INTERACTIVE GIS-BASED IMPERVIOUS SURFACE MODEL

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ABSTRACT

Research has shown that impervious surfaces, a consequence of development, have a direct impact upon stream quality. Local planners and land-use officials need simple tools to help them determine the amount of impervious surface within watersheds and to assess impacts from future development. This paper describes an ArcView GIS-based model being developed by the Northeast Regional Earth Science Applications Center that estimates imperviousness at the local watershed level. The model uses land-use land-cover data interpreted from multi-temporal 1995 Landsat TM imagery and land-use land-cover-specific impervious surface coefficients derived from large-scale planimetric data from Connecticut towns that range from rural to urban. Currently, there are two modes of operation. A user can evaluate all watersheds completely or partially within a town and generate a screen display that depicts estimates of stream quality based on existing land-use and land-cover conditions or a user can evaluate a single watershed. When assessing a single watershed there is an option to change existing forest and agricultural land to urban land uses to calculate future increases in impervious surface area and its impacts on water quality. The model is being developed as an educational tool that will be used by the Nonpoint Education for Municipal Officials (NEMO) Program at the University of Connecticut.

INTRODUCTION

Impervious Surface Impacts

A number of researchers have established that there is a direct and inverse relationship between the area of a watershed covered with impervious surface and the resulting stream conditions (Leopold, 1973; Klein, 1979; Jennings and Jarnagin, 2000). As watersheds are urbanized, impervious surface area increases resulting in runoff reaching watercourses sooner and in greater volume during storm events. Increased runoff volume and discharge rates cause physical changes to watercourses. Streambeds regularly are scoured due to higher storm flow velocities and stream channels permanently are deepened and/or widened as the streambed and banks are eroded to accommodate increased discharge. Pools and riffles, instream habitat structures typically found in streams in undeveloped watersheds, increasingly are eliminated as stream flow increases. These structural changes drastically alter aquatic and riparian habitats and have profound impacts on the suitability of the system to support a diversity of aquatic organisms.

In addition to changes to a watershed's flow regime and the physical characteristics of its watercourses, impervious surfaces also increase the amount of nonpoint source pollution (NPS) delivered to watercourses. NPS includes nutrients, pathogens, metals, sand, and other materials that are picked up by water as it runs across the landscape. Schueler (1994) reviewed research conducted by a number of investigators and concluded that even at relatively low levels of watershed imperviousness, water quality impacts occur.

Figure 1 shows the general relationship between the percent area of a watershed covered with impervious surfaces and stream quality, as defined by both water quality and habitat condition. The figure is based on an urban stream quality classification system proposed by Schueler (1994) and adapted by Arnold and Gibbons (1996). When less than ten percent of a watershed's area is covered with impervious surfaces, the green zone in figure 1, stream quality tends to be good or protected. Stream channels remain intact and in a near natural condition and nonpoint source pollution impacts are low enough that aquatic organisms are minimally disturbed. As the percent area of a watershed that is impervious increases from ten to twenty-five percent, stream quality decreases. This is represented in the yellow zone of figure 1. Increased storm flows and higher nonpoint source pollution loads combine to alter the physical and chemical environment and reduce biodiversity. Booth and Reinelt (1993) in a study of urbanization impacts on stream and wetland quality in western Washington State, concluded that at ten percent and above there was "demonstrable, and probably irreversible, loss of aquatic system function." At above twenty-five percent watershed imperviousness, stream quality often is so severely degraded that restoration may be achieved only at great expense and effort, if at all.

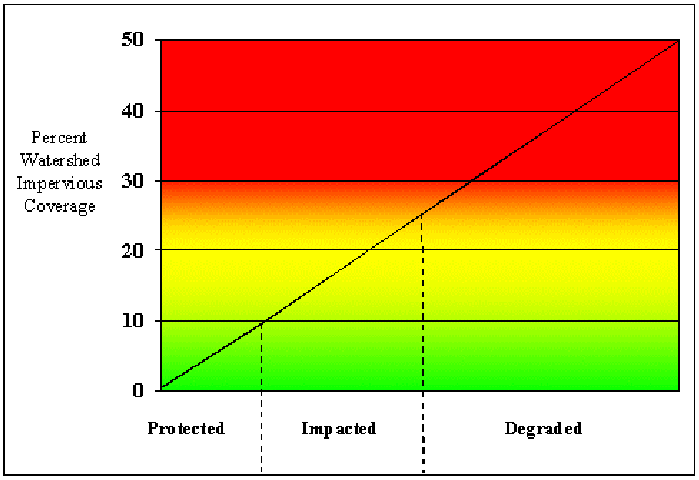

Figure 1 The background colors correspond to stream quality conditions from unpolluted and natural (green) to polluted and degraded (red). These conditions are related to the percent impervious area of a watershed.

The thresholds reported here are not absolutes and should be viewed only as general guidelines to help determine where a watershed falls along the percent impervious surface-stream quality continuum. The grading from green to yellow to red in the background of figure 1 is by design and is intended to represent gradual changes in stream quality as watershed impervious area changes. Variables such as topographic relief, distribution of impervious surfaces within a watershed, soil and land-cover types, stream network density, and other terrain characteristics can serve to raise or lower a particular watershed's percent impervious area thresholds. Thus, for any watershed, the slope of the line in figure 1 may change, but its trajectory will remain constant.

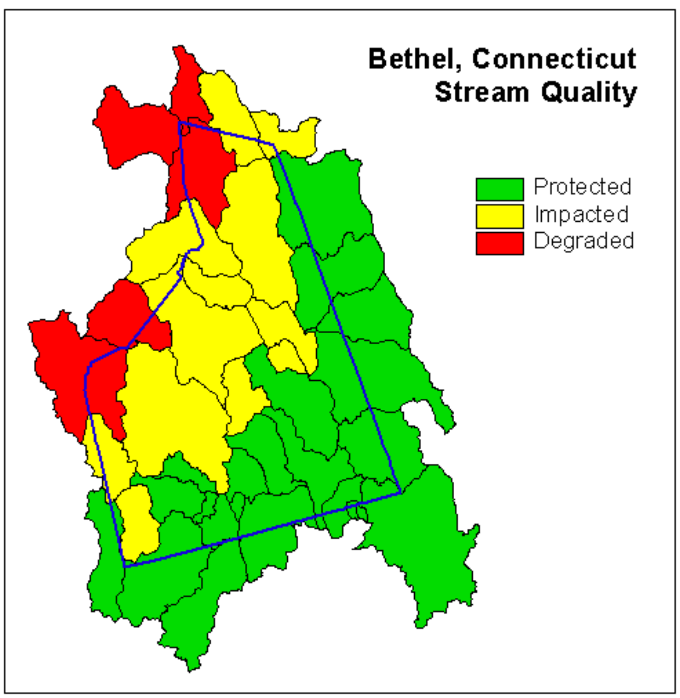

Figure 2 Watersheds in the town of Bethel, Connecticut are colored green, yellow or red to indicated the estimated stream quality.

The Nonpoint Education for Municipal Officials Program

In 1991 the University of Connecticut's Cooperative Extension System created the Nonpoint Education for Municipal Officials (NEMO) Program (Arnold, et al. 2000). It was designed to teach local land-use officials about the link between land use and water quality thereby encouraging the consideration of construction, site plan and zoning alternatives that would minimize future increases in impervious surface.

An educational tool used by the NEMO Program is a map that displays estimated stream quality within a municipality's watersheds based on the amount of impervious surface within each watershed. Figure 2 shows such a map for the town of Bethel, Connecticut. Watersheds are symbolized with the same colors as in figure 1. Watersheds that are shaded green have less than ten percent of their area covered with impervious surface and their water quality is estimated to be good. Watersheds that are between ten and twenty-five percent impervious are shaded yellow. Water quality in these watersheds may be impacted and caution is warranted, in terms of land-use decisions that will increase imperviousness, if water quality is to be kept from becoming degraded. Watersheds shaded in red are those where the impervious area exceeds twenty-five percent and stream quality likely has been severely impacted. Depicting watersheds using this simple stoplight metaphor dramatically drives home the point that land use and imperviousness affects water quality.

The Northeast Regional Earth Science Applications Center

The Northeast Regional Earth Science Applications Center (RESAC), located at the University of Connecticut, is one of seven new RESACs created in 1999 and funded by NASA. The Northeast RESAC's workplan expands remote sensing research and applications development that had been started at the UConn Laboratory for Earth Resource Information Systems (LERIS) to support the NEMO Program. The Center is focused on making remote sensing data useful and relevant to local land-use officials through the development of information products and applications that can be used in their day-to-day operations (Arnold, et al. 2000; Civco, et al., 2000). To this end, the Center is developing an interactive ArcView (Environmental Systems Research Institute, 1999) GIS-based impervious surface model. The purpose of the model is to provide an easy to use application to help municipal land-use officials estimate watershed imperviousness and determine how it may increase as a result of land-use changes.

IMPERVIOUS SURFACE MODEL

User Interface

The impervious surface model (ISM) runs within an ArcView GIS software environment and requires several ArcView GIS extensions to operate. These include Dialog Designer, provided by Environmental Systems Research Institute (ESRI) as part of the basic ArcView GIS 3.2 software, and Spatial Analyst that is available from ESRI as an add-on to the basic system.

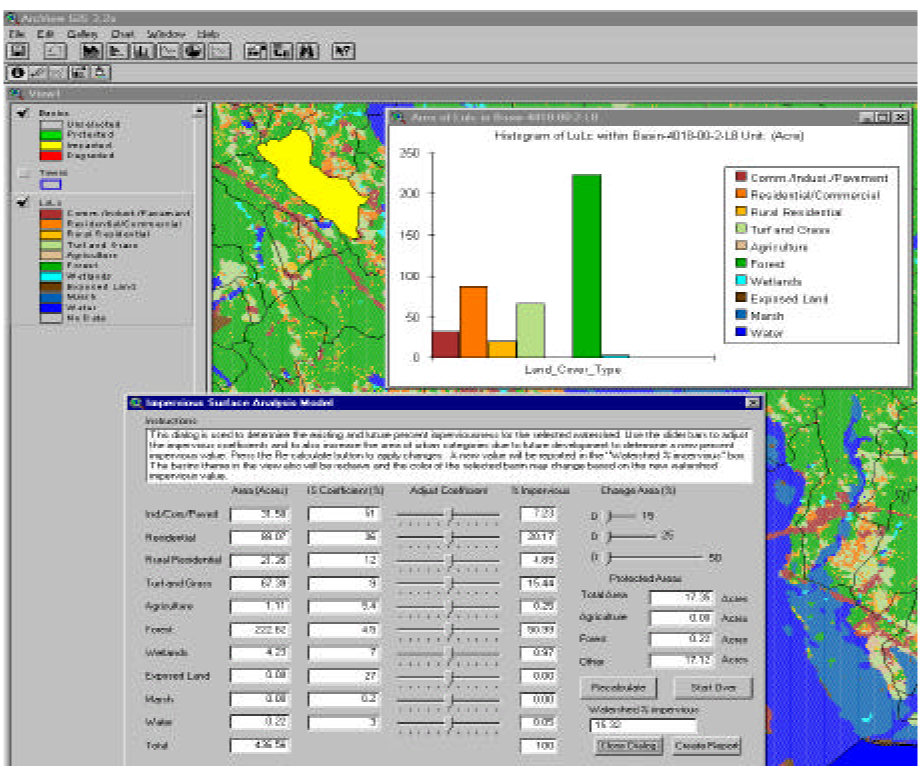

Figure 3 Screen capture of one of the model's interfaces created with ESRI's Dialog Designer

The Dialog Designer extension includes functions to create windows that contain buttons and tools to implement and control various model operations and to create forms within which model results can be reported. Figure 3 is an example of an ISM module interface that uses the Dialog Designer to analyze and report on impervious surface within an individual watershed. The interface allows a user to interactively explore how different land-use change scenarios may affect overall watershed imperviousness and thus water quality.

Model Assumptions

The ISM is designed for use in urban-forested landscapes where the predominant land-cover change is from forest to urban. The model uses several assumptions to facilitate implementation and to simplify its use as an educational application. Watershed-scale assumptions include:

- stream quality is a function of percent impervious surface area,
- each watershed operates independent of upstream watersheds,
- watershed characteristics such as soils, topography, stream density, etc. are not considered,
- no distinction is made between total and effective impervious area, and
- the spatial distribution of impervious surface and its proximity to drainage systems is ignored.

As with many models, these assumptions result in a gross over simplification of real world processes. However, the intent of the ISM is to help deliver the educational message that land use affects water quality and that estimating impervious surface area can be used as a simple assessment technique. The assumptions result in the ISM being suitable for producing qualitative rather than quantitative results.

Data Requirements

The model uses four digital spatial datasets that include:

- basins (watersheds),
- municipal boundaries,
- open space lands, and
- satellite derived land use and land cover (LULC).

The basins are a standard digital polygon dataset of the Connecticut Department of Environmental Protection. They originally were delineated on mylar overlays of 1:24,000 scale U. S. Geological Survey 7.5 minute topographic maps and were based on watercourse locations and natural drainage divides interpreted from ten-foot contour lines. The basins are the smallest mapped units of a hierarchical watershed system that includes local, subregional, regional and major basins. The basin polygons average 0.76 square miles in area and include drainage areas for impoundments and stream reaches. The entire dataset includes over 7,000 basins.

The municipal boundaries also are standard digital dataset of the Connecticut Department of Environmental Protection. They were created from U. S. Geological Survey digital line graph files that were based on 1:24,000 scale U. S. Geological Survey 7.5 minute topographic maps. In Connecticut there are 169 incorporated municipalities that collectively cover the entire area of the state. These data were in a vector-based polygon format.

The open space lands dataset was created for the ISM from several digital spatial databases. It included Connecticut Department of Environmental Protection parks and forests, municipal and privately owned open space, and water utility-owned undeveloped watershed lands. For purposes of determining future land-cover conversion to urban land uses, these data were used to identify the areas within basins that could not change to urban land uses. The data were in a vector-based polygon format.

The model's LULC data are in a 30-meter by 30-meter grid format. The data were developed from a 1995 28-category LULC database interpreted from multi-date 30-meter Thematic Mapper multispectral imagery and 10-meter SPOT panchromatic imagery using techniques developed at LERIS by Hurd and Civco (1996). For purposes of model simplicity, the 28-category LULC dataset was reclassified into ten categories similar to the Anderson classification system (Anderson, Hardy, Roach and Witmer, 1976). The intent was to keep separate those classes that included urban uses with high amounts of impervious surface area while combining other classes with generally lower amounts of impervious surface into level I categories. Table 1 summarizes the reclassification and lists the ten LULC categories currently used in the model.

Impervious surface coefficients, also shown in Table 1, were developed from high-accuracy planimetric GIS data from four Connecticut towns using a methodology developed by Sleavin (2000) and modified by Prisloe (2000). Impervious surfaces included roads, driveways, sidewalks, parking lots, and building footprints. No attempt was made to distinguish between total impervious area and effective imperviousness that includes only those impervious surfaces that contribute runoff directly to storm drains or watercourses. The coefficients are the percent area, for each of the model's ten LULC categories, covered with impervious surface.

The LULC-specific impervious surface coefficients were calculated by first converting the reclassified LULC grid data to a GIS polygon format. The polygon data were overlaid on the planimetric impervious surface data and summary statistics of the total area of each LULC class and the total area of impervious surfaces within each LULC class were prepared. These data were used to calculate the LULC-specific impervious surface coefficients.

$$LULC_{ISarea} / LULC_{Area} * 100 = \text{LULC coefficient}$$

Where $LULC_{ISarea}$ is the total area of impervious surface for a LULC class, and $LULC_{Area}$ is the total area for the same LULC class.

This methodology resulted in each of the ten LULC categories having a non-zero impervious surface coefficient. Logical inconsistencies, such as water having an impervious surface coefficient of 3, were the result of mixed pixel effects. For example, an entire pixel at a lake edge could be classified as water when it actually included water, upland and an impervious feature such as a house or road. Since the IS coefficients were derived from the comparison of planimetric data with the Connecticut statewide land-cover map, these coefficients will be valid with this LULC information only. Further analysis is warranted if these coefficients are to be applied to other sources of land-cover data.

Table 1 LULC categories from the original source data are listed in column 1, reclassified categories are listed in column 2 and impervious surface coefficients calculated for the reclassified data are in column 3.

ORIGINAL LULC CATEGORY	MODEL LULC CATEGORY	IS COEFFICIENT
Industrial_commercial_pavement	Industrial_commercial_pavement	51
Residential_commercial	Residential_commercial	36
Rural residential	Rural residential	12
Tree and turf complex	Turf and grass	9
Turf and grass	Turf and grass	9
Pasture & hay & grass	Turf and grass	9
Pasture & hay / cropland	Agriculture	9.4
Pasture & hay / exposed soil	Agriculture	9.4
Exposed soil / cropland	Agriculture	9.4
Exposed soil	Exposed lands	27
Shadegrown tobacco	Agriculture	9.4
Nursery stock	Agriculture	9.4
Scrub and shrub	Forest	4.5
Deciduous forest	Forest	4.5
Deciduous forest & Mt. Laurel	Forest	4.5
Coniferous forest	Forest	4.5
Dead & dying hemlock	Forest	4.5
Forest / clear cut	Forest	4.5
Mixed forest	Forest	4.5
Deep water	Water	3
Shallow water & mud	Water	3
Non-forested wetland	Wetlands	7
Deciduous shrub wetland	Wetlands	7
Deciduous forested wetland	Wetlands	7
Coniferous forested wetland	Wetlands	7
Low coastal marsh	Marsh	0.2
High coastal marsh	Marsh	0.2
Exposed ground & sand	Exposed lands	27

Technical operation

There are several ways that a user can run the model to calculate watershed imperviousness. One method focuses on all the watersheds completely or partially within a town. The user opens a Dialog and selects a municipality by highlighting its name from a list of the 169 towns in Connecticut. The system overlays the watershed data and determines which watersheds fall partially or completely within the selected municipality. Spatial Analyst Extension functions are used to calculate the area of each LULC category per watershed and customized Avenue[1] scripts use default impervious surface coefficients, as listed in Table 1, to calculate the percent impervious area for each watershed.

$$IS_w = \frac{\sum_{i=1}^{n} Area_i * IS_i}{TotalArea}$$

Where IS_w is the impervious surface coefficient for the entire watershed, IS_i is the impervious surface coefficient for each LULC category, and $Area_i$ is the area for each LULC category.

The results of the calculations are used to assign temporarily a percent impervious area value to each watershed. This value is used to select a display color of green, yellow or red that corresponds to stream quality (see figure 1) and the watersheds are redrawn in the view window. Figure 4 illustrates the results of this initial analysis for the town of Bristol, Connecticut. After running this analysis, the impervious surface coefficients can be adjusted up or down for any of the LULC categories and the ISM will recalculate each watershed's percent area of impervious surface and then redraw the map based upon the new values. Figure 5, which displays the results of such an analysis for Bristol, Connecticut, can be compared to Figure 4 to see how the model responds to changed impervious surface values.

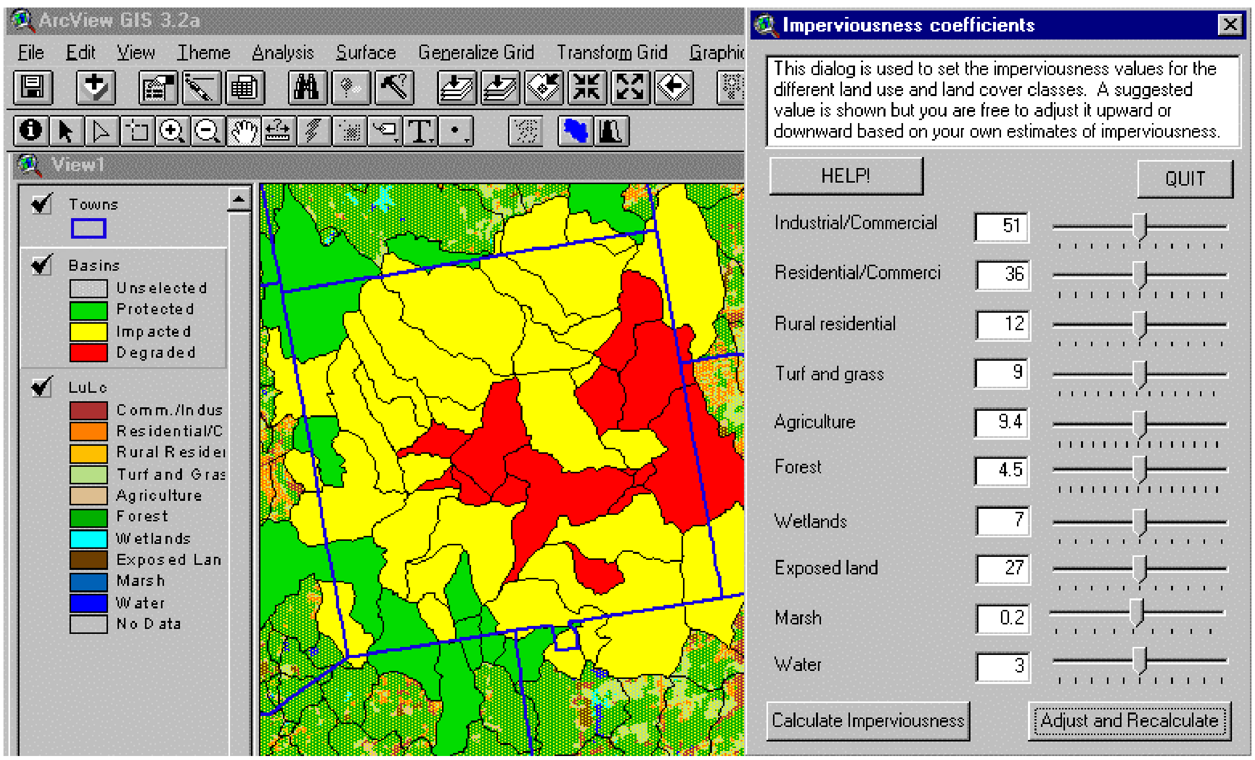

Figure 4. ISM display of watersheds in the town of Bristol after running the model using default impervious surface coefficient values. A Dialog Designer window is opened that contains slider bars to adjust impervious surface coefficients.

[1] Avenue is ESRI's object-oriented scripting language that is part of the ArcView GIS suite of software. All of the ISM's functionality is implemented through Avenue scripts attached to ArcView and Dialog Designer controls.

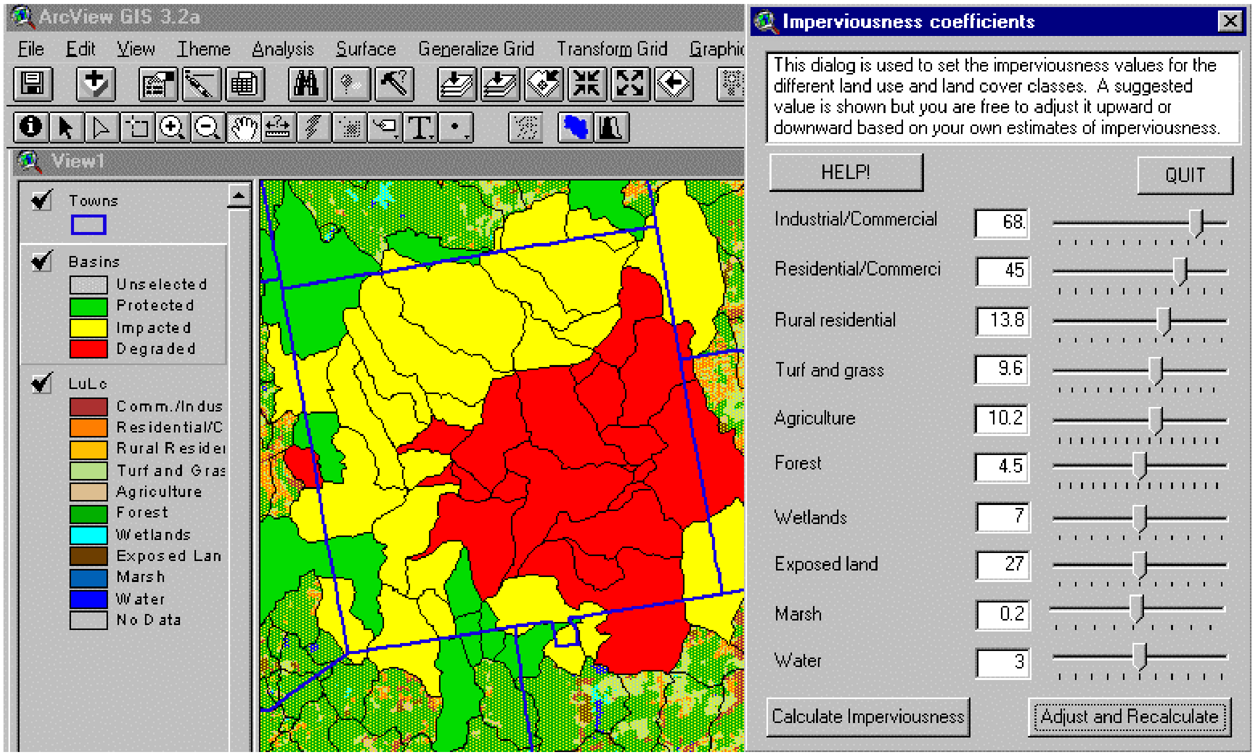

Figure 5. After adjusting the slider bars to increase the impervious surface coefficients and then clicking the "Adjust and Recalculate" button, the model redraws the map display to show a decrease in the number of green (protected) watersheds and an increase in yellow (impacted) and red (degraded) watersheds.

A second method of operation allows a more complete analysis but only for one watershed at a time. In this mode of operation, the user selects a customized watershed tool from the ArcView interface and clicks on a watershed in the map display. The action of clicking on a single watershed initiates several customized analyses, the results of which are reported graphically to the user. A bar chart is generated and displayed that shows the acreage of each of the ten LULC categories within the watershed (see figure 3) and a Dialog Designer window, as shown in Figure 6, is opened to report watershed characteristics. The Dialog Designer window displays that acreage of each LULC category, the total acreage of the watershed, the default impervious surface coefficients used to calculated watershed percent impervious area, the percent of total impervious area contributed by each LULC category, and the acreage of protected open space. The interface includes slider bars to adjust the impervious surface coefficients upwards or downwards. This permits users to interactively adjust model parameters based on local knowledge or to "play" with the model to see how changes in coefficient values would affect overall watershed imperviousness which is reported as a single value in the lower-right corner of the dialog window. Slider bars also can be used to increase the area percent of any of the three urban

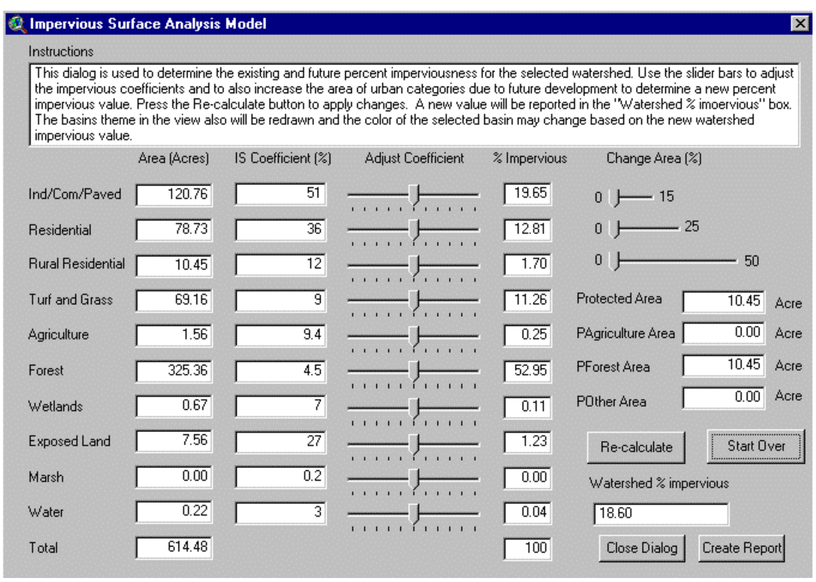

Figure 6 Dialog Designer interface for analyzing a single watershed

LULC categories to determine how future land-cover changes could increase watershed imperviousness. As any urban LULC category is increased, a corresponding decrease in area is proportionally applied to the agriculture and forest LULC categories. The model limits the conversion of forest and agriculture LULC categories to those areas outside any of the protected open space polygons. The turf and grass, wetlands, exposed land, marsh, and water LULC categories are left unchanged. After any adjustments are made using slider bars, the Recalculate Button on the dialog can be used to calculate the impacts to overall watershed imperviousness. Linked to the results displayed in the dialog interface is an ArcView map display of the watershed. The watershed is symbolized in green (less than 10% impervious area), yellow (10% - 25% impervious) or red (greater than 25% impervious). Whenever the results of recalculating cause watershed imperviousness to change from one of the above categories to another, the map display is immediately redrawn and the watershed is symbolized using the appropriate color. At any time, the Start Over Button can be clicked to reset the dialog interface to its initial parameters. The combination of slider bars, that adjust model parameters, and the Recalculate and Start Over Buttons allow for interactively testing an almost unlimited number of scenarios. Figure 3 depicts a display of the model showing the features discussed above.

DISSCUSSION AND CONCLUSIONS

Local land-use officials are making decisions on a daily basis that will affect the future of their communities. Too often these decisions are being made without a clear understanding of how natural resources, and in particular water resources, will be changed. The impervious surface model helps to explain to a largely non-technical audience the link between land use (and its associated impervious surfaces) and water quality. Because the model is simple and visual, it is easy to understand. Emphasis is on demonstrating qualitative relationships rather than collecting large quantities of technical data and then running them through a “black box” analysis that only highly trained scientists can interpret.

The model also will help land-use officials “see” the future and better understand how land-cover change from forest to urban may impact local water resources. The model provides some interactive capabilities to let users investigate various land-use change scenarios and determine how these may impact impervious surfaces and thus water quality. Hopefully, such information will encourage adoption of environmentally sound land-use plans and site development techniques such as the use of pervious pavements, narrower streets, etc. that will protect stream quality by reducing future impervious surface increases.

FUTURE IMPROVEMENTS

Plans are to improve the impervious surface model in several ways. One limiting factor at present is the land-cover data that was interpreted from 30-meter Thematic Mapper imagery. While 30-meter resolution data are generally acceptable for large geographic area analyses, they tend to be too inaccurate at the “local” level. Research is underway at the Northeast RESAC to develop more accurate land-cover data from higher resolution imagery using a variety of techniques including knowledge-based expert systems, neural networks, and multi-resolution imagery among others (Civco et al., 2000). It is anticipated this work will result in land-cover data that more accurately capture spatial patterns of land use at the neighborhood scale thereby making the data more applicable to local land-use issues.

Also being investigated are techniques to extract impervious surface data directly from remote sensing imagery. The advantage of such data would be to eliminate impervious surface estimating errors that arise from the application of uniform impervious surface coefficients to general land-use categories. Sleavin (2000) investigated methods to derive impervious surface coefficients by overlaying large-scale planimetric data on classified land-cover data. Significant differences were found in derived coefficients for the same land-cover categories in urban vs. rural areas. Direct measurement of impervious surface data from imagery would eliminate these problems and would increase the spatial accuracy of the model’s estimates of watershed imperviousness.

Lastly, improvements to the model’s data processing will be implemented. At the present time each watershed is treated independently of upstream watersheds. Plans are to add a function to determine cumulative impacts from upstream watersheds to more accurately represent real world conditions and to allow modeling of upstream land-use changes to determine impacts at a selected location.

ACKNOWLEDGEMENTS

This material is based upon work supported by the National Aeronautics and Space Administration under Grant NAG13-99001/NRA-98-OES-08 RESAC-NAUTILUS, *"Better Land Use Planning for the Urbanizing Northeast: Creating a Network of Value-Added Geospatial Information, Tools, and Education for Land Use Decision Makers*". The authors would like to recognize the following individuals for their contributions and support: William Sleavin, Laurie Giannotti, and Joel Stocker.

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