# Modeling Cities and Displacement through an Agent-based Spatial Interaction Model

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**Abstract.** This paper describes a stylized model of internally displaced person (IDP) dynamics in East Africa. Displaced people often require support from national governments, international agencies or major non-governmental organizations. Anticipating the timing and magnitude of displacement events, as well as the likely locations to which displaced people will move would be of great interest to the various organizations tasked with managing such events. The paper examines three alternative modeling frameworks based on a pruned spatial interaction model, a local interaction model, and a hybrid of these two approaches. Each of the pure approaches is found to have limitations that can be overcome by adopting the hybrid approach.

**Keywords:** Internally Displaced People, IDPs, GIS, Spatial Interaction Model.

## 1 Introduction

This paper describes a stylized model of internally displaced person (IDP) dynamics in East Africa. A wide variety of calamitous events can cause such displacement. These include phenomena such as drought, flooding, ethnic conflict, and political violence. Displaced people often require support from national governments, international agencies or major non-governmental organizations. Anticipating the timing and magnitude of displacement events, as well as the likely locations to which displaced people will move would be of great interest to the various organizations tasked with managing such events.

Within this paper we present a hybrid spatial interaction and agent-based model (ABM) that is part of the larger RiftLand modeling effort (Cioffi-Revilla et al, 2011). The RiftLand ABM seeks to model human subsistence, conflict and displacement in East Africa at multiple spatial scales. The RiftLand model covers and area approximately 2.5 million km$^2$ including all of Kenya, Uganda, Rwanda and Burundi; and parts of Sudan, Democratic Republic of Congo and Tanzania as highlighted in Figure 1. Within the model, people (agents) are modeled at the household level. Ethnic and national identities are based on anthropological literature provided by Human Relations Area Files (HRAF) at Yale. The model operates at a spatial resolution of 30 arc seconds (approximately 1km$^2$) and a temporal resolution of 1 day.

Within this sub-model we focus specifically on displacement and migration of households. In order to model inter-urban crisis migration in a way that is computationally efficient, yet has plausible movement dynamics, we combine a spatial interaction model with a locally connected network model based on a stylized version of the road network. This allows us to capture both the long-range planning behavior of IDP's (agents) as well as the intervening opportunities (Stouffer, 1940) provided by smaller cities that lie between major attractors of refugee flows.

Spatial interaction modeling is one of the most applied geographical techniques for understanding flows of people and goods between locations. It places a high emphasis on the importance of place in the simulation process. It attempts to simulate/predict the interaction (e.g. movement of people) between two or more geographical locations. The notion of such models is based loosely on Newton's Law of Universal Gravitational Attraction where two bodies attract each other in proportion to the product of masses and inversely as the square of their distances apart. Relating Newton's theory to a geographical context, 'force' is identified with movements between locations, while 'mass' is some measure of the trip-generating or trip-attracting characteristics of a location such as population size, which introduces the notion of competition between places (see Briassoulis, 2000 for a further discussion). Distance may be measured not only in physical terms (e.g. network / Euclidean) but also in terms of costs or time. The gravitational model has a direct analogy in geography (i.e. the greater the distance, the lesser travel occurs through the distance decay effect which discourages flows over longer distances).

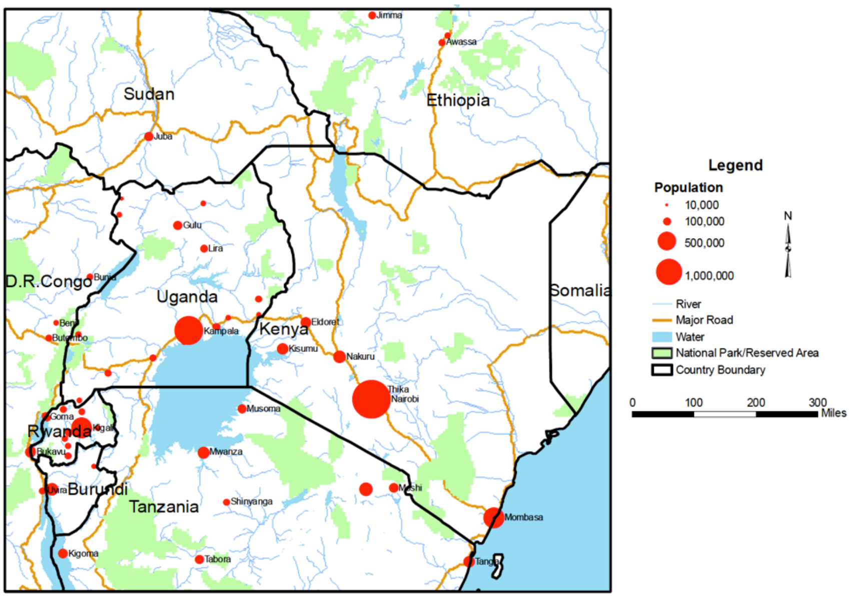


**Fig. 1.** The RiftLand model area and major population centers.

Spatial interaction models have been used to predict the size and direction of spatial flows between discrete places when changes occur to either the origin or destination of these interactions. Common applications include: migration (Stillwell, 1978); journey to work (Senior, 1979); residential location (Wilson, 2000) and retail location planning (Fotheringham and Trew, 1993). However, while they are widely used and serve as a valuable tool for geographical problems relating to flows; several key weaknesses are often identified (as highlighted by Torrens, 2000), particularly when contrasted with ABMs. These include lack of dynamics (often they work with only snap shots of time), they have weak attention to detail (often they focus on aggregates, such as aggregate flows of people and have limited spatial flexibility in the sense that they do not model micro-scale phenomena (as they model aggregates) and therefore fail to capture the how macro phenomena emerges from the bottom up. Moreover, they explain little about the behavior of individuals within the system that generate these aggregate patterns under study. ABMs can address many of these weaknesses. By their very definition, ABMs represent individuals but also they can explain how macro-level phenomena arise from micro-level interactions, while operating on numerous scales. As spatial interaction models are mathematical models, they often only consider quantitative parameters when estimating flows. This loses large amounts of qualitative behavioral information that can be incorporated within ABMs (see Heppenstall *et al.,* 2005). By combining ABM and spatial interaction models we can model action at a distance (e.g. flows of people) but use the individual agents (and their corresponding behavior) to decide to flow.

## 2 Data Preparation

This model is about how IDPs move through and make use of the absorptive capacity of the urban structure in space and time. For this reason, the primary data required for creating the model is a detailed map of urban areas. Many parts of the study area are far from major cities. For these areas, the relevant cities can be quite small - with populations as low as 5000 people. Because the model covers a large number of countries and reporting on city sizes varies widely between countries (with reporting on small cities being particularly inconsistent), we needed to create a consistently defined set of urban areas by combining 2009 nighttime lights data from the Earth Observation Program of NOAA's National Geophysical Data Center (Doll *et al.,* 2000) with population estimates from the Oak Ridge National Laboratory LandScan dataset for 2009 (Oak Ridge National Laboratory, 2010) as shown in Figure 2.

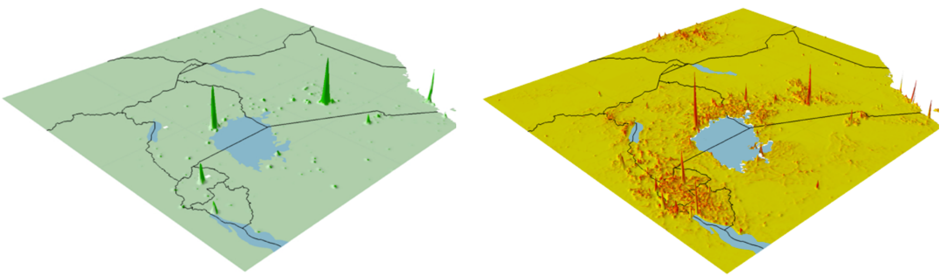

**Fig. 2.** Defining urban areas: Left: Urban areas derived rom nighttime lights. Right: Population Density derived from LandScan (yellow is low population density, red is high).

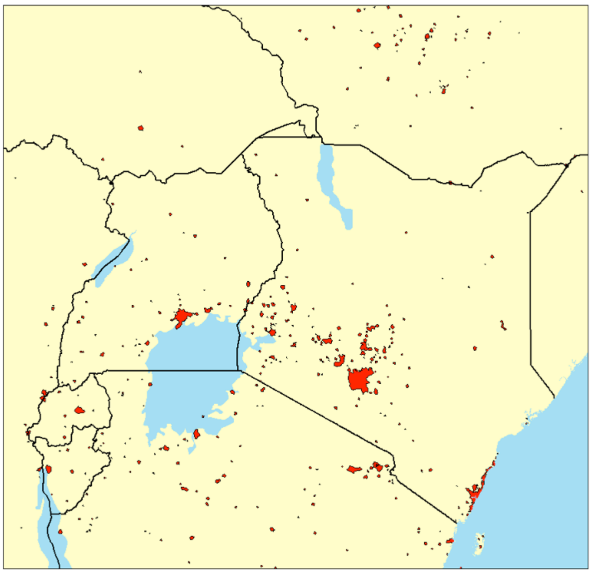

**Fig. 3.** Urban areas (red) defined by nighttime lights and population density.

Urban areas, shown in Figure 3, were defined by establishing a nighttime lights threshold, with contiguous lighted areas defining cities (see Florida *et al*. 2011). Population for each city was then calculated by overlaying these lighted urban polygons and summing the LandScan population estimates for each 30 arc second (approximately $1km^2$) grid cell within the urban area. The results generally align with published estimates for major cities and have the great advantage of producing consistent estimates over the full range of city sizes from Nairobi, with total metropolitan population of around 4 million, down to significant mid-sized places like Lodwar, Kenya, with a population of around 20,000 and numerous smaller places with populations in the mid-hundreds. Cities house about 20% of the population of the region.

## 3 Modeling

As described above, the basic idea of the model is that displaced rural people enter the urban system seeking refuge at the closest city. When that city exceeds its capacity to absorb and care for additional people, IDPs must move to a city with the capacity to deal with them. In extreme cases of displacement (e.g. the genocide in Rwanda) the flow of displaced people is so great that the urban system is completely overwhelmed and special encampments must be constructed. At this point, however, we are only examining smaller displacements such as those in Northern Kenya in 2009 (see Internal Displacement Monitoring Center, 2011) that make use primarily of the existing urban system.

In exploring how IDPs might move through the urban structure, we examine several frameworks for urban interaction: 1) a "pruned" spatial interaction model, 2) a local interaction model based on a triangulated irregular network (TIN), and 3) a hybrid of the pruned spatial interaction model with the local interaction model. The remainder of this paper will discuss the relative merits of these three frameworks.

### 3.1 Pruned Spatial Interaction Model

The traditional spatial interaction model creates a network edge (links) between each pair of cities in the model, a total of $399^2$ or 159,201 edges. If we use directed edges (which are appropriate in cases where flows are asymmetric) this number doubles to 318,402. This becomes cumbersome in terms of memory footprint, visualization, and model execution, as numerous links need to be examined for every potential movement. Fortunately, many of the links in such a model have very low weight - the interaction between two small places that are very far apart is so small as to be negligible. We leverage this property to achieve a lighter weight model by "pruning" the links such that a given percentage of the cities interaction is accounted for. Using this method, we can account for 90% of the interaction between cities with only 2,193 directed links. A network of this sort is shown in Figure 4.

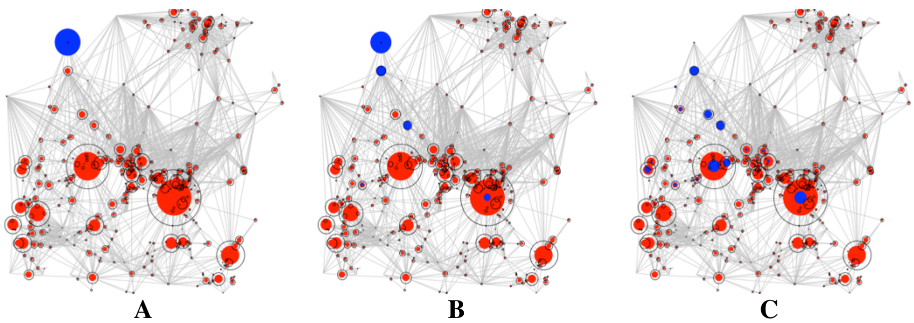


**Fig. 4.** Pruned spatial interaction model. City size is shown in red. IDP population is shown in blue, IDP capacity is shown as black circles, and links between cities as black lines. Note: City size and IDPs are drawn at different scales. **(A)** Shows large group of IDPs in a single city. (**B**) Shows IDP populations once the model has reached a steady-state in which IDPs have settled in the largest city.

While the pruning method reduces the number of links to a more manageable level, it still has some undesirable properties. Primary among these is that it predicts a large number of long distance moves - something we do not generally see with IDP movements in Africa where IDPs often move on foot or by improvised transportation. The actual movements of people between cities do not have the long-link character of traditional spatial interaction models, but rather the locally connected nature of a road network. IDPs generally do not fly from major city to major city, but rather pass through all of the small places in between - staying if there is capacity and possibly redirecting their course if conditions change. The tendency of migratory people to make use of adequate places in there path generally falls under the heading of "intervening opportunities" (Stouffer, 1940).

### 3.2 Local Interaction Model

Placing our nighttime lights based urban areas on the actual road network, and simplifying that network to have a topological structure that is suitable for network modeling presents a number of labor intensive GIS challenges. For our current purposes we use a triangulated irregular network (TIN) as a proxy for roads. The TIN approach connects nearby cities, while not skipping over intervening cities, as shown in Figure 5. In this respect, it has a topology that is much more like the road network. The advantage of this simulated road network is that it produces localized movements - from a given town to the next town down the road - rather than long-range hops that might require an airplane flight.

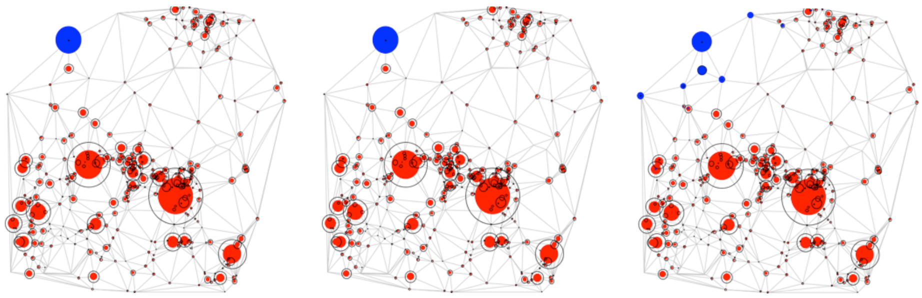

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**Fig. 5.** TIN network model approximating road network model. City size shown in red. City capacity shown as black circles and IDP population shown in blue. (**A**) Shows large group of IDPs in a single city. (**B**) Shows IDP populations migrating between cities. (**C**) Shows IDP populations once the model has reached a steady-state in which IDPs have settled in multiple nearby cities.

The disadvantage of the TIN approach is that it loses any sense of direct planning. Each city interacts only with its neighbors, so IDP movements do not take account of desirable places that are more than one link away. That said, neighboring cities that are connected to other cities with high capacity will be able to clear their IDP loads in time and accept more.

### 3.3 Hybrid Interaction Model

We can combine the good points of both of the pruned spatial interaction and local interaction models, by constructing a hybrid where the spatial interaction network is used for planning and the TIN network is used for routing. In this model variant, the a city that is over capacity examines the cities to which it is linked by the spatial interaction network and chooses a city toward which to send its excess people with a probability proportional to its interaction with that city. Rather than transferring households directly to the chosen city, however, we use the Floyd-Warshall all-pairs shortest path algorithm (see Murchland, 1965) to determine the best route to the desired city and send people to the next city on that route. This step is likely to put the receiving city well over its capacity and it, in turn, makes the same sort of calculation. A sample of the performance of this hybrid model is shown in Figure 6.

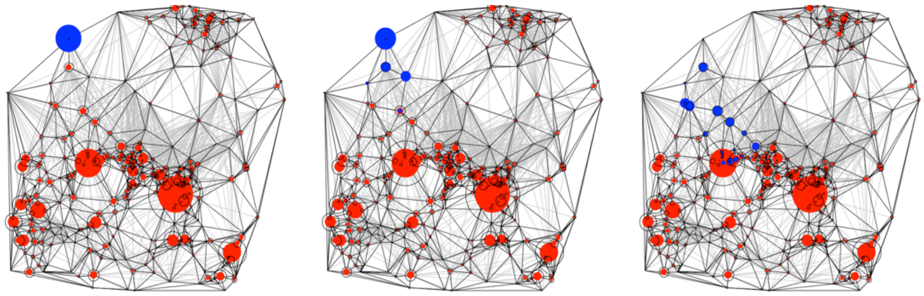

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**Fig. 6.** Pruned spatial interaction model. City size is shown in red. IDP population is shown in blue, IDP capacity is shown as black circles, and links between cities as black lines. Note: City size and IDPs are drawn at different scales. **(A)** Shows large group of IDPs in a single city. (**B**) Shows IDP populations once the model has reached a steady-state in which IDPs have settled in the largest city.

The destination of each IDP household is thus reexamined at each intermediate city and the destination city may change several times before the household finds a city with sufficient capacity to retain them. This kind of uncertainty is typical of the real world IDP experience and reflects the observed tendency of migrants to make use of intervening opportunities along the way.

# 4 Discussion and Further Work

This paper has presented a preliminary analysis of a model of IDP movement in East Africa. Much remains to be done to bring this model to the point where it has scientific validity and is suitable to guide policy. One obvious point for further work is to replace the TIN approximation of the road network with a topologically correct network based on the actual roads. This step is needed before we attempt to produce empirically valid results.

A second critical feature that needs to be added to the model before it can be applied in a broad variety of cases is a mechanism for the creation of temporary camps. When the need greatly outstrips the capacity of cities to absorb IDPs, temporary camps are generally created to house IDPs and international refugees (Internal Displacement Monitoring Center, 2011). A model of this sort will be useful for assessing the optimal placement of camps by simply adding “cities” with large capacities at critical locations. On the other hand, it would also be useful to endogenize the creation of camps - having the model add them in areas with major bottlenecks, etc.

National borders are often a major factor in the movements of displaced people - so much so that we use two different words for displaced people who have or have not had to cross a national border: the former are refugees while the latter are IDPs. It is a small adjustment to the model (as the households already have a nationality) to allow for the closing or other restrictions at national boundaries.

Currently, the model presented here stands alone as a model of IDP movement. However, it is being designed as the IDP sub-model of the larger RiftLand project discussed in Section 1. Once we have verified the workings of the model and validated its results to a satisfactory level, we will have the task of integrating this sub-model into the main RiftLand code base. We have designed the IDP model with this in mind and expect no major challenges with this reintegration, but experience will tell how smoothly the two projects merge.

Finally, it should be noted that the current model is concerned only with finding temporary places for displaced people. This model has no mechanism in it for people to return to their homes after the crisis has passed. Repatriation of IDPs is often at least as difficult as finding temporary accommodation for them (Pantuliano *et al.* 2008). We expect the repatriation process to depend on many factors that are modeled in the RiftLand model such as changing environmental conditions, ethnic stresses and political alignments. We maintain the ethnic identities and original home locations of displaced households in the current model with the intention of modeling their return once the IDP model has been integrated with its larger context.

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