database

9 Note that EPA's Smart Location Database was updated in 2013, after this study was complete. The 2012 release of the database is still available online. See Ramsey et al. 2012 or download the entire dataset (324 MB) at https://edg.epa.gov/data/public/op/ Smart_Location_DB_v02b.zip. For information about the latest release of the Smart Location Database, see http://epa.gov/smartgrowth/smartlocationdatabase.htm.

the "Model Validation and Reliability" section of this paper.

- ***What scale and resolution of remote-sensing analysis best balances data quality and data quantity to yield the most reliable model?*** Options considered for model development range from focused, high-resolution analysis of a relatively small number of samples (100 to 200) to a much broader analysis, considering the majority of block groups (approximately 200,000), but with estimates generated for each block group at lower resolution. Based on observations of data quality and reasonableness (above), a broad analysis was strongly preferred compared to a more focused analysis: (1) a broad range of potential independent variables (e.g., development density, destination accessibility) are likely to be needed to adequately describe the urban context, (2) regional variability may need to be considered in this or future analyses and can be much more rigorously supported by analyzing a large number of samples, and (3) observations of data quality and reasonableness indicate that the datasets that would be used in the broader analysis appear to have adequate quality and reliability.

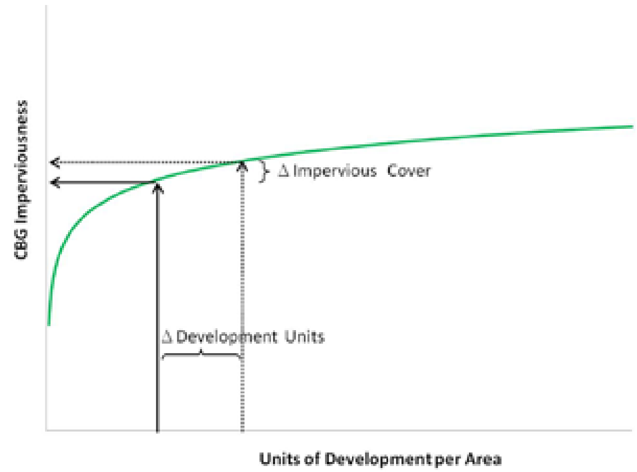


Figure 1. Conceptual model for estimation of impervious cover change

Table 2. Parameters used for regression analysis

Parameter ID	Description	Units	Source
HU2006	Housing units, estimated (2006)	Count	U.S. Census Bureau
EMP2006	Total employees; nonfederal (2006)	Count	LEHD (downloaded February, 2011)
UNP_IMP_06	Percent impervious cover in unprotected areas	%	Analysis of unprotected areas[10] and NLCD 2006 impervious cover dataset
UNP_IMPAC_06	Impervious acres in unprotected area (2006)	ac	Analysis of unprotected areas and NLCD 2006 impervious cover dataset
HU_DENS	Unprotected area housing unit density	HU/ac	Calculated from metrics above (housing units divided by unprotected area, acres)
EMP_DENS	Unprotected area employment density	EMP/ac	Calculated from metrics above (employees divided by unprotected area, acres)
D5AR*	Jobs within 30 miles, gravity weighted[11] (destination accessibility) Note: Various other parameters were evaluated as part of potential regression models that were not selected. More information about other parameters can be found in the ISGM project report (Geosyntec 2011).	jobs	U.S. Environmental Protection Agency, (Ramsey et al. 2012)

*Modeled input from Smart Location Database

[10] This analysis was concerned only with impervious land cover within the developable portion of each block group. Therefore, all areas known to be protected from residential and commercial development activity were eliminated from block group boundaries before land-cover analysis. Two national data sources were used to identify land area protected from development. NAVTEQ was used to identify city, regional, state, and national park lands. Protected Areas Dataset–U.S. (PADUS) version 1.2 was used to identify all public lands as well as private conservation lands permanently protected from development. This analysis is documented by Ramsey et al. 2012.

[11] This is a measure of "destination accessibility" and regional centrality included in the U.S. EPA's Smart Location Database (Ramsey et al. 2012). It istmeasured as the cumulative number of jobs that can be accessed from the origin census block group within a 30-mile radius, gravity weighted. Note that this metric was based on 2009 employment counts.

MODEL DEVELOPMENT

Model development consisted of (1) selecting the form of the ISGM, (2) selecting regression parameters, (3) conducting the regression analysis, (4) selecting the best-performing regression model, and (5) evaluating model reliability. The following sections describe this process.

Form of Impervious Surface Growth Model

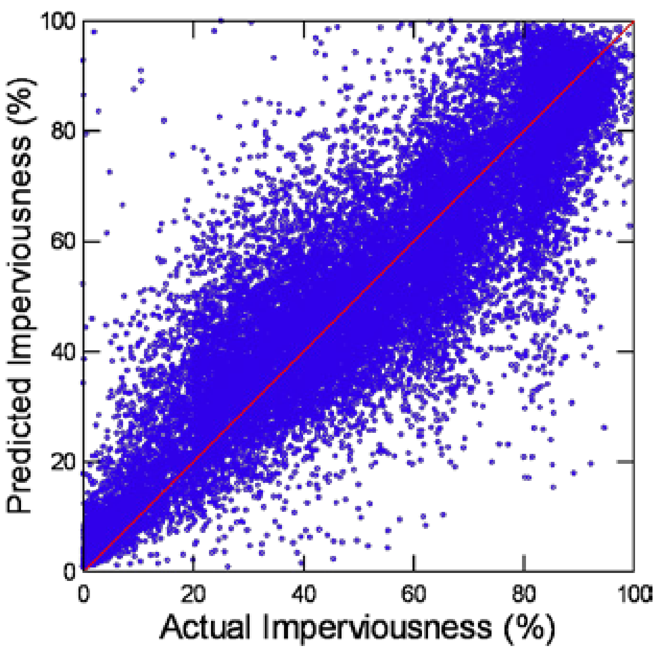
The ISGM is based on a multivariate, nonlinear regression equation that yields an estimate of average imperviousness based on the housing unit density, employment density, and destination accessibility of the unprotected areas of each block group. This estimate of imperviousness can be multiplied by the unprotected acreage of the block group to yield an estimate of the acreage of impervious cover in the unprotected area of each block group. The hypothetical addition of development units (i.e., housing units and/or number of employees) results in adjustments to the independent parameters (i.e., increased housing unit density and/or increased employment density) in the regression, which yields an increase in the impervious cover estimated by the regression. The difference in impervious cover predicted between the baseline condition and the hypothetical adjusted condition can be attributed to the hypothetical number of units of development added. This model is conceptually illustrated in Figure 1.

Parameter Selection and ISGM Regression Analysis

The regression equation selected for use in the ISGM was chosen from a large number of potential options based on an iterative and adaptive process. Initial parameters were selected for consideration based on the results of the scatter plot matrices and nonparametric correlation analyses conducted on the preliminary dataset. Parameters were added and removed from the regression, iteratively, to attempt to improve performance. Additionally, a range of model forms was evaluated. The dataset used for the regression analysis is described in Table 2.

A stratified sampling method was used to develop and test the regression equation.

1. From a pool of all block groups in the conterminous United States that contain unprotected land area, we first excluded block groups that do not contain sufficient and consistent data on which to base the development of the regression. The resulting block group dataset used for analysis included 181,809 block groups, each containing consistent estimates of the key independent and dependent parameters.



Raw R-square (1-Residual/Total)	:	0.954
Mean Corrected R-square (1-Residual/Corrected)	:	0.825
R-square (Observed vs. Predicted)	:	0.827
R (Correlation coeff.)		0.909

Figure 2. Comparison of predicted to proposed imperviousness and regression statistics

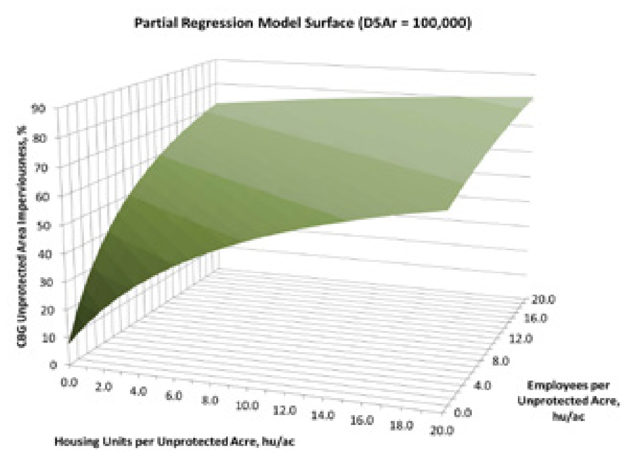


Figure 3. Partial graphical depiction of selected regression model (D5Ar = 100,000)

2. The analysis dataset then was stratified into five equal interval bins from 0 to 100 percent impervious cover, and an equal number of random samples were selected from each bin. Stratified random sampling conducted to develop the regression model yielded approximately 25,129 samples (i.e., approximately 5,000 data points per imperviousness bin) in 37 states.
3. Using this subsample dataset, many model trials were conducted using different forms of regression equations and different combinations of potentially significant explanatory variables. The nonlinear regression modeling tool in SYSTAT© Version 12 (http://www.systat.com/) was employed to find the best combination of coefficients for each trial and generate regression statistics. These statistics were evaluated along with an inspection of scatter plots of the predicted imperviousness versus measured imperviousness (NLCD 2006) for each trial. Based on these trials, a best-performing regression equation was identified.

Best-performing Regression Equation

The best-performing nonlinear regression model that was obtained has the following form and coefficients.

$$\%IMP = \frac{100}{1 + \frac{1}{0.008 + 0.1227 \times HU_{UAC} + 0.093 \times EMP_{UAC} + 0.000000739 \times D5AR}}$$

Where: %IMP is percent imperviousness of the unprotected area of the block group

HU_{UAC} is the housing units per unprotected acre

EMP_{UAC} is the employees per unprotected acre

$D5AR$ is number of jobs within 30 miles based on a gravity model

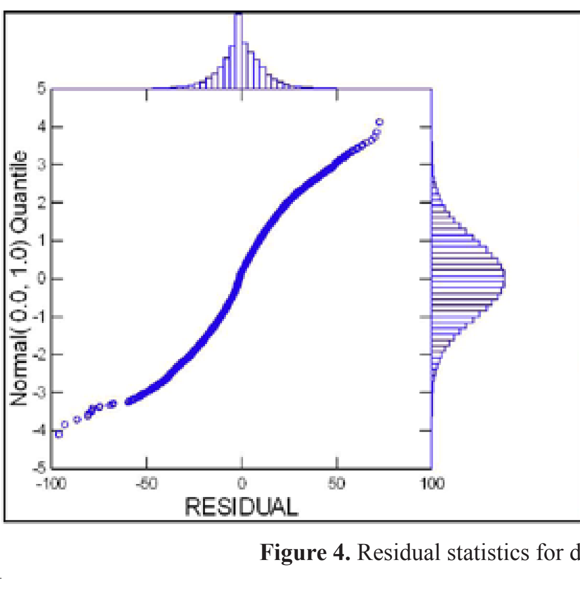
Figure 2 displays the comparison of impervious cover "predicted" by the best-performing regression model to the "actual" imperviousness measured by the 2006 NLCD. Figure 3 depicts the regression equation graphically for an example "solution surface" holding the D5AR variable to 100,000 jobs.

MODEL VALIDATION AND RELIABILITY

Model validation was an integral element of developing the regression model, and was part of the iterative process used to develop the selected model. The model was validated in three primary ways, as described in the paragraphs below.

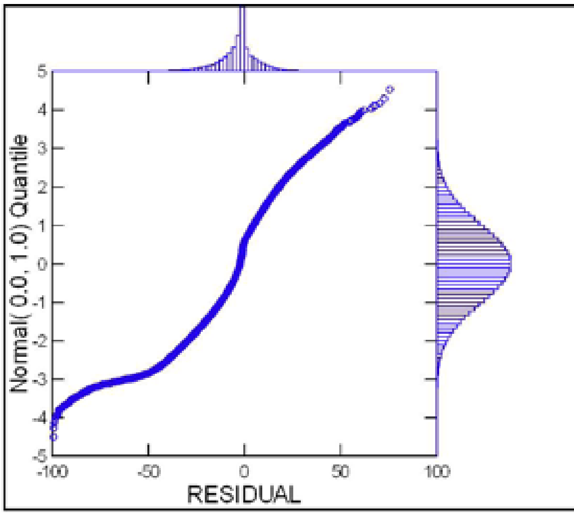
Application to Remaining Sample Data

The selected regression model was applied to the remaining 156,520 samples (block groups) that were not used in the development of the model. This validation was based on a comparison made between the residuals of the model development dataset (25,129 block groups, Figure 4) and the residuals of the remaining dataset (156,520 block groups, Figure 5). Residuals are fairly evenly distributed for both datasets, and the mean and median of residuals differ by only 1 percent to 2 percent imperviousness between the datasets–the standard deviations differ by less than 1 percent. These differences can likely be attributed to the greater influence of the middle of the range of imperviousness (30 to 60 percent) in the full dataset compared to the stratified model development subsample, as well as the presence of potential outliers. A truly normal distribution will have a skewness of zero and kurtosis of three. As shown in Figure 4 the skewness is only slightly negative and the kurtosis is slightly higher than three. While normally distributed residuals are preferred in regression analysis, residuals that are approximately normal and have approximately constant variance indicate that the regression equation will produce reasonably accurate predictions (Helsel and Hirsch 2002). This comparison indicates the model development subsample is reasonably representative of the full population.



	RESIDUAL
N. of Cases	25,129
Minimum	-95.753
Maximum	72.777
Median	-0.821
Arithmetic Mean	-0.543
Standard Deviation	11.967
Skewness (G1)	-0.061
Kurtosis (G2)	3.080
Anderson-Darling Statistic	201.184
Adjusted Anderson-Darling Statistic	201.190
p-value	<0.01

Figure 4. Residual statistics for data used in regression model



	RESIDUAL
N of Cases	156,520
Minimum	-98.817
Maximum	75.949
Median	-1.920
Arithmetic Mean	-3.144
Standard Deviation	10.896
Skewness (G1)	-0.700
Kurtosis (G2)	5.094
Anderson-Darling Statistic	29,289
AdjusteAnderson-Darling Statistic	29,289
p-value	<0.01

Figure 5. Residual statistics for remaining data not used in regression model

Comparison to Similar Independent Study

The relative error, variability, and magnitude of predictions from the best-performing regression equation were compared to a recent comparable effort by the state of California (Washburn et al. 2010). The California analysis used high-resolution remote sensing of randomly selected neighborhoods in several cities to estimate the imperviousness of a range of land uses in California. The sample set included more than 330 residential neighborhoods at densities ranging from 1 to 50 dwelling units per acre as well as a variety of other neighborhoods that were not classified by an analogous density metric. Among other outcomes, the analysis yielded a regression equation that can be used to correlate land-use imperviousness to housing unit density for residential land uses. Figure 6 shows the plot of imperviousness versus housing unit density derived from this analysis. For comparison, the ISGM regression model is overlaid on this chart (holding employment at 0 and D5Ar at the approximate median value of 100,000).

While these regressions are not directly comparable (block groups are generally at a larger scale and less homogenous than the neighborhoods surveyed), the relative magnitudes and shapes are similar. The ISGM equation appears to fit the California data fairly well, and the regression statistics of the ISGM equation (based on fit to nationwide block groups) compares favorably to the best fit that was found for the California ISC analysis (based on California neighborhoods).

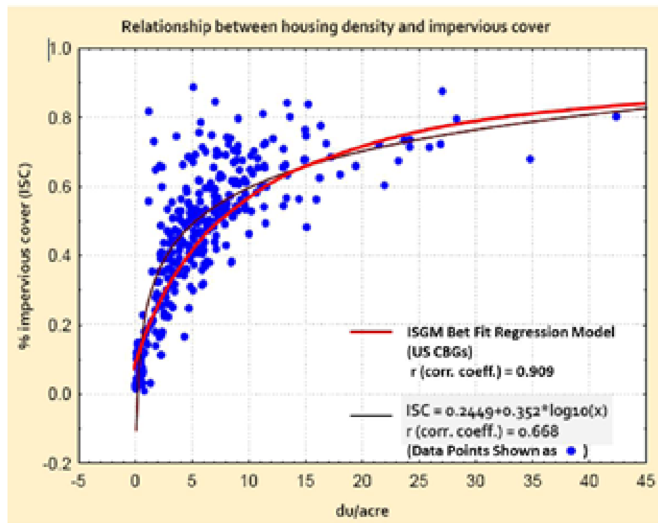


Figure 6. Comparison of ISGM results to California ISC analysis
Note: The correlation coefficient for the ISGM best fit regression model is based on its fit to the selected subsample of nationwide block groups for comparison; it is not based on the California land-use data that is plotted on this chart.

Reasonableness Inspection of ISGM Predictions

The ISGM was applied to a subset of block groups to predict the net ISG associated with hypothetical increases in housing units and employees. Twenty-four block groups from five U.S. cities were studied. These block groups were selected prior to application of the model to represent a cross section of block groups from different locations within the urban context (i.e., downtown versus suburban), different city sizes, and states with different land-use management policies. Net impervious surface growth per additional unit of development was estimated based on a nominal increase in development units of 100 units. Figure 7 shows an example case study block group from this reasonableness evaluation.

This inspection of multiple case study applications showed that results are reasonable and followed expected trends. Of the block groups inspected, the net residential ISG ranged from approximately 4,000 square feet per housing unit in urban fringe block groups to approximately 200 square feet per housing unit in highly urbanized block groups. Net employment ISG followed a similar trend to net residential ISG with somewhat lower values predicted. This is expected based on the form of the regression equation and appears to yield reasonable results in the block

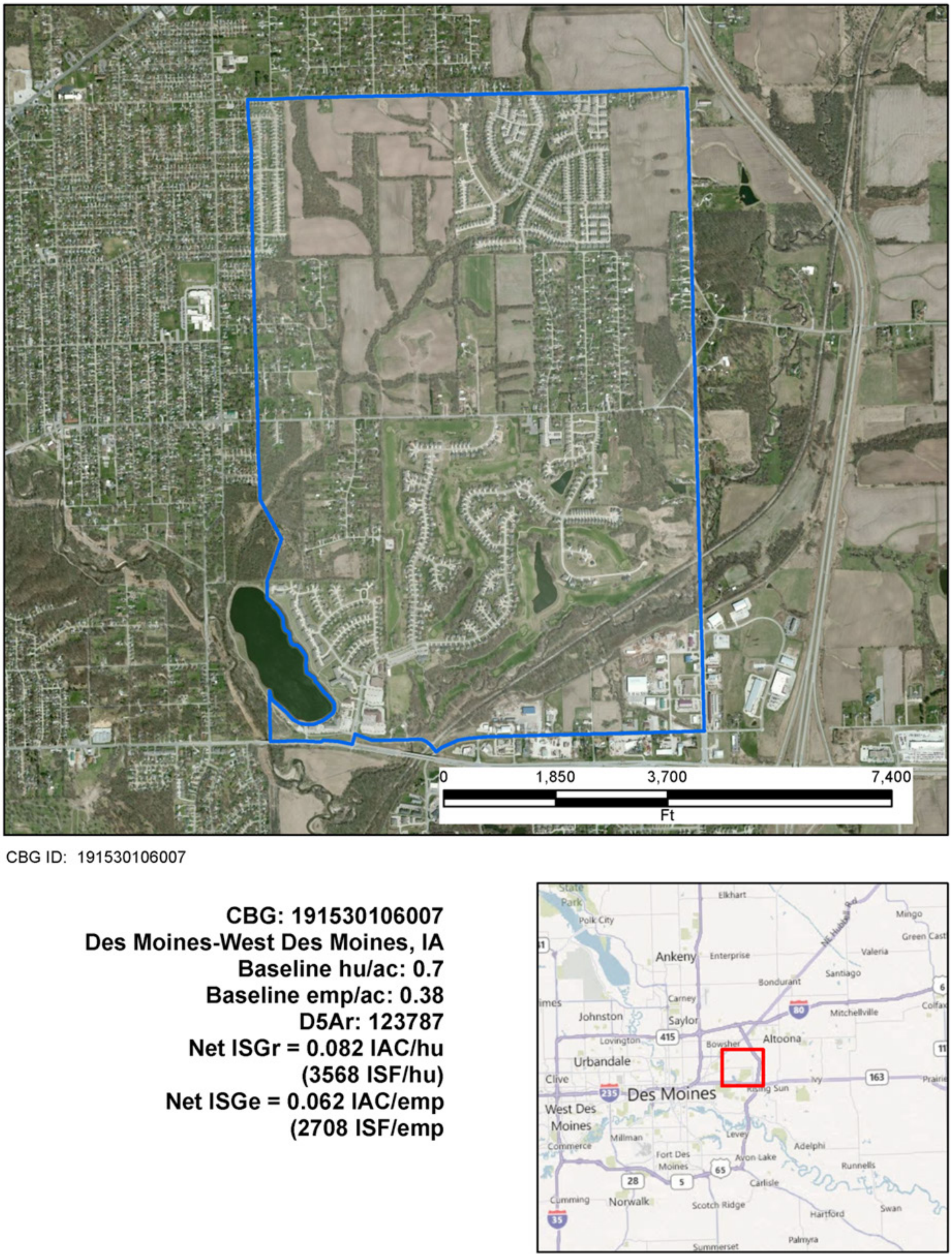


Figure 7. Case study application of ISGM to an example block group

Table 3. ISGM user interface fields

Field Type	Field ID	Field Description	Units	Source
User Input	CBG	Block group ID	text	User entered
	MSA	Metropolitan statistical area	text	Returned via lookup from ISGM Database based on block group ID Primary Key
	ADD_HU	Added housing units	hu	User entered
	ADD_EMP	Added employment units	jobs	User entered[12]
	ADD_Protected	Added acres of land protected from development	acres	User entered
Block Group Baseline Conditions	UNP_ACRES	Best estimate of unprotected area, ac	acres	Returned via lookup from ISGM Database based on block group ID Primary Key
	HU_DENS	Housing unit density (unprotected, baseline, 2010)	hu/acre	Returned via lookup from ISGM Database based on block group ID Primary Key
	EMP_DENS	Employment density (unprotected, baseline, 2009)	jobs/acre	Returned via lookup from ISGM Database based on block group ID Primary Key
	D5AR	Jobs within 30 miles, gravity weighted (2009)	jobs	Returned via lookup from ISGM Database based on block group ID Primary Key
Development-adjusted Block Group Conditions	HU_DENS_ADJ	Housing unit density (unprotected, adjusted)	hu/acre	Calculated based on 2010 conditions plus user-entered number of added housing units and added protected area
	EMP_DENS_ADJ	Employment density (unprotected, adjusted)	jobs/acre	Calculated based on 2009 conditions plus user-entered number of added jobs and added protected area
	D5AR_ADJ	Jobs within 30 miles, gravity weighted (D5Ar, adjusted)	jobs	Calculated based on 2009 D5ar plus user-entered number of added jobs
Results	ISG_NET	Net impervious surface growth	acres	{ISGM IMP (Adjusted) - ISGM IMP (Baseline)} See note[13]
	ISG_MAX	Maximum possible impervious surface growth in 2006	acres	Remaining impervious surface in block group (NCLD 2006). Value displayed if ISG_NET > ISG_MAX
	QUAL	Qualifier	text	Returns qualifying information where model predictions as applicable
	NOTES	Notes about results	text	Returns notes, as applicable.

[12] This field does not refer to jobs associated with construction. Rather it refers to the total number of additional people who are estimated to be working in the block group after the new construction is complete.

[13] ISGM IMP (Baseline) = Block group unprotected area impervious area predicted for the baseline (2009-2010) condition based on the ISGM regression equation using the baseline independent input variables. ISGM IMP (Adjusted) = Block group unprotected area impervious area predicted for the development-adjusted condition based on the ISGM regression equation using the development adjusted independent input variables.

groups inspected. While the magnitudes are reasonable, specific examples were observed where the regression may not fully describe the expected variability.

Summary of Validation and Limitations

Overall, the ISGM appears to be a valid basis for estimating net impervious surface growth across a wide range of urban, suburban, and rural conditions. While the model may overpredict or underpredict imperviousness at a block group level, it appears to provide a reasonably reliable estimate of relative net ISG, on average. However, four key limitations should be understood in applying the model:

- First, the model does not account for vacancy in commercial buildings. Using employment density as a proxy for commercial activity presents an inherent limitation to the model, which is most acute in areas with a great deal of vacant office or retail space. In such locations, the model would tend to be biased toward lower estimates of static imperviousness in the baseline condition than was actually present. In these cases, the net impervious surface growth predicted by the model would tend to be overestimated.
- Second, while the model accounts for impervious surface growth associated with off-site transportation infrastructure that is collocated within the same census block group, it does not account for impervious surface growth associated with transportation infrastructure outside of the same block group. For instance, a new highway built to serve a rapidly growing suburban area would likely increase impervious surface cover in areas outside of the block groups in which the rapid development is occurring. In these situations, the total net impervious surface growth associated with new development could be underestimated at the block group level. However, this issue is mitigated in part by the facts that units of census geography generally are much larger in lower density areas at the periphery of a metropolitan region—the very places where one may anticipate off-site impervious surface growth to be the greatest. With larger units of geography, more off-site impacts will be captured.
- Third, this model underestimates impervious surface cover in smaller block groups that have a large proportion of unprotected land cover devoted to transportation infrastructure. Examples could include an urban railyard or port industrial district or an urban block group bisected by a highway. In these cases, the model would tend to be biased toward lower estimates of static imperviousness than was actually present. This has the effect of predicting greater net ISG with added development units than would actually be expected and could result in some systematic overestimation of impervious surface growth associated with new development.
- Fourth, because the model is based on static estimates of imperviousness previous rather than change estimates, the model is inherently based on trajectories of neighborhood densification that represent past development patterns across the United States.. The model thus assumes that future development will follow similar densification patterns. So, for example, the model inherently assumes that new residential development at the outer periphery of a metropolitan region will be relatively low in density (as this is the prevailing development patterns in regions across the United States). This model does not account for factors such as local zoning or urban growth boundaries that may cause new development to deviate from these prevailing patterns. However, the destination accessibility variable (D5ar) does serve as an indicator of the "centrality" of the location and implicitly accounts for some of the factors that influence decisions about the type of development that will occur.
- Finally, and related to the fourth limitation above, the model does not account for innovative new development practices intended to minimize impervious surface cover. For instance, new residential neighborhoods with smaller lot sizes, narrower street widths, and a mix of land uses that promote walkability can potentially result in less impervious surface growth, per unit, than conventional large lot residential development. However, because the model works at the block group scale, it cannot account for density of development at the scale of a subdivision or development site. In other words, it cannot differentiate between two development proposals for a single block group—unless one proposal formally sets aside acreage as protected from development (essentially allowing the analyst to adjust the density associated with the remaining area inside the block group).

IMPERVIOUS SURFACE GROWTH MODEL TOOL

We developed a simple spreadsheet-based tool to provide access to the ISGM algorithms and to facilitate evaluation of the predicted effect of proposed development on net impervious surface growth. The interface consists of a form in Excel 2007 with fixed columns and an expandable number of rows. Each row can be used to estimate the net ISG based on a user-defined block group and a user-defined increase in units of development. Table 3 describes the fields in the tool and the algorithms used to return the estimated value. Full documentation of methods, limitations, and user instructions are provided in the Technical Report describing the development of the ISGM (Geosyntec 2011).

The ISGM User Interface is intended to allow bulk entry of block group development scenarios and return estimates of the net ISG associated with each scenario. For each row, the spreadsheet returns the estimated net impervious surface growth. The current version can support simultaneous computation of results of up to 25,000 scenarios.

CONCLUSION

In conclusion, we discuss how effectively the ISGM addresses requirements laid out at the beginning of this paper. We also discuss the potential suitability of the ISGM for various applications in watershed and land-use planning. Finally, we offer thoughts regarding enhancements that could extend the functionality of the ISGM in fruitful directions.

Model Requirements

We believe the ISGM represents a significant advancement in meeting the unmet scenario analysis needs described earlier in this paper.

- *Relevant for application throughout the United States.* The ISGM supports scenario analysis throughout the contiguous United States. Hawaii and Alaska were excluded from the modeling because of land-cover data availability.
- *Assesses net impervious surface impacts per unit of new development.* The ISGM returns an estimate of the net impervious surface growth per change in units of housing units and employees.
- *Assesses impervious surface cover as a function of development density and regional centrality.* The ISGM input parameters include development density (housing units per unprotected acre and employees per unprotected acre) and jobs within a 30-mile radius (an indicator regional centrality).
- *Accounts for off-site impervious surface growth.* The ISGM implicitly accounts for off-site impervious surface growth (e.g., roads, other infrastructures) that is within the block group where development occurs. It does not attempt to account for off-site impervious surface growth that may occur in other block groups.
- *Practical for routine use.* The ISGM interface has been developed to provide simple access to the ISGM and allow a large number of scenarios to be processed efficiently.

Model Reliability and Intended Uses

Although limitations have been identified, the ISGM generally is considered to provide reliable estimates of net impervious surface growth to support planning-level scenario analysis across a wide range of urban, suburban, and rural conditions. The model may overpredict or underpredict imperviousness at a block group level.

Potential Extended Applications

Give the importance of impervious cover and impervious cover growth in water resources applications, the tool is expected to have applications beyond its original intended functions.

- *Development site-selection analysis.* While more detailed site-specific analysis would always be required to fully understand the impacts of a proposed development project, the ISGM has the potential to allow users to quickly and roughly compare the estimated impervious surface impacts of a number of proposed development sites. Users of such information might include developers, urban planners evaluating development proposals, or citizens concerned about the impacts of proposed development on water quality.
- *Growth planning and impact analysis.* The ISGM has the potential to allow urban planners and policy makers to conduct rapid planning level analysis of the relative water quality impacts of various development and land-use scenarios. Given a regional growth projection in terms of numbers of new housing units and numbers of new jobs, the ISGM could be used to rapidly evaluate the comparative impacts of various growth management scenarios on impervious surface growth and (with further analysis) water quality. This information could be used in conjunction with information from other tools (e.g., estimates of vehicle miles traveled) to identify growth scenarios that minimize impacts.
- *Watershed and drainage planning.* Based on land-use policies and population growth estimates, the tool could be used to generate long-range estimates of impervious surface growth at a watershed or subwatershed scale. This information could be used to help identify receiving waters that are most likely to be impacted by future development, which, in turn, could be used to prioritize monitoring activities to collect baseline data. This information also could be used in drainage master planning to identify long-range needs for improvements to major drainage infrastructure to support future development.
- *Other potential uses.* Given the importance of impervious cover in storm-water planning, a variety of other potential uses may exist for the ISGM or the underlying regression model. For example, the regression model developed as part of the tool has potential to be used to improve estimates of impervious cover of various types of development.

Potential Enhancements

A number of potential enhancements currently are under consideration to improve the ISGM.

- *Translating output into percent impervious cover.* A simple extension of the ISGM interface could enable output to be translated output in terms of percent impervious cover. This currently is supported via postprocessing methods.
- *Integration into established GIS-based scenario planning tools.* The ISGM could be readily incorporated into other tools used for scenario planning, such as the EPA BASINS (Better Assessment Science Integrating point and Nonpoint Sources) program.
- *Ability to calculate impervious cover by watershed for land-use scenarios.* The ISGM currently provides estimates by block group. However, watershed boundaries do not necessarily align with block group boundaries. Incorporating a GIS interface for the ISGM could enable estimates to be generated for watershed boundaries.
- *Improvements utilizing impervious cover change datasets.* When impervious cover change estimates become available over a longer time window (i.e., release of newer versions of the NLCD for comparison with 2001 NLCD), the relative error in these estimates may be smaller relative to the magnitude of changes that have occurred over this longer time period. With improved reliability in change datasets, it may be possible to enhance the ISGM, particularly in suburban/urban fringe areas.

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