A Decade of SLEUTHing: Lessons Learned from Applications of a Cellular Automaton Land Use Change Model

This paper reviews the numerous and various applications of the SLEUTH urban growth model over the last decade. The SLEUTH is a Cellular Automaton-based urban growth model that uses historical geospatial data for calibration of its parameters. Applications have covered the major cities of the United States, including Detroit, Chicago, New York, Washington, San Francisco and Albuquerque. The model has also been applied in the Netherlands, Portugal, South America, Africa and Australia. Applications have examined the likelihood of urban encroachment on waste disposal sites, the generation of planning scenarios for public decision-making, and the expansion of informal settlements in Yaoundé, Cameroon. Regions covered have varied from a single small town to a whole multi-city urban region, and spatial resolutions have gone from tens of meters to kilometers.

The paper assembles for the first time the calibration results from the model applications, and attempts an inter-city comparison, expanding on Silva's concept of the "DNA of regions." This is possible because the successful calibration of the SLEUTH model from historical land use data gives a set of five parameters that capture the nature of the urban growth in a region. The discussion also summarizes the various lessons learned, especially in how to best calibrate the model. Recent results have shown not only that model performance can be significantly improved using high performance computing, but also that adaptations are possible for searching the parameter space that vastly improve how well the model forecasts growth and change into the future.

Key Words: SLEUTH, cellular automata, land use change, urbanization

History of the SLEUTH urban growth model

SLEUTH is a model for simulating urban growth and other land use changes that are caused by urbanization. The model was first created by the lead author, while visiting the United States Geological Survey as a research scientist in 1992. The model's cellular automaton (CA) approach was a direct descendent of prior work on modeling wildfire (Clarke et al. 1993; Clarke et al., 1995). The wildfire model involved extensive C-language coding of CA, and anticipated many of the subsequent issues for SLEUTH, including how best to match historical data, and how to automate the calibration process. While a NASA-ASEE fellow at the NASA Ames research center in 1991, Clarke had a series of discussions on land use change and urbanization in the San Francisco Bay Area with USGS Geographer Len Gaydos, who at the time was involved in various land use mapping and analysis tasks. After 1992, with the development of the first operational version of the SLEUTH model (then termed UGM for Urban Growth Model) Gaydos pursued an internal USGS research initiative that funded Clarke's further development work and established the Urban Dynamics research program at USGS. This early work is summarized in a paper by then USGS Research director Dave Kirtland (Kirtland et al. 1994). This funding allowed the further experimentation with the model and the extension to land use change (Clarke 1997), following a land use modeling meeting in Sioux Falls, SD. The reformulated model was released under project Gigalopolis (Clarke et al. 1997), which Clarke moved from New York's Hunter College to the University of California, Santa Barbara. At the same time, the project web site was built, and the model extended to version 2, which used dynamic memory allocation. With further funding from USGS and the EPA, the team transitioned the model code to a flat memory model and included calls to the Message Passing Interface, suitable for a Cray supercomputer. Key programming work was conducted at EPA by Tommy Cathey, and at USGS's Rocky Mountain Mapping Center by Mark Feller, resulting in the release of version 3 of the computer code.

The purpose of the USGS's Urban Dynamics program was to model the growth of major American cities as a vehicle for raising public awareness about the consequences of rapid urbanization at a time when the Internet bubble was at its peak, and urban sprawl continued unchecked across the American landscape. This public role was the consequence originally of a single press conference at the 1994 Association of American Geographers meeting in San Francisco (Clarke et al. 1996). Unexpectedly, the animated urban growth sequences created in the modeling work became a television success. Later work in Washington, D.C. and Maryland redoubled this public success, with the video sequences used in various smart growth initiatives at the federal political level. The original inspiration for using historical data in the calibrations was the awareness of the value of the USGS historical map holdings in their Reston Map Library, where a single paper copy of every edition of every map was kept, forming a remarkable historical record of urban growth. While the incompatibility of paper map products and remote sensing was a challenge, eventually many and varied sources were used for SLEUTH data creation, including historical road maps (for highways) and the CORONA declassified spy satellite data. To this day, the USGS continues to use SLEUTH as a major tool in its Urban Dynamics program, and has experience in modeling at least 8 urban regions with the model.

Release of the model's source code and full documentation to the World Wide Web was a timely and efficient way to meet the USGS's Freedom of Information Act requirements. Since SLEUTH was developed using US public funds, the model was effectively public domain. The web site started a UCSB discussion forum open to all users (at http://bbs.geog.ucsb.edu), since then supplemented by another public forum (sleuth-users@yahoogroups.com). This public exposure resulted in SLEUTH being highlighted in two major inventories of land use change models (Agarwal et al. 2002; Gaunt and Jackson 2003), both of which compared and classified the model and its functionality. Hill et al. (2001) used SLEUTH as a first example of a model to fit into a new content standard for model metadata. The number of SLEUTH applications has been far more than the author ever imagined over a decade ago. After over a decade of SLEUTH modeling, we now consider the breadth and depth of these studies. Our goal is to assess whether of not the model's results, in terms of calibration parameters, have significance beyond their ad hoc application. At the outset of work on SLEUTH, an original goal was to be able to make conclusions and observations about urban form and process as a by-product of the model's use. Silva (2001) has called this assessing the “DNA of Regions”.

There are few current means by which the trajectories of urban growth in different locations and regions around the nation and the world can be directly and quantitatively compared. An advantage of the SLEUTH model's calibration is that it distills historical growth and its spatiotemporal patterns into a set of five parameters that are directly comparable across applications and even scales. These parameters have been chosen and computed so that they are somewhat scale-less in their values, although some scale sensitivity has been reported in various studies. The parameters have initial values (the value at the start of the calibration process), final values (at the end of runs, having been self-modified by the process), and averaged values that include means over multiple Monte Carlo iterations. It is the initial values that are investigated in most work. The set of five values was retrieved case-by-case from the published and unpublished literature related to SLEUTH, and are analyzed and mapped here for the first time other than in the context of their own application.

An Inventory of SLEUTH Applications

The majority of SLEUTH applications have been for urban forecasting or for integrated modeling of urban growth with some other social or physical process model or planning effort. Table 1 is a compendium showing the variety of urban modeling using SLEUTH. Some of this work is not formally published, but collected by posting a request on the discussion forums, and from published and unpublished academic papers.

[Insert Table 1]

* U.S. Geological Survey/ Geography Discipline/ Rocky Mountain Mapping Center

Not surprisingly, most of the SLEUTH applications are in the United States, mostly from the efforts of the US Geological Survey and research at UCSB.

In addition to modeling extant urban regions, SLEUTH has shown to be a tool in exploring theoretical investigations of urban processes. Bierwagen's (2003) dissertation focused on simulating generic urban forms and examining the connectedness in the landscape in order to asses the viability of different urban growth forms on butterfly habitat. Syphard et al. (In Press) investigated the impact of future urbanization on fire regimes in California's Santa Monica Mountains by loose-coupling SLEUTH with the land use model LANDIS. Goldstein et al. (2004) compared using SLEUTH for the "backcasting" of urban extent with spatiotemporal interpolation. As a backcasting tool, SLEUTH has been used extensively, most notably in Herold et al. (2003), where the use of landscape metrics in the historical development of an urban region is presented, and by Goldstein et al. (2000), where historical urban-wildfire conflicts are investigated.

Significant Findings of the Applications

With such a substantial number of model applications, it is difficult to distinguish the individual contributions of each application, as they have all built upon prior work, experiences, and lessons learned. What follows is a set of selected applications that stand out as essential works in the history and development of the SLEUTH model.

The application of SLEUTH to the San Francisco Bay area by Clarke et al. (1997) was the first major application of the model to a metropolitan region. In this research, the historical urban extent was determined from cartographic and remotely sensed sources from 1850 to 1990. Using this information, coupled with transportation and topographic data, animations of the spatial growth patterns were created, statistics describing the spatial growth were calculated, and the model was used to predict future urbanization. This initial publication provided the foundation for all subsequent applications. The paper documents the details of the SLEUTH model, describing the necessary data layers, the five coefficients and what they control, and the four types of urban growth. In addition to the 'basics' of the model that were described, the concept of self-modification was introduced, and a detailed explanation of how the model controls itself and parameter values are allowed to change with time was presented. While the method of calibration used in this work was primitive compared to current methods (Goldstein 2004a), this research introduced the complete SLEUTH model and led to other applications.

While early applications of SLEUTH focused solely on the modeling of urban growth, the coupling of the Deltatron model, the portion that simulates land use change, increased the models ability to represent multi-attribute landscape change over time. Candau and Clarke (2000) document this sub-model, and its use for modeling land use change in the EPA's MAIA (Mid-Atlantic Integrated Assessment) region. Much like Clarke et al. (1997), the paper is the documentation on how the land use change CA model (Deltatron) functions. In modeling the eight state MAIA region, Candau and Clarke were able to compile land use data classified at Anderson Level I for 1975 and 1992, produce a map of predicted land use in the year 2050, and introduced the concept of the uncertainty map, whereby the number of times a land use is predicted at a given location during Monte Carlo simulation determined the certainty of that prediction holding true. These three accomplishments were critical in moving SLEUTH from only having the capability to model urban growth, to becoming more dynamic in its simulation abilities, and incorporating the feedbacks between urban growth and land use change that are seen in real-world systems.

In any application of SLEUTH, one of the most time consuming processes is the calibration period. While briefly discussed in Clarke et al. (1997) and in Clarke and Gaydos (1998), Silva and Clarke (2002) present a more refined focus on the calibration of SLEUTH during the application of the model to Lisbon and Porto, Portugal. The paper presents four key findings from the application: (1) SLEUTH is a universally portable model that can not only be applied to North American cities, but to European and international cities as well; (2) increasing the spatial resolution and detain of the input datasets makes the model more sensitive to local conditions; (3) using a multistage 'Brute force' calibration method can better refine the model parameters to find those that best replicate the historical growth patterns of an urban system; and (4) the parameters derived from model calibration can be compared between different systems, and the interpretation can provide the foundation for understanding the urban growth processes unique to each urban system. It was from the concept of point (4) that Silva (2001) developed the concept of Urban DNA, and that the following section is based. The work of Silva and Clarke in documenting the calibration proceed of SLEUTH in their application of the model to Lisbon and Porto provided a basis for the work of others applying SLEUTH (Jantz et al. 2003; Yang and Lo 2003; Dietzel and Clarke 2004a), and made those applications more robust through a better understanding of the calibration process.

Most recently an important advance has been made in the use of SLEUTH; coupling model outputs with other spatiotemporal models to provide greater insight into problems dealing with future urbanization. Some of these applications involved the coupling of SLEUTH outputs with social modeling efforts, while others rest more in the domain of physically-based modeling. Claggett et al. (2004) were successful in coupling SLEUTH with the Western Futures Model (Theobald 2001). By doing so, they demonstrated the ability of the SLEUTH to move beyond just providing a spatio-temporal picture of urban growth, but actually categorizing the growth into different classes of 'development pressure' based on forecasted population growth. Working almost in parallel, Leão et al. (2004), coupled SLEUTH outputs with a multi-criteria evaluation of landfill suitability (Siddiqui et al. 1996) to determine zones around Porto Alegre City (Brazil) where future land would not be urbanized, yet was suitable for landfills. Arthur (2001) coupled SLEUTH to an urban runoff model in Chester County, Pennsylvania. Syphard et al. (In Press) examined the consequences of urban development on wildfire regime and vegetation succession in Southern California's Santa Monica Mountains. Cogan et al. (2001) compared using SLEUTH outputs with the California Urban Futures model (Landis 1994) of urban development to assess stresses on biodiversity. This research demonstrates that SLEUTH can be successfully coupled with other models displaying the potential of the model to be incorporated into a wide array of applications ranging from urban development to environmental assessment and beyond.

Through the NSF-funded research project, "Urban Change Integrated Modeling Environment", the value of using scenarios as a presentation of SLEUTH results, became evident. The application of SLEUTH to Santa Barbara reported by Herold et al. (2003) was part of a broader study that sought to increase local residents' awareness of smart growth principles and planning options through modeling. Both SLEUTH and SCOPE were used to create a set of scenarios that could be used to experiment with alternative futures. SCOPE is a systems dynamics model in the Forrester tradition, coded in the STELLA modeling language and including various social, economic, and demographic variables (Onsted 2002). SLEUTH allows policy and plans to be incorporated through new transportation layers, and through variations in the excluded layer. The UCSB Urban Change Integrated Modeling Environment was the result (http://zenith.geog.ucsb.edu/scenarios). Choosing scenarios and using models, including SLEUTH, further led to research on the nature of scenario planning (Xiang and Clarke 2003) and on simplicity in modeling (Clarke 2004). More recently, the link between parameters, model behavior, and scenario generation has been the subject of further investigation (Dietzel and Clarke 2004b).

SLEUTH has been used for exploratory visualization as well. Acevedo and Masuoka (1997) presented the general methodologies used to create 2-D and 3-D animations of the Baltimore-Washington DC region. Candau (2000) presented the possible ways of visualizing the uncertainty of the location of urban growth in a simulated landscape. Aerts et al. (2003) continued this thread by experimenting with subjects about their understanding of the uncertainty of the forecasted urban growth in a section of Santa Barbara using two different techniques. While the myriad of visualization techniques has expanded since SLEUTH's introduction, the understanding and interpretation of simulation forecasts is still a nascent research topic, especially given the accessibility of modern visualization techniques to stakeholders.

The work reviewed here has led to the evolution of the SLEUTH model from its early stages and first applications, to more recently the use of the model as the basis for evaluation of geographic phenomena. As the use of the model continues to spread around the world, we are learning more about the comparative growth of cities and regions. Building on the work of Silva (2001) and the concept of urban DNA, we aims to use the inventory all the known SLEUTH applications and their subsequent parameter values to derive a map of the DNA of cities in the USA, and globally.

Spatial Distribution of SLEUTH Calibration Results: The DNA of World Cities and Regions

What follows is a snapshot of the “DNA of the world cities” in map and table form (Figures 1 and 2). These figures were made using the most current calibration coefficients of SLEUTH (Table 2). As with the listing of Urban modeling in Table 1, this work has been collated from peer-reviewed literature, white papers, Master’s and Doctoral Theses, and by personal contact. By current estimates from the SLEUTH user forums, this compendium is incomplete. Efforts are currently underway to make available all of the modeling data, including spatiotemporal data layers and calibration coefficients of all urban regions modeled with SLEUTH on a common website hosted at UCSB through the existing model website.

[Insert Table 2]

[Insert Figure 1]

[Insert Figure 2]

On the United States maps, we note major differences between interior versus coastal cities. Coastal cities seem to have higher Diffusion and lower Road coefficients. We speculate that this is caused by the reflection effect of coasts, such that there is more likelihood for outward diffusion because it is restricted in the direction of the ocean. In the interior, cities can be centers of transportation routes connecting radially in any direction, and so increasingly are shaped by the actual road pattern. Both Breed and Spread seem closely linked to the phenomenon of sprawl, while the Slope coefficient seems more localized in impact.

With regard to specific cites in the United States, some of the results reinforce social commentary on the cities. Houston, Texas, is the fourth largest city in the United States. The population of Houston grew 25.8% between 1990 and 2000, well above the national growth rate of 13% (Clemonds and Li 2004), so the high spread parameter value is not surprising given the required growth to accommodate the increasing population. Additionally, the high road gravity parameter value associated with Atlanta did not come as a surprise, as it is commonly know that transportation routes drive development in Atlanta, causing it to have the highest travel delays in the United States for cities between 1 and 3 million in population (Texas Transportation Institute 2004). Globally, the data are too sparse to draw broad conclusions or even speculation. Additional application could fill this gap in the future, but knowledge of the socio-economic and political structure of Mexico and the Netherlands provides some insight in the parameters from applications in these areas. In the Netherlands, there is a very structured planning process where even development on an individual parcel must be evaluated for its impact on the national plan and government goals. With this regulatory structure, it is not surprising that the SLEUTH application to the Netherlands had a very low diffusion parameter, and a relatively high breed parameter. These parameter values reconfirm our notions about Dutch planning; that the high degree of regulation does not permit the development of many new settlements (low diffusion value), but that when new development occurs, the development is not just one small parcel, but the development of that area as a whole (higher breed parameter). The high spread values found for Mexico City and Tijuana are characteristic of much of the growth in Latin American countries, where unenforced regulation and the lack of central planning allows growth to occur wherever squatters or land owners choose.

While at this time it is not possible to wholly understand what an entire parameter set means in terms of development of a city or country, it is possible to gain insight by looking at individual parameter values and their meaning compared to what is commonly known about the area. An examination of the global distribution of SLEUTH parameters, begs the following question: are the SLEUTH calibration parameters correlated with socioeconomic characteristics at an international scale? If we aim to answer this question, we will first need to somehow resolve the different spatial and temporal resolutions and extent of the various urban domains. Next, we will need to decide on what socioeconomic measures would be adequate for this type of investigation. Additionally the spatial domain (or extent) of comparisons would warrant assessment. Luckily, the numbers of cities being modeled with SLEUTH is increasing, and we can soon start to investigate the answers to these questions.

Current and Future Research on and with SLEUTH

Current research using SLEUTH is dual-faceted. While some researchers are using the model as a tool for application (Jantz et al. 2003; Yang and Lo 2003; Claggett et al. 2004; Leão et al. 2004), others are still investigating simple properties of the model and making major refinements (Dietzel and Clarke 2004a; Goldstein 2004a). While the list of applications continues to grow (Table 1), research into the model has been mainly focused on the calibration, and how to better improve the process.

While the work of Silva and Clarke (2002) was an important step forward in our understanding of the calibration process, it illustrated not only that considerable computational power was necessary to calibrate SLEUTH, but also that, depending on how a user interpreted the goodness of fit measures, a variety of parameter sets could lead to the 'best fit.' Goldstein's genetic algorithm (Goldstein 2004a) has tackled the problem of the burdensome amount of time necessary to calibrate SLEUTH using the brute force method. While the algorithm still requires a fast CPU on a computer, a calibration that previously took several days, now takes minutes or a few hours, an order of magnitude decrease in the time required to execute model calibration, and a leap forward for SLEUTH. Through their work with self-organizing maps, Dietzel and Clarke (2004b) have determined what the optimal metrics are to use in making a more robust calibration of the model to historical data. When coupled together, these two research papers completely overhaul the previous calibration methods for SLEUTH, and mark a new era in model efficiency and calibration robustness.

There are still some very basic ideas behind the model that are yet to be fully explored. In the greater modeling context, one challenge central to the understanding of SLEUTH forecasting, and to a lesser extent, backcasting, is the amount of information produced by the sometimes diverse Monte Carlo simulation runs. Goldstein (2004b) has begun to explore this issue, and much is being learned about the spatial differences between Monte Carlo results and how to quantify their differences. Averaging over Monte Carlo runs hides the details of individual emergent, atypical results. In order to tap into the "lost" information present in the Monte Carlo realizations, Goldstein has devised the Area Weighted Summation Metric, which can lend insight into the possibly chaotic Monte Carlo runs, and has used the idea of "momentum" to explore the difference in spatial spread of each temporal simulation.

Other concepts that will be examined in the near future will include practical, computational and analytical issues of SLEUTH. For example, the number of Monte Carlo iterations needs elucidation, so as to reduce computational load while providing enough variety in the results. A multi-dimensional sensitivity testing of SLEUTH is needed. This would include the sensitivity to the data layers, the calibration coefficients, and the many parameters preset inside the model, such as "critical slope" and the self-modification control parameters.

An idea necessary for SLEUTH development as well as for the greater spatiotemporal modeling community is that of ontology. There are many theoretical questions that have applied value. This includes the formalization of what constitutes an urban pixel, a landscape type, and more challengingly, a time step. When SLEUTH input data comes from different sources, such as both from maps and imagery, does it have the same meaning? The significance of spatial and temporal scale is necessary in this exploration as well. Currently model applications give little or no heed to these issues. These ontological questions are even more pertinent to model coupling exercises, since each model has its own history and rests in a different intellectual domain, let alone spatial and temporal scale and computing environment.

With SLEUTH's first decade now behind us, we note that many of the restrictions faced in the early days on use of the model have now been overcome. The computational problems of calibration and forecasting have yielded to better methods and more computing power. The type of data that SLEUTH requires is now also far more ubiquitous, reliable and consistent. One of the original goals of the SLEUTH work was to scale the model upward toward continental and global scales. We contend that the impact of urbanization globally is just as much a factor in global change as many other physical factors, such as methane production and climate, indeed these factors are highly interconnected. With a new generation of remote sensing instruments capable of timely land cover mapping globally at medium resolution, and with the release of data such as the Shuttle Radar Topographic Mapping Mission's global digital elevation model, a global application at the scale of 1km, or even nested continental and regional applications at finer scale may be possible in the near future. Given SLEUTH's ability to raise awareness of urbanization issues locally, and regionally, we can only imagine what impact might global scenarios have. Should this work become possible, the authors would welcome its contribution in the tradition of the first decade of SLEUTHing.

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Table 1. Known SLEUTH Applications.

Geography	Research Group / Affiliation	Application	Reference
Albuquerque, NM	USGS/GD/RMMC*	Urban Change	Hester 1999; Hester and Feller 2002
Alexandria, Egypt	Newcastle University	Urban Change	Azaz 2004
Atlanta, GA	Florida State University, Tallahassee, Department of	Urban Change	Yang and Lo 2003; Yang 2004
Austin, TX	USGS/GD/RMMC*	Urban & Landuse Change	USGS/RMMC 2004
Chester County, PA	Penn State Meteorology and Atmospheric Science	Coupled Modeling	Arthur et al. 2000; Arthur, 2001
Chicago, IL	USGS Urban Dynamics	Urban Change	Xian et al. 2000
Colorado Frontrange	USGS/GD/RMMC*	Urban & Landuse Change	USGS/RMMC 2004
Detroit, MI	USGS Eros Data Center	Urban Change	Richards 2003
Houston, TX	Texas A&M University	Urban Change	Oguz et al. 2004
Lisbon, Portugal	University of Massachusetts UCSB Geography	Urban Change	Silva 2001; Silva and Clarke 2002
Mexico City, Mexico	Paola Gomez, UCSB Bren School	Urban Change	UCIME 2001
Monterey Bay, California	UC Santa Cruz Environmental Studies UCSB Geography	Biodiversity loss / model integration	Cogan et al. 2001
Netherlands	Berlage Institute	Urban Change	Tack 2000
New York, NY	Montclair State University	New York Climate and Health Project	Oliveri 2003; Solecki and Oliveri 2004
New York City, NY	USGS/GD/RMMC*	Urban Change	USGS/RMMC 2004
Oahu, HI	University of Hawaii at Manoa	Urban Change	James 2004
Phoenix, AZ	Arizona State University, School of Life Sciences	Urban Change	Breling-Wolf and Wu 2004
Porto, Portugal	University of Massachusetts	Urban Change	Silva 2001; Silva and Clarke 2002
Porto Alegre, Brazil	The University of Melbourne, Department of Geomatics	Coupled Modeling	Leao et al. 2001, 2004
San Antonio, TX	USGS/GD/RMMC*	Urban & Landuse Change	USGS/RMMC. 2004
San Francisco, CA	UCSB Geography / USGS Urban Dynamics	Urban Change	Clarke et al. 1997
San Joaquin Valley, CA	UCSB Geography	Urban Change / Calibration testing	Dietzel and Clarke 2004a; Dietzel et al. In Press
Santa Barbara, CA	UCSB Geography	Urban Change / Coupled modeling	Candau and Clarke 2000; Goldstein et al. 2000, 2004; Herold et al. 2002, 2003
Santa Monica Mountains, CA	San Diego State University	Vegetation Succession	Syphard et al, In Press
Seattle, WA	USGS/GD/RMMC*	Urban Change	USGS/RMMC 2004
Sioux Falls, SD	UCSB Geography	development of GA	Goldstein 2004a
Sydney, Australia	The University of Southern Queensland	Urban Change	Liu and Phinn 2004
Tampa/S. Florida	USGS/GD/RMMC*	Urban Change	USGS/RMMC 2004
Tijuana, Mexico	Université Paul Valéry	Urban Change	Le Page 2000
Washington,DC/Baltimore	University of Maryland, College Park, Department of Geography	Urban Change	Jantz et al. 2003
Washington/Baltimore	USGS/GD/RMMC* / UCSB Geography	Urban Change/ Change Visualization	Acevedo 1997; Clarke et al. 1997
Yaounde, Cameroon	University of Melbourne, School of Anthropology	Urban Change	Sietchiping 2004

Table 2. Known SLEUTH parameter values gathered from the applications and references in Table 1.

Location	**Parameter Value**				
US Cities	Diffusion	Breed	Spread	Slope	RG
Atlanta, GA	55	8	25	53	100
Austin, TX	47	12	47	1	59
Colorado Frontrange	11	35	41	1	91
Houston, TX	1	3	100	22	17
New York, NY	100	38	41	1	42
New York City, NY	21	41	9	90	45
San Joaquin Valley, CA	2	2	83	10	4
Santa Barbara, CA	40	41	100	1	23
Santa Monica Mountains, CA	31	100	100	1	33
Seattle, WA	87	60	45	27	54
Sioux Falls, SD	1	1	12	34	29
Tampa/S. Florida	90	95	45	50	50
Washington,DC/Baltimore	52	45	26	4	19
Washington/Baltimore	55	50	26	6	18
Oahu, HI	5	96	12	1	50
International Cities					
Lisbon, Portugal	19	70	62	38	43
Mexico City, Mexico	24	100	100	1	55
Netherlands	2	80	5	4	5
Porto, Portugal	25	25	51	100	75
Tijuana, Mexico	3	8	70	42	22
Yaounde, Cameroon	10	12	25	42	20

Figure 1. Maps of SLEUTH parameter values for known cities within the United States.

Figure 2. Global maps of SLEUTH parameter values for known cities.