# ASSESSING DEVELOPMENT PRESSURE IN THE CHESAPEAKE BAY WATERSHED: AN EVALUATION OF TWO LAND-USE CHANGE MODELS

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**Abstract.** Natural resource lands in the Chesapeake Bay watershed are increasingly susceptible to conversion into developed land uses, particularly as the demand for residential development grows. We assessed development pressure in the Baltimore-Washington, DC region, one of the major urban and suburban centers in the watershed. We explored the utility of two modeling approaches for forecasting future development trends and patterns by comparing results from a cellular automata model, SLEUTH (***s***lope, ***l***and use, ***e***xcluded land, ***u***rban extent, ***t***ransportation), and a supply/demand/allocation model, the Western Futures Model. SLEUTH can be classified as a land-cover change model and produces projections on the basis of historic trends of changes in the extent and patterns of developed land and future land protection scenarios. The Western Futures Model derives forecasts from historic trends in housing units, a U.S. Census variable, and exogenously supplied future population projections. Each approach has strengths and weaknesses, and combining the two has advantages and limitations.

**Keywords:** land conservation, land-use change, predictive modeling, urban sprawl, vulnerability assessment, Mid-Atlantic, Chesapeake Bay

## 1. Introduction

Habitat loss and degradation are major problems throughout the Mid-Atlantic Region. Terrestrial habitat loss and degradation result from various causes such as land development, poor resource management practices, invasive species, and air pollution. In the eastern half of the region, urban sprawl is a major cause of this loss and degradation (USEPA, 2001a). Most of the eastern half of the Mid-Atlantic Region falls within the Chesapeake Bay watershed, an area covering more than 168,000 square-kilometers and intersecting six states and the District of Columbia.

The Chesapeake Bay is North America's largest and most biologically diverse estuary, home to more than 3,600 species of plants, fish, and animals (Chesapeake Executive Council, 2000). The bay watershed is also home to about 15.7 million people, most of whom live in and around

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major urban areas, such as Baltimore, MD, Washington, DC, and Norfolk and Richmond, VA. Urban areas in the watershed have greatly expanded over the past 30 years. If current trends continue, they may expand by more than 60% over the coming 30 years (Boesch and Greer, 2003). The conversion of forests and farmlands to urban land uses poses a threat to terrestrial and aquatic habitats, air and water quality, and the economic sustainability of the region. This threat is magnified if future development is poorly planned, dispersed and fragmented; characteristics typically associated with urban sprawl. Smart Growth America recently rated Washington, DC as the 26th most sprawling metropolitan area in its assessment of 83 metropolitan areas throughout the United States (Ewing et al., 2002).

The administrator of the U.S. Environmental Protection Agency (U.S. EPA), chair of the Chesapeake Bay Commission, governors of Virginia, Maryland, and Pennsylvania, and the mayor of the District of Columbia formally recognized the threat that development poses to the bay watershed when they signed the Chesapeake Bay 2000 Agreement and committed to permanently preserve 20% of the land area from development and target the most valued lands for protection (Chesapeake Executive Council, 2000). The Bay Program Partners have begun an inventory of valued lands, defined as forests, farms, and wetlands that serve to protect water quality, provide wildlife habitat, and preserve cultural heritage. These lands will be given priority for conservation on the basis of their value and vulnerability to future development.

The term "vulnerability" was defined as exposure and susceptibility to sources of impairment. In the bay watershed, land development is one of the major causes of water quality impairment and forest loss and fragmentation (Boesch and Greer, 2003). To estimate vulnerability, we need models to assess the level of commercial and residential development pressure and the relative susceptibility of lands to development. These models should be spatially explicit to discriminate development pressures between adjacent patches of forests and farmlands and to identify the changes likely to occur within small watersheds. The modeling options for simulating development pressure across a five-state region are, however, constrained by data availability. Accurate data on land value, opportunity costs, and landowner characteristics used in agent-based economic models, and critical to explaining and understanding local-scale development patterns (Bockstael, 1996), are only available for selected areas and are difficult to extrapolate to other areas (USEPA, 2000).

The U.S. EPA has compiled two extensive reviews of models for projecting development (USEPA, 2000; USEPA, 2001b). These models were reviewed for use in the Chesapeake Bay watershed on the basis of their data requirements, complexity, and regional applicability (C. Bisland, personal communication). The reviewers identified nine models for further consideration, including the California Urban Futures Model-II, California Urban and Biodiversity Analysis Model, Land Transformation Model, What IF, Land-Use Change Analysis System, Smart Growth Index, Regional Economic Modeling, Inc., SLEUTH (***s***lope, ***l***and use, ***e***xcluded land, ***u***rban extent, ***t***ransportation), and Western Futures Model (WFM). After further investigation, SLEUTH and the WFM were selected for further study because of their reliance on available data, appropriateness for regional-scale modeling, and potential complementarities. The WFM (Theobald, 2001a, b) requires two historic time steps of housing-unit data from the U.S. Census Bureau and county-level population forecasts. The data requirements for SLEUTH (USGS, 2002) include four historic time steps of urban extent, which can be derived from remotely sensed imagery, and two time steps for a transportation network, slope, and a layer designating land that is wholly or partially excluded from development. For this study, we used an existing dataset and calibration coefficients produced in a previous application of SLEUTH to the Baltimore-Washington, DC region (Jantz et al., in press). We also present results of future development forecasts for the same area using a modified version of the WFM.

The goal of this research was to identify the strengths and weaknesses of these two models in the context of regional scale vulnerability assessments of valued lands. Because each model focuses on a different aspect of the development process, the potential exists for the two models to provide a complementary assessment of vulnerability. We therefore also explored the potential of using an integrated modeling approach for assessing development pressure.

## 2. Methods

### 2.1 Modified Western Futures Model

To better understand the extent, rate, and pattern of land-use change in exurban and rural areas, Theobald (2001a,b) developed the WFM to map and forecast development patterns at the census block group scale along the urban-to-rural gradient. In essence, the WFM is a supply/demand/

allocation model. The number of housing units that an area of land can accommodate represents supply, and demand is represented by county-level population projections. The allocation part of the model constrains and redistributes projected growth in each census block group using the average projected density of neighboring block groups.

The WFM forecasts future housing units by multiplying the current ratio of county population to housing units by county-level population projections. Projected county-level housing units are then allocated to individual census block groups on the basis of each block group's proportional increase in housing units over the previous decade. The housing-unit density of each block group is calculated by dividing the projected number of housing units by the area of the block group. If the projected housing-unit density of a block group exceeds the average projected density of its neighbors, surplus housing units are distributed to neighboring block groups according to the relative difference between the subject block group's density and that of its neighbors. To map development, Theobald (2001b) classified block groups as urban, suburban, exurban, or rural, using liberally defined housing-unit density thresholds.

For this study, the WFM was modified in several ways. First, census tracts were used instead of block groups because the 1990 census tract data have been spatially normalized to the 2000 tract boundaries (The Urban Institute, 2002). Second, housing-unit densities within the model were adjusted to represent the number of housing units per area of developable land within each tract as suggested by Theobald (2001b). The area of developable land was estimated by subtracting the area of excluded lands (e.g., slopes > 22%, public and/or protected lands, open water, and wetlands) from the total area of each block group. Third, to facilitate integration with SLEUTH, we aggregated the forecasted number of housing units within each tract to a uniform grid of square-mile (~2.6 square-kilometers) cells according to the proportion of developable area within each cell. The 1-square-mile cell size was used to facilitate the communication of housing-unit density statistics to decision-makers in the United States and represents a compromise between the resolution of census tract geography and the SLEUTH model. After the forecasted numbers of housing units were aggregated to the overlay grid, they were multiplied by estimates of mean lot size to derive an area of new residential land per cell that was constrained by the area of developable and undeveloped land per cell. Mean lot size estimates were derived for all cells in the overlay grid by calculating the percentage of developed land within each grid cell from a 2000 land-cover map (Varlyguin et al., 2001). Each grid cell was divided into five classes representing percent area of urban land, using the Jenks' optimization algorithm (Jenks and Coulson, 1963) to identify breakpoints between classes that minimize the sum of the variance for each class. Residential parcel centroids attributed with lot size for Montgomery County, MD were intersected with the classified grid cells to derive a mean lot size value for each grid cell class.

Although the WFM has been applied nationally (Theobald, 2001b), the model's accuracy has not been formally assessed. Before using the WFM, we evaluated its accuracy by comparing forecasted numbers of housing units with published housing-unit data from the U.S. Census for the year 2000. For this analysis, the total 2000 population count from the U.S. Census was used to simulate county population projections for the year 2000. County and tract census data for 1990 and 1980 were used to convert population to housing units and to distribute projected county housing units to the census tracts. The method was further evaluated to test the degradation of forecasted results over a 20-year period. For this test, the numbers of housing units per census tract were forecasted from the year 1980 to 1990 and 2000. These forecasted results were then compared with published 1990 and 2000 housing data from the U.S. Census Bureau. The redistribution algorithm was also tested for its effect on the overall forecast accuracy by using the WFM to forecast the number of tract housing units in 2000 with and without density constraints.

### 2.2 SLEUTH Model

SLEUTH is a coupled urban growth and land-cover change model developed by Clarke, et al. (1997) through sponsorship from the U.S. Geological Survey's (USGS) Urban Dynamics Program. As a cellular automata model, space is represented as a regular grid of cells that change state as the model iterates. State changes are regulated by a set of conceptually simple rules that specify a set of neighborhood conditions, such as slope suitability, that must be met before a change can occur. SLEUTH is calibrated to simulate urban development patterns over an historic time period, and it then forecasts these patterns into the future under a set of exclusion layers representing land use. Within the urban growth module, urban dynamics are simulated using four growth rules:

1) Spontaneous new growth, which simulates the random urbanization of land.

2) New spreading centers, which simulate the development of new urban centers.
3) Edge growth, which represents the outward spread of existing urban centers.
4) Road-influenced growth, which simulates the influence of the transportation network on development patterns.

SLEUTH is a probabilistic model that uses Monte Carlo routines to generate multiple simulations of growth. During calibration, each simulation is compared with the control years within the time series, and averaged fit statistics are produced to measure the performance of a set of coefficient values in reproducing the observed urban development patterns. Users can employ a single fit statistic, such as one that focuses on how well SLEUTH matches the rate of growth, or a set of fit statistics to define the model's performance, and then choose a set of parameter values that optimize the model's performance. This set of parameter values is used to predict historic patterns and rates of growth into the future. When predictions are produced, multiple simulations are run to create images showing the probability of any cell becoming urbanized over a series of annual time steps (USGS, 2002).

SLEUTH has been applied to urban centers, including San Francisco (Clarke et al., 1997; Clarke and Gaydos, 1998), Santa Barbara (Candau, 2002; Herold et al., 2003), Atlanta (Yang and Lo, 2003), and the Baltimore-Washington, DC area (Clarke and Gaydos, 1998; Jantz et al., in press). The more recent application by Jantz et al. (in press) used a finer resolution dataset (45-meter cell size) that was derived from remotely sensed imagery, which more accurately captured low-density settlement patterns. During calibration, the compare statistic, a ratio of the number of mapped and modeled urban pixels for the final control year in the calibration time series, was used to evaluate the performance of the model. The compare metric focuses only on how well the model matches the overall rate of growth in the urban system, but the derived set of growth parameters also allowed the model to capture urban patterns.

In this study, we use the results from a *current trends* scenario for the year 2010, which includes natural resource protection and growth management policy measures that are currently in place. For example, all parks and easements were fully protected from development, while partial protection was given to large, contiguous wetlands and riparian buffers along streams. In Maryland, Priority Funding Areas were incorporated, as were several major planned roads and areas of development that were either planned or in early stages of development in 2000 (Jantz et al., in press). To represent development pressure in 2010, we used a continuous probability map produced by SLEUTH, where each 45-meter cell was associated with a probability of being developed.

We also performed a temporal accuracy assessment of SLEUTH. Using the original time series of urban development, which included an initial time step in 1986 and subsequent steps in 1990, 1996, and 2000, we initialized SLEUTH in 1986 and predicted growth to 2000. One hundred Monte Carlo simulations were performed. The resulting probability images for 1990, 1996, and 2000 were transformed into binary images of urban extent using a threshold of 50%, and these images were compared with the mapped images of urban extent at multiple scales: 1-square-mile grid cells, watersheds, and counties.

### 2.3 Model Integration

To facilitate model integration, the SLEUTH output data were aggregated to the same overlay grid of square-mile cells used with the WFM by calculating the average probability of development within each cell. The overlay grid cells were then classified into two qualitative rankings of development pressure on the basis of the likelihood of development (from SLEUTH) and the area of new residential development (from WFM). The output data from both SLEUTH and WFM were divided into five classes of development pressure ranging from "very low" to "very high" using the Jenks' optimization algorithm. The results from SLEUTH and the WFM were combined on the basis of their level of spatial agreement and disagreement. Development pressure was considered "very high" in cells with both the greatest probability of urban growth (two highest valued classes from SLEUTH) and the greatest amount of projected residential development (two highest valued classes from WFM). Development pressure was considered "high" for cells in the two highest valued classes from either SLEUTH or the WFM. Development pressure was considered "very low" for cells in the lowest valued class from both SLEUTH and the WFM and "low" for cells in the lowest valued class from either the WFM or SLEUTH. All other class combinations from SLEUTH and the WFM were classified as exhibiting "moderate" development pressure.

## 3. Results

### 3.1 Historic Trends (1990–2000) and Model Accuracies

In this study, we focused on changes in impervious cover, representing a combination of residential, commercial, and industrial development, and residential land conversion as estimated using housing unit and estimated lot size data. The overall patterns of change are similar for both impervious cover and residential land conversion, however, the magnitudes of change differ (Figure 1). The suburban expansion occurring outside the urban centers of Washington, DC and Baltimore, MD can be observed in both datasets. The patterns of impervious surface growth were more dispersed and finer grained, particularly in outlying areas, compared with the patterns of residential land development. Rural areas near Frederick, MD in the northwest quadrant of the image and areas in rural Virginia in the southwest quadrant show particularly dispersed patterns of impervious growth compared with the more concentrated increases in residential development.

Given accurate population projections, the WFM provided reasonably accurate forecasts of the number of housing units per census tract over a 10-year projection period ($r^2 = 0.73$, $p < 0.001$). The accuracy of the 20-year forecasts was, however, significantly lower ($r^2 = 0.32$, $p < 0.001$). The redistribution algorithm only minimally improved the overall accuracy, contributing an insignificant increase in the explained variance between the forecasted and actual number of housing units per census tract.

SLEUTH displayed minimal degradation in accuracy over the 1986–2000 time period. At the coarsest scale of the county level, the comparison of mapped to modeled urban cells produced an $r^2$ value of 0.99 in 1990. In 2000, the $r^2$ had declined to 0.98. At the watershed scale, the 1990 $r^2$ value was 0.99, and in 2000 it had declined to 0.97. For the 1-square-mile grid scale, the $r^2$ value was 0.97 in 1990 and 0.94 in 2000.

### 3.2 Projections of Future Growth (2000–2010)

The patterns forecasted by the WFM were slightly less dispersed from urban centers than the patterns of the previous decade (Figure 2). In particular, the WFM forecasted significant new growth for the southeast section of the District of Columbia and northern half of Baltimore, MD. The high growth forecasts in these two areas result from the redistribution

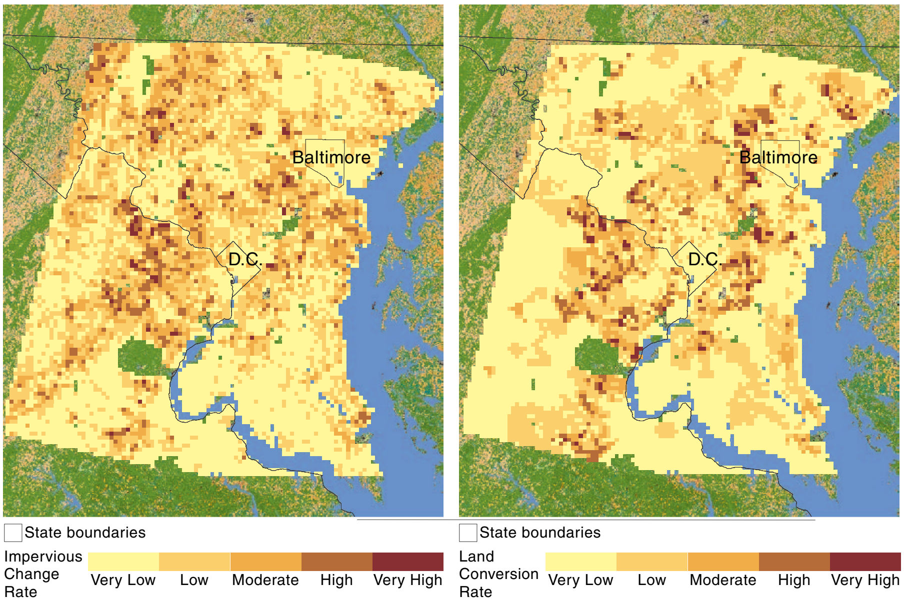


*Figure 1.* Historical patterns of development (1990–2000) based on change in impervious cover, left image, and change in residential land conversion (housing units * lot size), right image. Grid cells containing fewer than 50 acres of developable land are not displayed.

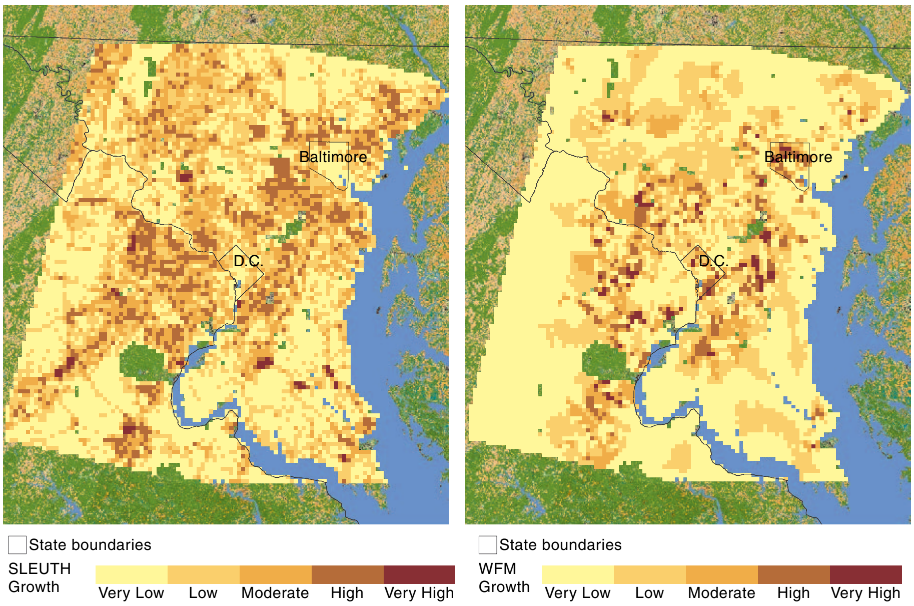


*Figure 2.* Forecasted patterns of development (2000–2010) based on the SLEUTH model, left image, and WFM model, right image. Grid cells containing fewer than 50 acres of developable land are not displayed.

of large projected increases in inner city housing to adjacent areas with larger estimated lot sizes and more undeveloped land.

Development patterns forecasted by SLEUTH were similar to those observed in the 1990 to 2000 time period but also showed an intensification of development around established urban areas (Figure 2). A continuation of development pressure in outlying areas was further projected. SLEUTH predicted higher development pressures near the urban centers of Washington, DC and Baltimore, MD than were observed in the past, and there was also an indication of increasing development pressure in southern Maryland.

### 3.3 Integration of Modeling Results

The final map of "development pressure" illustrates the relative likelihood of future development in the study area (Figure 3). Red cells identify areas where both the WFM and the SLEUTH forecasted development pressure to be "high" or "very high". Orange cells include areas where either the WFM or the SLEUTH forecasted development pressure to be "high" or "very high". Purple cells represent areas where both the WFM and the SLEUTH forecasted "very low" development pressure, and lavender cells represent areas where either the WFM or the SLEUTH forecasted "very low" development pressure. All other combinations of forecasted model results appear as yellow.

The highest concentrations of development pressure generally occurred along major transportation corridors near urban centers. In Maryland, development pressure was high along the U.S. 301, U.S. 15, U.S. 50, I-95, and I-270 corridors. In northern Virginia, development pressure was high along the U.S. 15, U.S. 50, I-95, I-66, State Route 7, and State Route 28 corridors. Development pressure tended to be lowest in areas distant from urban centers and major transportation.

## 4. Discussion

### 4.1 Historic Trends (1990–2000) and Model Accuracies

Differences between the historic trends in residential development and impervious surfaces were most pronounced in the low to moderate range of both datasets. These areas typically fell within the suburban-rural interface where low-density subdivisions were likely to be built. Low-density development is difficult to distinguish using Landsat satellite imagery (McCauley and Goetz, 2003), but impervious areas located

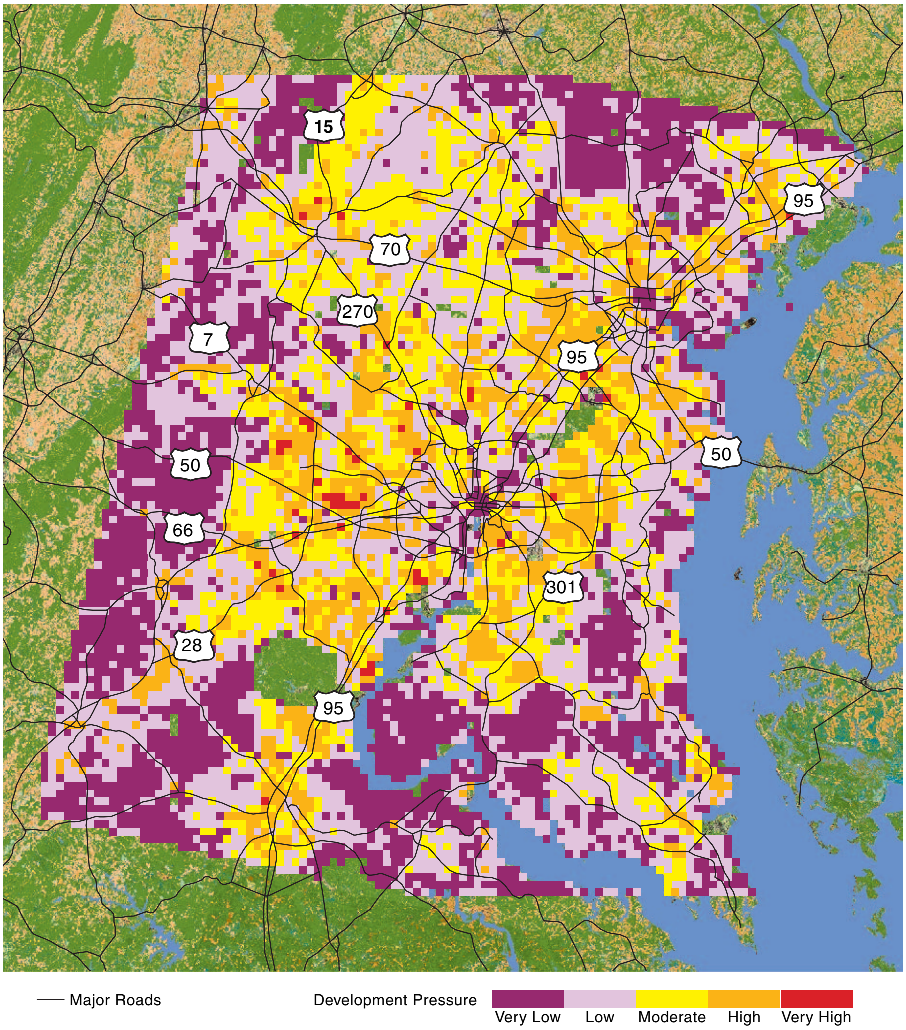


*Figure 3.* Development pressure forecasted to the year 2010 in the Baltimore-Washington, DC, metropolitan region as assessed by combining forecasts from the SLEUTH and WFM models. Grid cells containing fewer than 50 acres of developable land are not displayed.

within low-density residential areas were detected by the subpixel impervious surface mapping algorithm used to produce the maps for SLEUTH calibration (Smith et al., forthcoming). In outlying suburban areas, however, new commercial and industrial developments, representing significant increases in impervious surfaces, are often spatially segregated from residential areas owing to zoning regulations. These distinctions between land uses of impervious areas cannot be distinguished from the Landsat maps.

The significant degradation of the WFM's accuracy over time and the minimal improvement in accuracy attributable to the inclusion of density constraints indicate that the method may not be suitable for simulating longer-term demographic and economic processes at the census-tract scale. An analysis of census-tract population and housing-unit change from 1970 to 2000 showed that change is not always linear and some areas experience a reverse in growth trends. For example, central cities suffering from decades of population decline can become revitalized, such as is occurring in Baltimore. In contrast, suburban areas can experience population declines as job centers relocate to exurban areas and land values and housing preferences facilitate development in outlying rural areas (Lucy and Phillips, 2001).

SLEUTH was able to capture development patterns successfully over the 1986 to 2000 time period and showed minimal degradation in accuracy through time. It should be noted, however, that dramatic shifts in urban development patterns were not observed over this relatively short time series and the growth rate approximates a linear trend (Jantz et al., in press), making it difficult to draw conclusions about SLEUTH's performance for longer-term predictions.

### 4.2 Projections of Future Growth

When evaluating the WFM projections, we noted much higher projections surrounding urban centers than expected. The District of Columbia and Baltimore City both lost population between 1990 and 2000, but both are anticipating population increases in the coming decade. With little land remaining for development, the WFM reallocated much of the projected inner city growth to neighboring areas. These forecasted high growth areas, however, most likely misrepresent urban land consumption rates because the estimated mean lot size (0.19 acres) for the areas immediately adjacent to the city centers is higher than would be expected for new development in these already heavily developed regions. The mean lot size estimates used in this analysis may also underestimate land consumption in rural areas because data to derive the mean lot sizes originated from Montgomery County, MD a suburban county with strong growth management policies.

The intensification of development near the urban centers of Washington, DC and Baltimore, MD forecasted by SLEUTH was difficult to interpret. SLEUTH gives precedence to edge growth (Clarke et al., 1997) and may result in projections that overpredict the amount of infill development that could occur (Jantz et al., in press). However, the expectation that development could intensify in these areas is warranted, given that population projections indicate continued growth.

Previous research has noted an inability to simulate low-density settlement patterns with SLEUTH (Jantz et al., in press; Yang and Lo, 2003). Although there was evidence that SLEUTH was unable to produce an appropriate level of dispersed development using fine-resolution data, we found that a continuous probability map could be used to represent development pressure in a way that captured potential low-density settlement patterns. Predicting the exact spatial locations of these particular conversion events was difficult since their frequency was relatively low and their manifestation across the landscape was essentially random. The low probabilities of development projected in outlying areas accurately reflect the likelihood that any individual cell within a rural landscape would be converted into residential use. SLEUTH's probabilistic output was more useful when interpreted as the likelihood of development occurring in space, rather than when used to estimate the area of new development by converting the probabilities into area estimates through the use of thresholding (e.g., Jantz et al., in press).

### 4.3 Integration of Modeling Results

Because SLEUTH and the WFM represent different aspects of the development process, the areas of agreement and disagreement are presented in the final map as measures of development pressure. In Figure 3, the scarcity of red cells, showing model agreement of high growth forecasts, may result from the contrasting bias in both models: SLEUTH tends to overestimate infill while the WFM tends to underestimate infill (SAIC, 2002; D. Theobald, personal communication). However, it may also indicate that relatively high rates of population growth seldom spatially coincide with areas exhibiting a high percentage of impervious surfaces and fragmented development patterns. This pattern and intensity of imperviousness may indicate areas that have approached their near-term carrying capacity for new development.

For the purposes of assessing the threat of development to forests and farmlands, the areas of "low" development pressure (lavender cells in Figure 3) adjacent to large areas of "very low" development pressure are of most interest. These areas potentially represent the leading edge of development where the fragmentation of forests and parcelization of farmland are most likely to occur. While the development pressure was lower in these areas relative to areas closer to existing urban centers, this was consistent with how low-density development is represented in the models used for this analysis: as housing unit density in the WFM and as developed land in the SLEUTH model. However, development occurring in these areas, particularly low-density development, has a disproportionate impact on the natural resource base.

Although the overlay grid enhanced our ability to interpret and display data from SLEUTH and small census tracts (less than 1-square-mile in size), it also misrepresented the resolution of the census data from larger tracts. The sizes of census tracts are proportional to their population density (U.S. Census Bureau, 2000) so that larger tracts tend to be located in rural and outlying suburban areas where much of the growth over the past decade has occurred. Between 1990 and 2000, 75% of the growth in housing units occurred within 25% of the census tracts in the study area, and the mean size of those tracts (31-square-kilometers) is more than twice the mean size of the remaining tracts. Therefore, to capture more accurately the spatial distribution of housing unit changes in rural areas, we should use finer scale census geography. Census blocks are the finest scale geography used by the U.S. Census Bureau. The mean size of populated blocks in the study area is 0.3-square-kilometers and ranges to more than 30-square-kilometers in rural areas. The spatial resolution of the data must be increased to map the patterns of development within large rural census blocks. Jones et al. (1997) have used road density surface maps to distribute county population values, and similar methods could be used to distribute census block housing information, assuming the availability of digital historic road data coincident with the decennial census.

Integrating the models proved informative, but it did not achieve an accurate representation of growth rates and patterns beyond 10 years because the models cannot capture many of the social, political, and economic factors necessary for simulating longer-term growth rates and patterns. At the parcel scale, land development is most likely influenced by factors such as land value, tax policies, development regulations, and physical parcel features (Bockstael, 1996). At the regional scale, interest rates and employment and demographic trends can influence land development rates and patterns. In urban areas, land development may be driven by trends in employment, crime, and education, whereas in rural areas, it may be driven more by local amenities, aesthetics, land values, and proximity to employment centers. State growth policies, such as Maryland's Priority Funding Areas, and local zoning and ordinances can also strongly influence the spatial patterns of growth in areas where they apply. Income, employment, and agricultural productivity statistics are available at the county and sub-county scale from the U.S. Census Bureau and U.S. Census of Agriculture, and Jackson et al. (2004) have integrated such factors into a Resource Economics Model (REM) originally developed by Hardie et al. (2000).

## 5. Conclusions and Future Directions

This study demonstrates that the WFM and SLEUTH models are complementary and can be logically integrated to spatially capture residential, commercial, and industrial growth over a 10-year period. The WFM was originally designed to focus on detecting growth in low-density rural areas. The scope of SLEUTH encompasses commercial, industrial, and high-density residential growth, aspects of development that were not well simulated by the WFM. Even though the models can be used in a complementary fashion, further investigation into the relationships between impervious surface area and housing density is needed to better interpret the differences between the models.

The SLEUTH model accounts for some of the geographic factors influencing land development, including slope, proximity to roads, and proximity to existing development and can be tailored to account for regional growth management policies. The WFM accounts for demographic influences and trends and could be altered to simulate nonlinear growth trajectories. Missing from both models, however, was an explicit accounting for economic factors. Integrating economic data into the WFM and SLEUTH is warranted to improve the accuracy of their longer-term forecasts. However, this study demonstrated that to assess threats to forests and farmlands throughout the Chesapeake Bay watershed, it was most important to accurately forecast change along the suburban-rural interface. Unfortunately, simulating fine-scale land-use changes in rural areas using census data was hampered by the large size of census boundaries in rural areas. To further explore this issue, researchers should investigate different methods of distributing population and housing data in rural areas. In an attempt to better capture these fine-scale development patterns, Theobald (personal communication) has recently made several revisions to the WFM.

SLEUTH's utility stems from its potential ability to simulate the patterns associated with low-density, dispersed development, but the dominance of the edge growth parameter limits some aspects of SLEUTH's ability to capture "sprawl". Although it has been suggested that SLEUTH can be universally applied to any urban area (Silva and Clarke, 2002), assumptions concerning growth processes that are integrated into the model's code may not be widely applicable. This may be partly because SLEUTH was developed in areas where topographical and other constraints limit the formation of the highly dispersed settlement patterns that are observed in the Chesapeake Bay region. Recent developments in remote sensing methods, however, allow better representation of fine-grain, low-density settlement patterns that SLEUTH can utilize. Simple modifications to the software may also increase SLEUTH's range of performance, and coupling SLEUTH with nonspatial regional models of economic trends, policy scenarios, and population growth holds promise.

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