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The SLEUTH Land Use Change Model: A Review

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Abstract

SLEUTH is a cellular automata (CA) model that has been successfully applied worldwide over the last 15 years to simulate land use change. The objective of this paper is to review the current status of the SLEUTH land use change model. Clarke et al. (2007) and Clarke (2008a) provided detailed reviews of the model and its application from its initial days until about 2005. This paper brings the debates, modifications and applications of the model up to date, and provides a brief discussion of past SLEUTH applications. We next highlight the technical modifications published after 2005 and provide a detailed review of applications published until 2012. Structurally, first this paper presents a brief history and description of the SLEUTH model, and then reviews the recent successful technical modifications and applications.

***Keywords**:* SLEUTH; Cellular automata; Land use; Cover change; Modeling

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1. Introduction

Land use change is driven by interaction in space and time between humans and the environment that can be captured by computer simulation models (Veldkamp and Verburg, 2004). In the last few decades, land use change models have played an important role in understanding the causes, mechanisms and consequences of land use dynamics. The models have provided an opportunity to explore and evaluate land use policies, and have helped to visualize alternative futures. The success of these land use models is directly related to the availability of high-resolution satellite images, with better precision and accuracy, and to the availability of increased computational power. Among the types of model that have been used to study land use change, the impact of cellular automata (CA) models has arguably been the greatest (Batty, 1997; Batty et al., 1997; Couclelis, 1997). These '*flexible*' CAs divide the landscape into cells, and their behavior is determined by transition rules that capture the uncertainties of the real world system and simulate the pattern and process of urban growth (Batty, 2005). These mechanistic models have become successful largely because of their simplicity (Torrens and Sullivan, 2001). SLEUTH is one such CA model that has been successfully applied worldwide over the last 15 years to simulate land use change.

The objective of this paper is to review the current status of the SLEUTH land use change model. Clarke et al. (2007) and Clarke (2008a) provided detailed reviews of the model and its application from its initial days until about 2005. This paper brings the debates, modifications and applications of the model up to date, and provides a brief discussion of past SLEUTH applications. We next highlight the technical modifications published after 2005 and provide a detailed review of applications published until 2012. Structurally, first this paper presents a brief history and description of the SLEUTH model, and then reviews the recent successful technical modifications and applications.

2. The SLEUTH Model

From humble origins as a cellular automata model for simulating wildfire spread and behavior (Clarke et al., 1993; Clarke et al., 1995), SLEUTH has become one the most popular simulation models of urban growth and land use change. The model has been revised and modified many times to reach its present version (Clarke, 2008a). From the beginning, the model and its documentation and source code have been publicly available and this fact has led to the model being modified by several researchers worldwide, other than its original authors, to adapt for their local applications.

SLEUTH has been known to be applied to over 66 different cities and regions (Clarke and Gaydos, 1998; Clarke et al., 2007; Clarke, 2008a). The Land Cover Deltatron Model (LCD) is tightly coupled (i.e. integrated at the code level) with the earlier Urban Growth Model (UGM) and together they are called SLEUTH. The name of the model is an acronym for the six gridded raster maps used as input data layers in the model. The model is open source and runs under Unix, Linux and

Cygwin, a Windows-based Unix emulator (Clarke, 2008a).The model uses two land use maps with a consistent classification scheme along with at least four urban maps to represent the unique historical pattern of growth during the model's calibration and application (Gazulis and Clarke, 2006).The two land use layers are used in calculating the class-to-class transition matrix among the different land use classes (Clarke, 2008b).The exclusion layer is included to control urban growth in areas where urbanization is restricted according to local land use policies (for example water bodies, protected areas, etc). Digital elevation models are used to create the slope and hill shade layers for the area of simulation. Lastly, it requires multiple weighted road maps from different time periods that determine the probability of urban development according to accessibility of the location. The two cellular automata run in sequence and the output of the newly urbanized cells determines the number of times the deltatron code executes (Clarke, 2008b).

In SLEUTH, the urban areas behave like a living organism, trained by transition rules that influence the state of changes within the CA as a set of nested loops. The outer loop executes Monte Carlo iterations and the inner loop executes the growth rules. The model reads the historical maps and uses their parameters to compute how well any specific model run replicates the transitions between the input years (Clarke and Gaydos, 1998; Gazulis and Clarke, 2006; Sietchiping, 2004; Dietzel and Clarke, 2007).The calibration process uses a 'brute force calibration' technique, which sequentially narrows down the range of SLEUTH behavior parameter values, leaving the set which best replicate the historical data (Clarke et al., 1996; Silva and Clarke, 2002). The 'goodness of fit' (Clarke, 2008b) is determined by the Optimal SLEUTH Metric (Dietzel and Clarke, 2007; Clarke, 2008b) and the combination of parameters with the highest OSM is used for forecasting. There are five parameters which control the behavior of the system and represent the past urbanization trends (Clarke et al., 1997; Gazulis and Clarke, 2006).These parameters are the dispersion coefficient, the breed coefficient, the spread coefficient, the slope resistance factor and the road gravity coefficient (Clarke et al., 1997; Sietchiping, 2004; Gazulis and Clarke, 2006).These coefficient values determine the growth rate by altering the degree to which each of the four growth rules influences urban growth within the system(Clarke et al., 1997; Gazulis and Clarke, 2006). The four growth types that determine the probability of a cell becoming urbanized are termed: diffusive growth, new spreading center, organic growth and road influenced growth (Clarke and Gaydos, 1998). There is a meta level of growth rules called 'self-modification' rules, which help to avoid linear and exponential urban growth in the model (Silva and Clarke, 2002). The land use dynamics of the Deliration model also run in sequence and follow a four-step process, which consists of the phases: *initiate change, cluster change, propagate change,* and *age deltatrons* respectively (Clarke, 2008b). The slope of the land use class also alters the probability of the cells to change. Model execution takes place in the form of a growth cycle (each representing one year) and a series of growth cycles make up the whole simulation process. Figure 1 shows the general structure of the model.

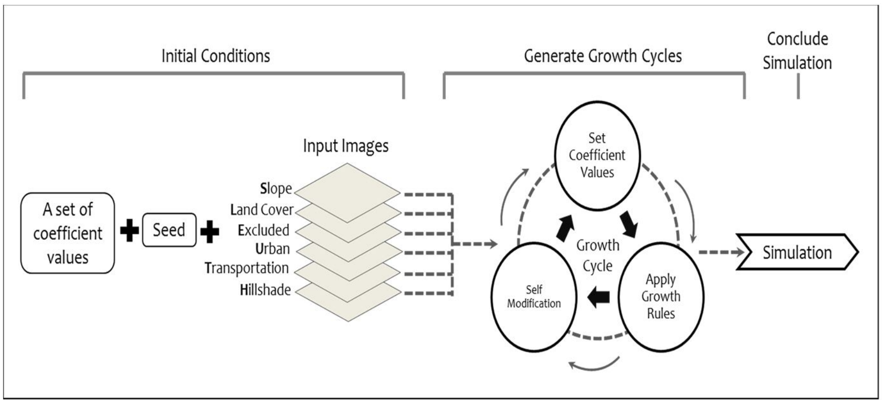

Figure 1. Structure of the SLEUTH model

3. Technical modifications of SLEUTH

SLEUTH, being open-source, has attracted numerous applications throughout the world. A detailed account of applications and data can be found in the data and results repository for the SLEUTH project at: http://www.ncgia.ucsb.edu/projects/gig/Repository/SLEUTHapplications.html. A number of successful attempts have been made to reduce SLEUTH's computation time and to make it more efficient. In the early 2000s, different phases of sensitivity testing, for example, temporal sensitivity (Candau, 2002), land use class aggregation (Dietzel and Clarke, 2006) and Monte Carlo stochastic sensitivity (Goldstein et al., 2005), improved the performance of the model and increased the confidence of its results. Clarke et al.(2007) and Clarke (2008b) have provided brief reviews of technical modifications until about 2007. Discussed below are the technical modifications made in the recent past, to the best of our knowledge, which have helped to overcome some of the limitations of SLEUTH and to enhance its performance and applicability.

3.1. Optimal SLEUTH Metric (OSM)

Dietzel and Clarke (2007) worked on the development of an optimal SLEUTH metric (OSM) during the calibration phase to determine the best goodness of fit measure for this model. During the each step of the brute force calibration process thirteen parameters are computed, and these are used to determine the goodness of fit of the run to the known historical input data. The runs with the highest values indicate that within the given ranges, '*there is a region of the five-dimensional parameter space that may contain a peak in the model's simulation ability*'

(Dietzel and Clarke, 2008). However, it proved difficult to narrow down the parameter set which will yield the optimum result. To identify that set, studies used three different datasets (to represent the major spatial processes and patterns of urban growth) that were calibrated exhaustively (i.e. with unit increments in the parameters) and used visual interpretation of self-organizing maps to identify the metrics necessary to derive the optimum result (Dietzel and Clarke 2007; Dietzel and Clarke, 2008). Based on these results a single goodness of fit metric, known as the OSM (Optimal SLEUTH Metric, the product of the 'compare', 'population', 'edges', 'clusters', 'slope', 'X-mean', and 'Y-mean' metrics) was derived that provides the most robust results for SLEUTH calibration (Dietzel and Clarke, 2008). The source code for OSM calculation can be found on the project website at: http://www.ncgia.ucsb.edu/projects/gig/Dnload/download.htm.

3.2. pSLEUTH

pSLEUTH is a parallel version of SLEUTH developed in 2010 (Guan and Clarke, 2010). In this version of the model, the authors used an open source general-purpose *parallel raster processing programming library* (pRPL) to improve its computational performance, especially during the calibration process. The advanced features of pRPL enhanced the capabilities of SLEUTH to work efficiently with massive raster data in a shorter period of time. Further, it helped to replace simplified assumptions during the calibration stage with a more exhaustive calibration process, which can result in the production of different 'best-fit' parameter combinations than the simplified calibration process and thus produces different simulation results (Guan and Clarke, 2010). In parallelizing the model, both data parallelism and data–task hybrid parallelism (grouping the processors) were used with both static and dynamic tasking as the load-balancing strategy. To test the performance of pSLEUTH, it was applied to simulate urbanization of the continental US for 1980 and 1990 at 1km resolution and with an image size of 4948 x 3108 pixels. The results showed a great reduction of computation time for the calibration process with multiple processors; in effect it achieved a speedup of 24 using 32 processors (Guan and Clarke, 2010). The parallel version of SLEUTH and details about pRPL can be found in:
http://www.geog.ucsb.edu/~guan/pRPL/index.htm.

3.3. SLEUTH-3r

Jantz *et al.*, (2004; 2005) identified several limitations of SLEUTH, which affected the simulation of the urban areas and the performance. The problem they identified were: first, SLEUTH's bias towards edge growth, which restricts the suitable level of dispersed growth in fine resolution data; secondly, inappropriate fit statistics; thirdly, the model's inefficient memory use; and fourthly, the model's inability to identify areas where growth is more likely to occur (Jantz *et al.*, 2010). To address these issues Jantz *et al.* came up with a new version called SLEUTH-3r.

The first three limitations were addressed by modification of the source code of the original version and allowing interactivity in setting the model coefficients, and the fourth limitation was addressed by dividing the region of interest according to groups of minimum variability of the urban growth pattern by using cluster analysis and simulating each of them independently (Jantz *et al.*, 2010). SLEUTH-3r was successfully tested for the Chesapeake Bay Watershed under multiple scenarios. The modified model has been reported to be 5 times more computationally efficient, reduces memory usage by 65%, and enhances the model's ability to use economic, cultural and policy information (Jantz *et al.*, 2010). The technical details and the SLEUTH-3r version of the model can be found in http://egscbeowulf.er.usgs.gov/geninfo/downloads/

3.4. SLEUTH-GA

Genetic algorithms (GA) are heuristic methods that can simulate natural evolution to generate an optimal result. Use of GA in SLEUTH has been tested multiple times for better model calibration (Goldstein, 2004; Shan *et al.*, 2008; Clarke-Lauer and Clarke, 2011). Goldstein (2004) applied SLEUTH with a GA algorithm to Sioux Falls, South Dakota. The 2011 study used elitism and tournament selection, combining gene competition strategies, both uniform and self-crossover and mutation. The simulation tested over 200 generations, with 18 chromosomes in each run, one Monte Carlo iteration, and calibration was repeated 10 times. The results showed that 70% of the chromosomes performed better than brute force calibration technique with only one fifth of the CPU time resulting in a better goodness of fit measure (Clarke-Lauer and Clarke, 2011). In another study conducted by Shan et al. (2008), GA was used to enhance the efficiency of transition rule calibration in SLEUTH. Their modification was tested in Indianapolis, Indiana for 20 generations with 30 strings and used binary encoding, elitism and rank selection, and single crossover and mutation (Clarke-Lauer and Clarke, 2011). Their results showed that the model with GA calibration of transition rules take 6.5 hours of computation time compared to 27 hours of exhaustive search (Shan *et al.*, 2008). Recently, Clarke-Lauer and Clarke (2011) improved on Goldstein's method (2004) to reach global optima and thus better optimization results. They redesigned the calibration of the model and added choices on encoding, fitness evaluation and survival selection. These approaches were tested on the supplied demonstration 'Demo_city'data (Clarke-Lauer and Clarke, 2011). The results showed that using a GA for calibration may make only minor improvements in the goodness of fit of the model but it greatly decreases the computation time of calibration (by a factor of 5). The SLEUTH-GA source code used by Clarke-Lauer and Clarke (2011) (Clarke-Lauer and Clarke, 2011) can be found at https://sourceforge.net/projects/sleuth-ga/.

4. SLEUTH applications

The key aspects that made SLEUTH a popular land use change model were its open access, availability of source code, and ease of use (Clarke, 2005). This part of the paper provides an overview of, first, the general applications of the model in the United States and the rest of the world, followed by an overview of studies where the model was coupled with other types of social and physical models. The paper concludes with a review of applications of the model under different scenarios. Figure 2 shows the published applications of SLEUTH until 2012.

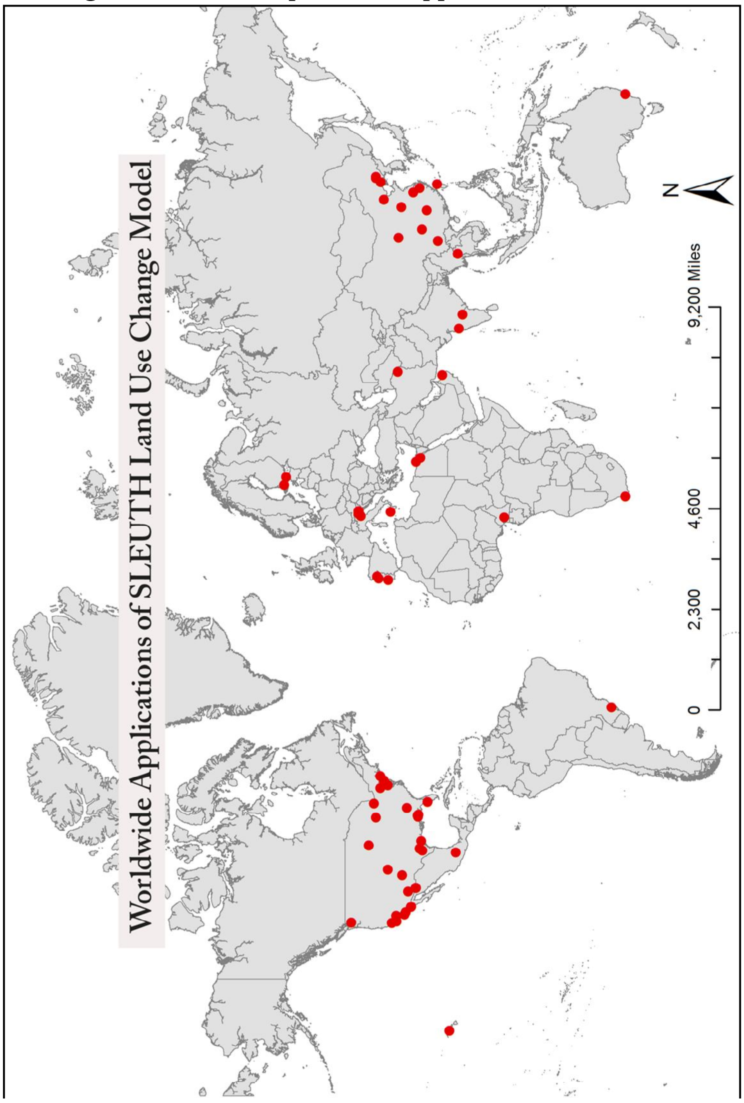

Figure 2. Worldwide Application of SLEUTH Land Use Change Model (Please see Appendix below for details)

4.1. Applications in the United States

Comprehensive reviews of different applications of SLEUTH up to 2005 have been provided in Clarke et al. (2007) and Clarke (2008). The application of the UGM started with simulation of historical urban growth in the San Francisco Bay area (Clarke *et al.*, 1997) and the Washington-Baltimore region (Clarke and Gaydos, 1998), followed by a number of applications in Santa Barbara for technical development of the model while simulating the fire regime (Goldstein et al, 2000) and the urbanization process (Candau and Clarke, 2000; Herold *et al.*, 2003; Goldstein et al., 2004). The model was applied to assess the landscape pattern stress on biodiversity in Monterey Bay, California (Cogan, 2001); to understand the effect of different urban growth forms on butterfly habitat (Bierwagen, 2003); to '*backcast*' urban extent (Goldstein, 2004), to explore theories of urban area evolution using landscape metrics in the San Joaquin Valley, California (Herold *et al.*, 2003; Dietzel *et al.*, 2005a; Dietzel *et al.*, 2005b); to study the effect of urbanization on habitat patterns of the Santa Monica Mountains, California (Syphard *et al.*, 2005); for an assessment of land use change in the Detroit River corridor in Michigan (Richards, 2002); and to investigate the effect of urbanization of surface run-off in the Spring Creek Watershed in Centre County, Pennsylvania (Carlson, 2004). Other studies dealing with urbanization affects include assessment of the Tampa Bay Watershed in Florida (Xian and Crane, 2005), urbanization in Atlanta, Georgia (Yang and Lo, 2003); Albuquerque, New Mexico (Hester, 1999); Honolulu, Hawaii (James, 2004); the New York Metropolitan Region, New York (Esnard and Yang, 2002); and the Houston Metropolitan area, Texas (Oguz *et al.*, 2004).

4.2. Applications in the Rest of the World

The first application of SLEUTH outside the United States was conducted in the Lisbon and Porto Metropolitan areas of Portugal by Silva and Clarke (2002; 2005). Other than in the US, SLEUTH has the highest number of applications in China. Rapidly growing cities like Chongqing (Huang *et al.*, 2008), Changsha City (Yin et al, 2008), Yingkou City (Xi *et al.*, 2008), Beijing (Yi, 2009), Dianchi Basin-Kunming (Lu *et al.*, 2009), Shenyang-Fushun (Xi *et al.*, 2009), Lanzhou (Xibao *et al.*, 2006 and Xie *et al.*, 2010), Hangzhou (Liu and Liu, 2009), Shenyang Metropolitan Area (Wu *et al.*, 2009), Nanjing (Zhang *et al.*, 2010), and Xinxiang city (Li *et al.*, 2010) have been simulated under 'business as usual' condition or alternative scenarios to evaluate the effect and extent of urbanization. The SLEUTH model has been also applied for mapping and monitoring urban growth in other countries such as Alexandria, Egypt (Azaz, 2004), Tijuana (Le Page, 2000) and Mexico City (Gomez, 2001) in Mexico, Cabeceiras de Basto, Portugal (Henriques, 2010), Cape Town, South Africa (Watkiss, 2008), Tampere, Finland (Iltanen, 2008), Muscat, Oman (Al-Awadhi, 2007), Gorgan City, Iran (Mahiny and

Gholamalifard, 2007), and for Pune (Kanta Kumar *et al.*, 2011) and Hyderabad (Gandhi and Suresh, 2012) in India. SLEUTH has been also used for simulating urban sprawl in Pordenone, Italy and for testing theories of entropy (Martellozzo and Clarke, 2011); for comparative study of urban sprawl among Padova-Mestre, Palermo (Italy), Helsinki (Finland), and Bilbao (Spain) (Caglioni *et al.*, 2006); for comparison of urban growth at multiple resolutions between Chiang-Mai (Thailand) and Taipei (Taiwan) (Sangawongse *et al.*, 2005); for comparison between urban growth patterns of the border towns of Nogales (Arizona, USA) and Nogales (Sonora, Mexico) (Norman et al, 2009); and for modeling informal settlements in Younde, Cameroon (Sietchiping, 2004).

4.3. SLEUTH coupling

Over the years, researchers have used the SLEUTH model in conjunction with other social and physical models, varying from loose coupling to tight coupling, to explore various issues of environmental dynamics. Arthur (2001) coupled SLEUTH with an urban runoff model to study the effect of urbanization on local microclimate and surface hydrology in Chester County, Pennsylvania. Leão *et al.* (2001; 2004) used SLEUTH in combination with a multi-criteria evaluation (MCE) of landfill suitability (Siddiqui *et al.*, 1996) in Porto Alegre City, Brazil to determine the areas suitable for landfill and thus unsuitable for urbanization in the city. Another such SLEUTH and MCE application was done by Mahiny and Gholamalifard (2011) in Gorgan, Iran, to determine the land availability for landfill and to forecast the sprawling of the town until 2050. Claggett et al. (2004) coupled SLEUTH with the modified supply demand allocation model called the Western Futures Model (Theobald, 2001), '*to assess development pressure*' based on forecasts of population growth in the Baltimore-Washington, DC region (Clarke, 2008a). Syphard *et al.*, (2007) coupled SLEUTH's urban growth model with the LANDIS landscape model to '*simulate the combined effects of urban development and high fire frequency on the distribution of coastal shrublands*' in the Santa Monica Mountains, California (Clarke et al., 2008a). Silva et al. (2008) tightly coupled SLEUTH within a '*countervailing cellular automata*' (CVCA) model and tested it in Lisbon and Porto, Portugal to promote the use of landscape ecological strategies within metropolitan planning applications.

4.5. SLEUTH and scenario modeling

SLEUTH has been used extensively for scenario modeling to evaluate alternative futures. One of the most popular goals of scenario planning with SLEUTH (Xiang and Clarke, 2003) was to evaluate policy for planning and decision making purposes.

Onsted (2002) used SLEUTH and the SCOPE system dynamics model to explore alternative futures by scenario modeling using different socio-economic variables in Santa Barbara, California. Jantz *et al.* (2003) applied SLEUTH to simulate urban land use change in the Washington-Baltimore metropolitan region under different urban policy scenarios to assess the future urbanization of the region. Similar efforts have been conducted by Berling-Wolf and Wu (2004) for the Phoenix Metropolitan area in Arizona with multiple resolutions of urban land use data, by Oguz *et al.,* (2007) for the Houston-Galveston-Brazoria CMSA in Texas and, by Rafiee *et al.,* (2009) for Mashad city in Iran. Solecki and Oliveri (2004) used SLEUTH to simulate land use change in 31 counties of New York under different climate change scenarios from the IPCC 2002. Donoso (2008) applied SLEUTH to simulate urban sprawl in Escambia, Santa Rosa and Okaloosa counties of Florida experimenting with different road gravity parameters to evaluate different smart growth strategies. Syphard *et al.* (2011) simulated urban growth patterns in San Diego, California twice using two different sources of historical data under three different conservation scenarios to evaluate the sensitivity of the model to its input data. In the past few years, the exclusion layer of the model has been used extensively to forecast alternative futures and to evaluate policies. Onsted (2007) experimented with the exclusion layer to evaluate land conservation status in California counties. Onsted and Clarke (2011) used it to evaluate urban growth under California's Williamson act in Tulare County, and Chaudhuri and Clarke (*in press*) used it to create multiple historical scenarios of political changes and to evaluate the effect of territorial cohesion of Europe on urbanization of trans-border cities of Gorizia, Italy and Nova Gorica Slovenia.

5. Conclusion

Over the last 15 years, since its first publication, SLEUTH has continuously been explored, modified and applied worldwide by the land use change modeling and planning communities. Over these years, one of the biggest criticisms and yet a strength of SLEUTH is its simplicity, which has led to an increasing number of applications. Clarke et al. (2007) and Clarke (2008a) identified multiple limitations of SLEUTH, some of which have been addressed since then, and these have been reviewed in this paper, but some are yet to be explored. With increasingly efficient computational infrastructure, new generations of geospatial data and, more interdisciplinary applications, we are optimistic that these limitations can be addressed successfully in the near future.

Acknowledgement

Details about the applications and modification of the model can be found in the SLEUTH website's Publication (http://www.ncgia.ucsb.edu/projects/gig/Pub/pubs.htm) and Repository pages (http://www.ncgia.ucsb.edu/projects/gig/Repository/SLEUTHapplications.html).
The authors would like to thank everybody who has made their work available to

us. Work on SLEUTH over the years has been funded by the National Science Foundation, the United States Geological Survey, the Environmental Protection Agency and many others.

Appendix: Worldwide application of SLEUTH

Country	City/ Region	Country	City/ Region
Australia	Sydney	India	Pune
Brazil	Porto Alegre		Hyderabad
Cameroon	Yaounde	Italy	Gorizia
China	Beijing		Pordenone
	Chongqing		Palermo
	Changsha City		Padova-Mestre
	Dianchi Basin	Iran	Mashad City
	Kunming		Gorghan City
	Shenyang	Mexico	Mexico City
	Fushun		Tijuana
	Lanzhou		Nogales-Sonora
	Nanjing	Netherlands	
	Hangzhou	Portugal	Lisbon
	Shenyang Metropolitan Area		Porto
	Xinxiang City		Cabeceiras de Basto
	Yingkou City	Oman	Muscat
Egypt	Alexandria	Spain	Bilboa
	Cairo	South Africa	Cape Town
Finland	Helsinki	Taiwan	Taipei
	Turku	Thailand	Chiang Mai
USA	Phoenix	USA	Escambia County
	Nogales		Santa Rosa County
	Monterey Bay		Okaloosa County
	San Francisco		Atlanta
	San Joaquin Valley		Oahu
	Santa Barbara		Chicago
	Detroit		Spring Creek Watershed
	Albuquerque		Sioux Falls
	Austin		San Antonio
	Seattle		New York City
	Houston		Chester County
	Santa Monica Mountains		Washington DC
	San Diego		Baltimore
	Colorado Springs		Tampa

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