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A hybrid approach to modeling territorial control in violent armed conflicts

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Abstract

Territorial control is central to the understanding of violent armed conflicts, yet reliable and valid measures of this concept do not exist. We argue that geospatial analysis provides an important perspective to measure the concept. In particular, measuring territorial control can be seen as an application of calculating service areas around points of control. The modeling challenge is acute for areas with limited road infrastructure, where no complete network is available to perform the analysis, and movements largely occur off road. We present a new geospatial approach that applies network analysis on a hybrid transportation network with both actual road data and hexagon-fishnet-based artificial road data representing on-road and off-road movements, respectively. Movement speed or restriction can be readily adjusted using various input data. Simulating off-road movement with hexagon-fishnet-based artificial road data has a number of advantages including scalability to small or large study areas and flexibility to allow all-directional travel. We apply this method to measuring territorial control of armed groups in Sub-Saharan Africa where inferior transport infrastructure is the norm. Based on the Uppsala Conflict Data Program's (UCDP) Georeferenced Event Data (GED) as well as spatial data on terrain, population locations, and limited transportation networks, we enhance the delineation of the specific areas directly controlled by each warring party during civil wars within a given travel time.

KEYWORDS
geographic information systems, hexagon grid, hybrid movement, network analysis, spatial analysis, territorial control

1 | INTRODUCTION

Case histories and social scientific theory indicate that the degree to which warring parties control territory decisively influences the dynamics of wars (Diehl, 1991). Territorial control has become central to explanations of the onset, dynamics, and outcomes of civil wars – large scale violence occurring within the borders of a country. In one of the most influential recent works on the topic, Kalyvas (2006) develops a model in which territorial control by a warring party can be complete, incomplete, or contested, and theorizes that violence against civilians should be most extensive in zones of incomplete territorial control. Other important works on civil war also highlight the role of territory. For example, Humphreys and Weinstein (2006) suggest that competition for territory creates less discipline among armed groups' fighters. Fearon and Laitin (2003) argue that civil wars are more likely to begin in countries with non-contiguous and mountainous terrain, where rebels can more easily establish a long-term presence. Mampilly (2011) analyzes how rebel groups that control territory must also develop strategies to extract revenue from, and to govern, the local population.

Territorial control is thus central to much recent work on civil war, but we lack reliable and valid measures of this concept across conflicts. Kalyvas (2006) and Humphreys and Weinstein (2006) develop sophisticated accounts of shifts in territorial control for individual conflicts. But they do not extend this approach to a range of conflicts. The absence of a measure of territorial control that can be applied across episodes of civil conflict is an important barrier to both scholarly progress and the extent to which such research can help to inform public policy. It prevents scholars from determining the degree to which findings based on individual conflicts – such as the Greek Civil War of the 1940s (Kalyvas, 2006) – can or cannot be applied to other civil wars. Furthermore, the influence of territorial control likely varies considerably across civil wars, depending on contextual factors such as the strategy of warfare, the existence of natural resource wealth that can be exploited by rebels to finance their violence, or the support provided by outside actors to governments and rebels. Reliable and valid data on territorial control across a larger number of conflicts would allow researchers to theorize and assess how such contextual factors matter for the course and outcomes of such conflicts.

Providing a stronger theoretical and empirical footing for the role of territorial control would also permit researchers to develop more sophisticated expectations and policy advice about ongoing conflicts. The Islamic State is a prominent recent example. In 2014, the Islamic State seized large swathes of territory in Syria and Iraq. It also imposed taxes on the population of this territory, produced and sold oil in large quantities to fund its operations, and recruited thousands of soldiers and supporters from the region as well as from distant states. An important policy debate concerns the degree to which these factors are connected. For example, does territorial control make it easier for the Islamic State to attract and train foreign fighters? How important is the availability of natural resource wealth for sustaining a strategy of territorial control? Does controlling large amounts of territory place a rebel group at a long-run strategic disadvantage against a campaign of air strikes that can target garrisons, transport nodes, and oil production facilities? Existing studies of civil war are limited in their ability to answer such questions because they have not been able to assess the role of territory in a large number of comparable conflicts.

The geographic perspective on war and organized violence has cogently been discussed and debated in several influential contributions to the political geography and conflict studies bodies of literature (e.g. Linke & O'Loughlin, 2016; O'Loughlin & Raleigh, 2008; Raleigh, Witmer, & O'Loughlin, 2010). From the GIScience perspective, measuring territorial control within war and organized violence can be seen as an application of computing service areas or functional regions. Service areas, also known as (drive-time) buffer, hinterland, catchment area, or market area, have been applied to many geographical, political, transportation, economic, and business questions (Upchurch, Kuby, Zoldak, & Barranda, 2004). The service area of a center is commonly defined as the geographic space over which the influence of that center is greater than or equal to that of any other center (Hanjoul, Beguin, & Thill, 1989; O'Kelly & Miller, 1989; Thill, 2015). The fundamental task of calculating service areas in Geographic Information Systems (GIS) is to delineate the region, with either an assumed geometric shape such as a circle or irregular shape based on travel cost, from or towards a central location (Farhan & Murray, 2005). Examples include the radius-based circular service area of a cell tower, or the half hour driving market area of a grocery store. Thiessen polygons and Voronoi diagrams (Boots, 1980) are related constructs that permit the spatialization of socio-economic and environmental concepts.

A warring party's control of territory can be defined as the geographic region in which troops can reach and take action within a certain response or reaction time. Based on publicly accessible violent event data, as well as other administrative and military data sources, the places and spaces where a warring party has significant influence or even dominant control can be reasonably retrieved. For example, if a warring party takes control over a location as the result of a violent clash between two rebel groups, we assume that this control extends to some area surrounding the battleground. We are able to use other data sources, such as the location of national and local capitals and military bases, to get a more complete picture of the points that are likely to be controlled by governments. By combining the different data types we are also able to determine whether the territorial control is likely to be complete, incomplete, or contested. For instance if there are rebel operations in the vicinity of a local capital, government control is more likely to be incomplete than complete. However, if the government's sovereignty has not recently been violently contested, we consider control to be complete. The locations of uncontested sovereignty, complete, incomplete, and contested control that we identify are used as the central locations in the geospatial process of territory creation. The remainder of the work is to decide the shape, size, and boundary of the controlled area, decisions similar to what is required in delineating other types of service areas.

In this research we aim to measure yearly territorial control in Sub-Saharan Africa, based on events data on battle outcomes in combination with spatial data on terrain, population locations, and transportation networks. Given the inferior transport infrastructure and unique mobility of armed groups in Africa, however, existing GIS methods such as simple buffer analysis, road network analysis, and cost-surface analysis using either a vector or raster data model are not well suited to this task. In response to this research need, we developed a novel GIS approach on the basis of Uppsala Conflict Data Program's (UCDP) Georeferenced Event Data (GED) dataset for 1989-2010 as well as spatial data on land cover, terrain, population locations, and available sparse transportation networks. In what follows, we explain the background to this approach, describe its implementation, and provide a brief illustration from the civil war in Liberia in the early 2000s. We close by discussing the limitations of our approach to measuring territorial control, potential applications of the resulting data to research questions about civil war, and how the methodology could be used to address policy questions or to develop a near-real-time system for measuring territorial control in on-going conflicts.

2 | LITERATURE REVIEW

Political scientists studying armed conflicts have occasionally used Geographic Information Science and Technology (GIST) to describe and analyze the spatial dimensions of conflict. For example, works such as Asal et al. (2016), Buhaug and Rød (2006), and Buhaug and Lujala (2005) have used GIS to assess hypotheses about civil conflict at the subnational level. Croicu and Sundberg (2012) use event data to create conflict polygons, defined as geographical areas within which conflict events occur. Although this approach allows one to sketch the area within which conflict occurs, it does not permit one to identify which warring party, if any, actually exercises control over this area or territories outside of these polygons (Farhan & Murray, 2005). A more sophisticated approach would be to derive the shape and size of territories from theoretically-motivated assumptions, similar to calculating the business market area using the Huff model (Okabe & Kitamura, 1996), or using the parabolic model of transport planning (Farhan & Murray, 2005).

We propose to measure territorial control based on travel cost, which is commonly evaluated by factors including distance, travel time, monetary cost, travel mode, traffic, or some combination. With the increasing availability of high resolution data, creating service areas by travel cost has become a more feasible approach. Technically this type of approach to service areas can be categorized as either network analysis or cost surface analysis in GIS, according to the type of geographic information used to compute travel cost. The former is commonly applied in urban environments with city street network datasets, while the latter is usually adopted in undeveloped areas where movement is not restricted to an infrastructure network. For example the 15-minute service area of an emergency center created by the network analysis approach encompasses all the urban space that can be reached within 15 minutes by an ambulance. Where and how far the ambulance can travel within this time is determined by a number of factors including vehicle speed, the topology of the road network, and real time traffic. In contrast, the cost surface analysis method is more satisfactory when only raster layers are available. Each raster grid cell is assigned with a passing cost based on information such as slope and vegetation. Calculating the service area involves determining how many grid cells can be passed through within a total cost limit (e.g. Eastman, 1989).

The geospatial delineation of territories becomes challenging when neither vector road network data nor raster layers can alone solve the problem adequately. In the context of many war-torn regions, applying only network analysis would ignore the off-road movement that is actually quite common given the deficiencies of the established

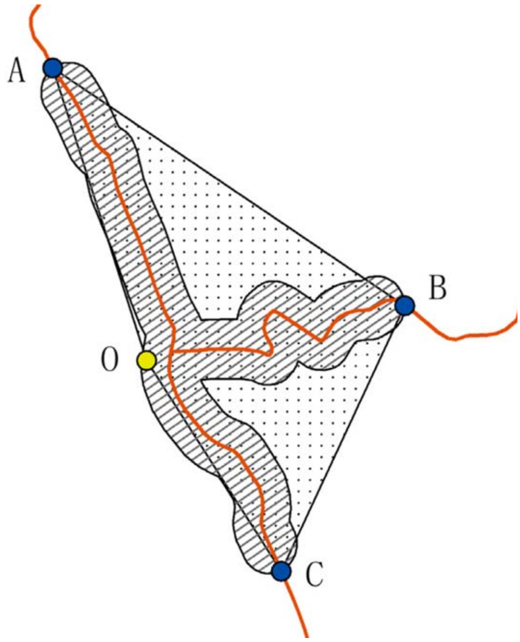

FIGURE 1 Service area with network analysis

transportation network. On the other hand, cost surface analysis would compromise the topological and attributive accuracy of those roads that do exist, however poor their quality may be.

Figure 1 illustrates a conceptual example of service area created by network analysis. In this case only a few roads (orange lines) are available for troops to move from their known control center O. Using network analysis we can easily obtain the furthest points (A, B, C) on the road network that they can reach within a certain time. However, such information is bound to underestimate the likely area controlled by the warring party. Common solutions such as drawing a bounding box with a convex hull (dotted area) or creating a simple buffer from the reachable roads (hatched area) can only lead to a very coarse approximation of actually reachable territories. The various situations of off-road movements, such as driving army trucks on the savanna, are not accounted for. Yet, troops are capable of moving in any direction on the two-dimensional planar surface with many types of military vehicles instead of being bound to drive on the one-dimensional road network. Also, control centers may not be on the road network, so that snapping them to the road network is a necessity of network analysis. Therefore, in order to measure territorial control more realistically in situations experienced in Sub-Saharan Africa, we also need to simulate the off-network movement on the basis of various raster layers (e.g. land cover type, slope), in addition to the limited road vector data.

In general, there are two ways to combine raster layers and road vector data: convert road vector data to raster layer and then perform cost surface analysis, or convert raster layer to vector data and carry out network analysis. Upchurch et al. (2004) applied the first approach to calculate the service area of light rail stations. They performed cost surface analysis on the raster cells with different impedances. In particular, they assigned extremely low impedance values to the cells traversed by any road so that moving across such cells becomes much easier. As this approach brings together raster layer and road vector data to calculate service areas, it relies heavily on the grid cell size to reasonably rasterize roads. Moreover, the rasterization process eliminates the directionality and topology of the road network. Last but not least, the rasterization process would probably compromise the accuracy of the positional and attributive information of road features as well. For instance assigning impedance would be tricky when a cell simultaneously contains segments of a multi-lane paved highway and segments of a single-lane dirt road restricted during the wet season. Admittedly, a cost-surface remains a potential solution. However in this study we choose the alternative approach as it is believed to be more suitable in our context. After converting the raster layer to road vector data, we apply network analysis with both actual road data and the converted artificial road data to represent on- and off-road movement, respectively. This approach holds great advantages, including scalability to small or large study areas and flexibility to allow all-directional travel. The detail of the procedural steps of the approach and a demonstration exercise are presented in the following.

3 | METHODOLOGY

3.1 | Step 0. Assemble data layers

Our basic assumption when calculating territorial control is that a warring party, i.e. a government or rebel group, has effective military control of the area where its troops can reach and take action within a certain response or reaction time, centering on the location already known to be under its control. In other words, our primary task is to delineate the drive-time buffer surrounding the center locations. Here we retrieve these locations from several sources: the UCDP GED violent event data, major cities, and government military bases in the study area.

The GED records a set of clearly specified warring parties and geocoded locations of battles between these parties, as well as acts of lethal violence directed at civilians (Sundberg, Lindgren, & Padskocimaite, 2010; Sundberg & Melander, 2013). More specifically, we make use of a subset of the GED to which additional variables have been coded detailing which actor initiated a battle and which actor controlled the battleground afterwards (Strandow, 2012; Strandow, Findley, Marineau, & Wu, 2013). This dataset contains information for about 21,000 directed dyad clashes in Sub-Saharan Africa from 1989 to 2008. By combining information about initiation and control we are able to determine whether a warring party defended, conquered, or otherwise contested a location. We connect these observable events to our range of territorial control by assuming that an instance of successful defense, in a previously uncontested area, suggests *complete* control of the territory. An instance of conquest, or repeated cases of successful defense, suggests unconsolidated or otherwise *incomplete* control. If both warring parties control different parts of a location, this partial control is termed *contested* control. We also label control as contested if a location switches hands several times during a year or if several areas of control overlap geographically.

In the empirical material on violent events, we find that it is not always possible to know whether warring parties were actually trying to assume territorial control. In the conflicts we study, actual attempts to control territory commonly occur alongside uncommitted low-intensity raids. There are for instance ambushes on moving columns where neither party has an interest in claiming the territory. We do not presently lump these sorts of events into the contested control category, since we want to ensure that this category illustrates direct territorial contestation. We instead flag such events as either a warring party's *area of interest* – if we know who initiated the clash – or as an *unclear clash* when we lack details.

Although information about areas of interest and unclear clashes do not directly inform us about the continuum of territorial control between warring parties that we seek to uncover, it is still useful for our purposes. By knowing about these areas where government sovereignty is in some manner contested, we are able to delineate in which areas the government's sovereignty is not contested. It is this *uncontested sovereignty* that we use to determine whether the presence of capitals and government military bases signify complete or incomplete control. For example we can reasonably assume a major city or a government military base is under complete governmental control if it has not suffered from any recent violent clash, and that it is under incomplete control if the area has recently experienced violence. In this article we obtain all provincial cities and government military bases as the centers of default governmental control. Information about actual territorial control following violent events takes precedence over this assumed government control. If rebels take over parts of a capital, that capital is moved to the contested control category.

Besides information on territorial centers, the other essential aspect of calculating controlled areas is about movement, which includes the transport mode, transport infrastructure, and movement speeds in various situations. According to the literature, the troops of warring parties in Sub-Saharan Africa are largely motorized. The vehicles enable the troops to move at relatively high speed on the road and an acceptable speed off the road, e.g. on the savanna. The condition of the transport infrastructure in Sub-Saharan Africa makes it crucial to consider both on- and off-road movement. In this research, after systematic comparison[1] of digital road and railway data sources for completeness and accuracy, we chose the data layer from EUROPA Technologies (https://www.europa.uk.com/) given its greater completeness and accuracy over our study region and period of time. Most existing roads on this continent are unpaved roads and numerous small

TABLE 1 Maximal speed reference table

Land cover type	Maximal speed (km/h)
Road	35
Railway	20
Water	0
Evergreen Needle Leaf Forest	5
Evergreen Broad Leaf Forest	5
Deciduous Needle Leaf Forest	5
Deciduous Broad Leaf Forest	5
Mixed Forests	5
Closed Shrublands	5
Open Shrublands	7.5
Woody Savannas	7.5
Savannas	10
Grasslands	10
Permanent Wetland	5
Croplands	7.5
Urban and Built-Up	10
Cropland/Vegetation Mosaic	10
Snow and Ice	5
Barren or Sparsely Vegetated	10

trails of lesser significance not incorporated in the model. Although a full assessment of the quality of the road data layer remains elusive, the hybrid raster/vector process used to delineate controlled territories mitigates its impact on the overall quality of the product. Thus, the process itself will remain valid when better data become available.

Given the inferior condition of roads in Sub-Saharan Africa and that off-road movements are commonplace, we have also collected geographic raster layers including Digital Elevation Model (DEM) and land cover type from public sources such as USGS (http://www.usgs.gov/) to model off-road movement in a way that is more consistent with terrain conditions. We refer to the Intelligence Preparation of the Battlefield Field Manual (https://fas.org/irp/doddir/army/fm34-130.pdf) to obtain the theoretically maximal driving speed on each type of land cover. A lookup table of speeds (Table 1) for road, railway, and each land cover type provides a full specification of movement friction across the study region. Also, we calculate slope across the landscape with DEM data and quantify slope's influences on driving speed as the "Slope's Impact" as reported in Table 2. Moreover, the impedance of crossing a river is considered. Given the fact that the spatial resolution of land cover raster data is usually too coarse, e.g. 500 m, to represent most rivers, we obtain the vector data of rivers from EUROPA Technologies. We then assign the "River's Impact" as 0.5 if an artificial road segment intersects with any river.[2] In the following territorial delineation process, we calculate speed as *Equation* 1. For example, the on-road speed with a 6-degree slope will be 17.5 km/h, while the off-road speed on grasslands with slope under 5 degrees but

TABLE 2 Slope's influence on speed

Slope (degree)	Difficulty	Slope's impact
<5	Easy	100%
5-10	Moderate	50%
10-20	Hard	20%
20-40	Difficult	10%
>40	No-go Situation	0%

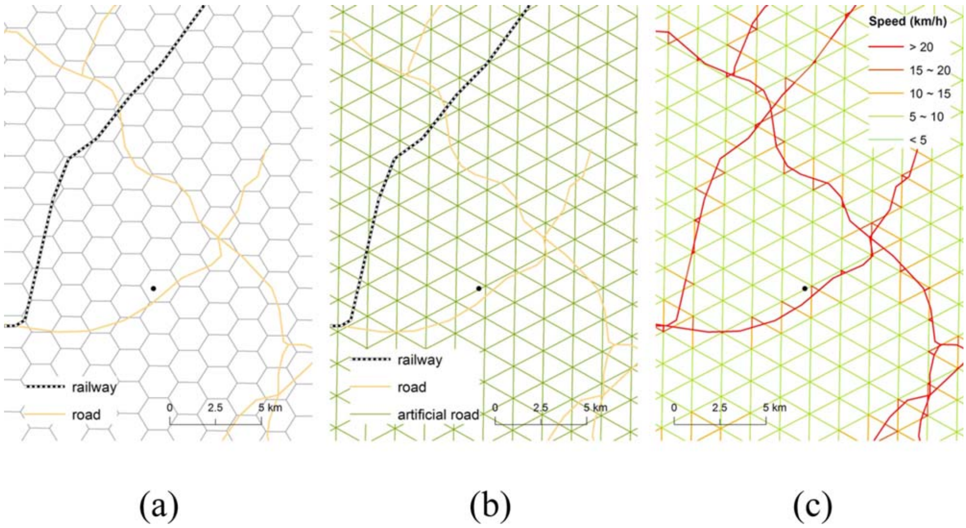

FIGURE 2 (a) Real roads, railways, and hexagon fishnet; (b) real roads, railways, and hexagon-fishnet-based artificial roads; and (c) a hybrid road network with corresponding speed

intersected by a river will be 5 km/h. Under these assumptions and with these prepared input datasets, the next step is to build the network and create the service area. We introduce our main algorithm step by step as follows:

$$\text{Final Speed} = \text{Maximal Speed} * \text{Slope's Impact} * (\text{River's Impact}) \tag{1}$$

3.2 | Step 1. Build the hybrid road network

We combine on-road and off-road movement by performing network analysis on a hybrid transportation network consisting of both real and artificial road data. The key is to build this hybrid network, especially the artificial road for simulating off-road movement. Moving off-road can be very complex, however. Technically a warring vehicle can move in any direction on any passable terrain. Particularly in Sub-Saharan Africa where most roads are unpaved, a warring vehicle is able easily to switch between moving on- and off-road. On the other hand, simulating off-road movement can be rather simple but coarse. For instance, the cost surface analysis mentioned previously is such a solution but it would ruin the directionality and topology of road networks if combined with real road data. In this study we seek a balanced but efficient alternative in order to avoid extreme complexity while preserving as much accuracy as possible.

To this end, we first create a hexagon fishnet covering the entire study area (as shown in Figure 2a). The choice of the hexagonal shape is a trade-off between computational efficiency and result accuracy. Here we set the length of a side to 1 km. Next we obtain the center of each hexagonal cell and connect all the nearest neighbors as an artificial road network. The real roads and railways are then integrated into this network, and the topology is built to have junctions between real roads/railways and artificial roads. Illustrated as Figure 2b, the hybrid road network is comparable to a regular road network where the real road/railway is like a highway system allowing high-speed travel, and the artificial road is like a local street leading to every neighborhood. After assigning the corresponding speed calculated with Equation 1 to each small road segment, we finally build an integrated hybrid road network as shown in Figure 2c.

3.3 | Step 2. Create service area with network analysis

The next step is to perform service area analysis on the hybrid road network. The two necessary input data are the starting point and the road network. Figure 3 shows an example of a service area. The blue point is a violent conflict event in 2003 between the Ivoirian-backed Movement for Democracy in Liberia (MODEL) and Liberian government military forces. The winning side is MODEL. Here it is used as the center location or starting point to delineate MODEL's territory. By setting a travel time limit, e.g. one hour, the algorithm will simulate a movement away from point O

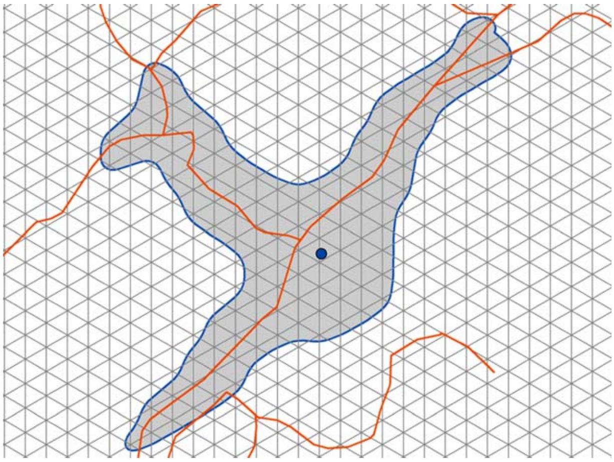

FIGURE 3 An example of calculated territory: real roads in red, hexagonal cells in black, and controlled territory are shaded and surrounded by blue

along the hybrid road network. Because the allowed speed on each road segment varies, the moving process becomes difficult on some parts but smooth on others. Using the Network Analysis extension of ArcGIS, we calculate all the network segments that are reachable from point O within an hour. Then we identify the hexagon grid cells containing these reachable network segments and smooth the outline using the Polynomial Approximation with Exponential Kernel (PAEK) technique. After all these steps, we obtain a simulated one-hour controlled territory of MODEL, as illustrated by the shaded region surrounded by blue lines in Figure 3. In other words, the MODEL warring party established such a territory after their winning battle against the Liberian government. Assuming it has a garrison located at the blue point, MODEL can undertake effective military operations in an hour at any place within this territory.

Observing the geometry of this territory, it is clear the real road has an accessibility advantage over artificial roads. The troops of MODEL can first get on the real road and travel quickly towards the northeast, northwest, and southwest. The troops have the option to get off the real road at any point and travel along the artificial road at a lower speed. That is why the territory includes the corridor area near the real roads as well. Moreover, the troops do not necessarily have to travel along the real roads. If any unusual event happened in the southeast, the troops can also travel less quickly off the real road towards the event location. Overall, the real road and railway network is critical in the territory-creating process and it dictates the final shape of the territory. Artificial roads are also essential in the algorithm as they reasonably simulate the off-road movement and enable flexible switching between on- and off-road travel.

3.4 | Step 3. Resolve overlapping territories

Following the above steps, we can delineate the territory for each center location, including conflict events, major cities and military bases. One difficulty is that this procedure can lead to overlapping areas of control since events are collapsed to calendar-year time intervals. If two conflict events happened in two different years, we can automatically use the more recent one to update the previous one. However if two conflicts happened in the same year, we need additional information including the controlling warring party and degree of control to resolve the overlapping issue. If the overlapping area belongs to two territories controlled by the same warring party, and their degrees of control are also the same, i.e. both are "Complete Control" or "Incomplete Control", then we merge these two territories into a larger one. If the overlapped area belongs to two territories controlled by the same warring party, but their degrees of control are different, e.g. one is marked as "Complete Control" and the other as "Incomplete Control", the overlapped area is controlled by this party, and we assign the entire territory as "Incomplete Control". The rationale behind this solution is that the lower level of control always takes precedence over an area of more complete territorial control. If the overlapped area belongs to the territories controlled by different warring parties, we isolate the area as a new region whose control situation is classified as "Contested Area". Cases where more than two parties or two events are at play are handled similarly.

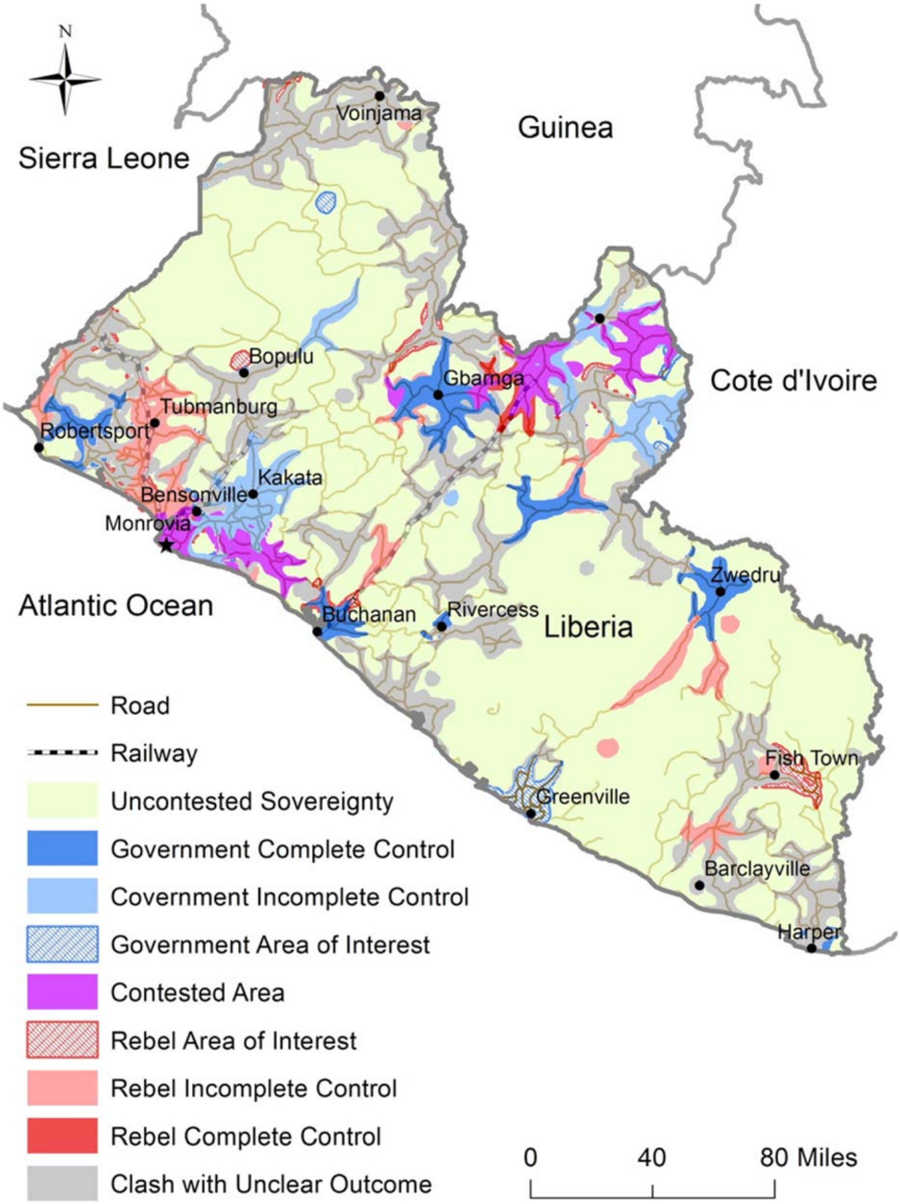

FIGURE 4 Territorial control in Liberia, 2003, based on one-hour travel time

3.5 | Step 4. Visualization

The final step is to visualize territorial control on annual maps. Here we select one of our study countries, namely Liberia, as an example. Figure 4 illustrates the territorial control in 2003 based on one-hour travel time. We first map the "Uncontested Sovereignty" symbolized by light green within the country's borders. This area fills large sections of the country where there are no violent activities or no non-government actor controls territory. Then we use a diverging color scheme to illustrate the situations from complete control by the government to the complete control by rebel groups. Mapping areas controlled by the government, we differentiate the degree of control with blue for complete control, light blue for incomplete control, and blue hatch lines to represent area of interest. We map rebel groups' territorial control in the same fashion, with red, light red, and red hatch lines representing complete control, incomplete control, and area of interest, respectively. The overlapped regions between territories of government and any of the rebel groups are independently labeled as "Contested Area" and are colored in purple. For the clashes lacking details of outcome we color their influence regions as grey to indicate the non-peaceful yet unclear situation of control. From the map we can observe evidence of the impact of roads on the shape of territories. A few exceptions are the small and roundish territories in the maps, which are calculated purely by off-road movement since there is no road or railway available in those areas. The map indicates a chaotic political situation in Liberia in 2003. A significant proportion of the land is suffering ongoing violent conflicts or under some sort of control after military operation. Most major cities including the capital Monrovia are popular targets of both sides. No clear conclusion of the political tendency can be drawn as both the government and rebel groups take control of sizable territories. Moreover, the evident and scattered purple regions manifest the violent contests that were the theme of the country's political condition at that time.

4 | DISCUSSION AND CONCLUSIONS

In this article we presented a novel GIS approach to calculate territorial control of political and military groups in Sub-Saharan Africa based on travel cost and a comprehensive database of violent events. The key innovation of this method is to consider both on and off-road movements through the application of network analysis on a hybrid transportation network with both real road data and hexagon-fishnet-based artificial road data. The hexagon-fishnet-based artificial road is well-suited (in terms of accuracy and scalability) to the task of simulating off-road travel, given the limited information available. The geometric property of the hexagon guarantees all-directional travel with minimal directional and length distortion when moving along the artificial road. Also, the hexagonal fishnet provides a good trade-off between computing efficiency and the resulting resolution. Compared with existing GIS approaches of calculating service areas, our approach stands out as a solution for making use of vector data and raster layers simultaneously to combine on-road and off-road movements. Moreover, all the steps of our approach can be implemented easily with existing functionality in common GIS software.

The products of our approach, i.e. calculated territories in a vector data model of GIS, can be utilized in a number of ways. Instead of a single static map like Figure 4, a series of maps can be drawn to illustrate the temporal changes of the political control situation. (The animated figures are available in the online version of the article). Figure 5 consists of all annual maps of Liberia in our 1989-2003 study period, except for years 1998 and 1999 which have no record of violent event. The collection of maps is an explicit way of showing how the situation of territorial control varied over time. The anti-government rebel groups carved out their territories in the early 1990s and maintained their dominance until a series of peace agreements culminated in the election of rebel leader Charles Taylor to the presidency in 1997. During the two years of relative peace that followed, the government of Liberia reestablished its sovereignty. Discord still simmered and surfaced again with clashes initiated by the recently established Liberians United for Reconciliation and Democracy (LURD). The anti-Taylor rebellion was later expanded to include the rebel group MODEL. Figure 5 illustrates the back and forth switch of territorial control that followed between 2000 and 2003. Eventually the rebels expanded their control and came close to conquering Monrovia. In 2003 a transitional government was established and Charles Taylor was ousted (UCDP Conflict Encyclopedia).

Another meaningful direction of application is to extract useful information covered by the territories with GIS techniques. Figure 6 shows the area of control/contest in each year. Linking these numbers to the annual maps in Figure 5, we can confirm our observation that in the mid-1990s the rebellion consistently achieved a greater proportion of territorial control than the government. After the regime change and the conflict resurgence in 2000, Figure 6 complements Figure 5 in illustrating the rebels' great efforts in securing territory up until 2001. When the government was further pressured in 2002, it managed to effect an increase in territorial control, but in 2003 the rebels' territory expanded again. However, most rebel territories are categorized into "Incomplete Control", which implies an unstable reigning situation. The region labeled as "Contested Area", on the other hand, maintained a relatively fixed total land area, although their locations changed frequently across space as the front lines shifted. The land areas in Figure 6 can

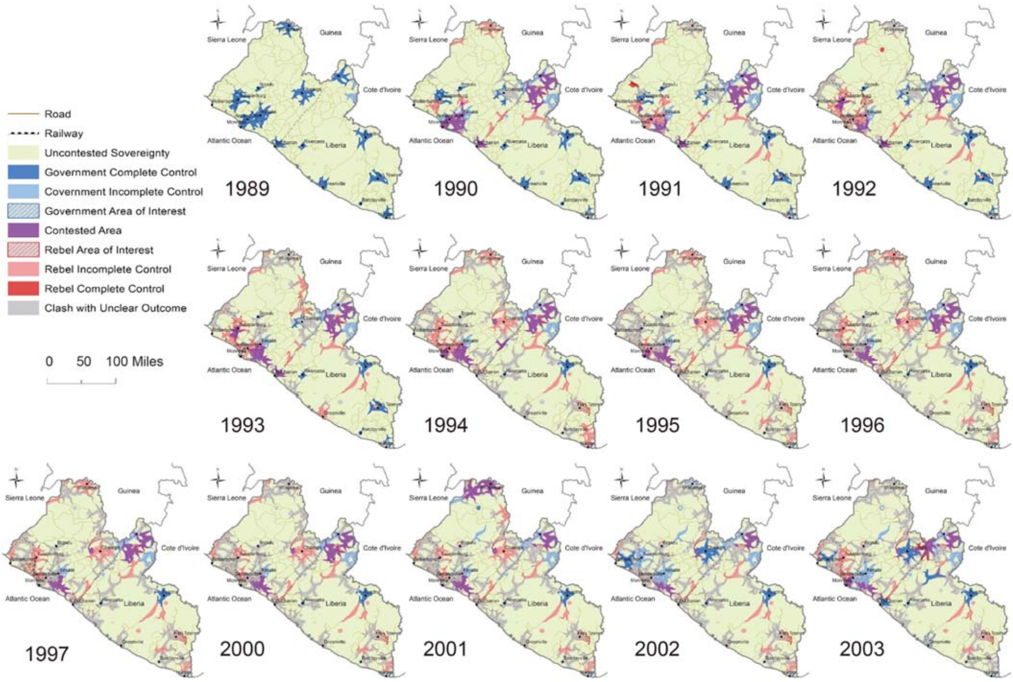

FIGURE 5 Annual maps of territorial control in Liberia

be replaced by other information, for example population or natural resources, to draw specific conclusions for other research topics.

Our specific application is based on event data detailing the location and outcome of battles and other conflict events in Sub-Saharan Africa. However, it should be noted that this approach can, with appropriate modifications, be

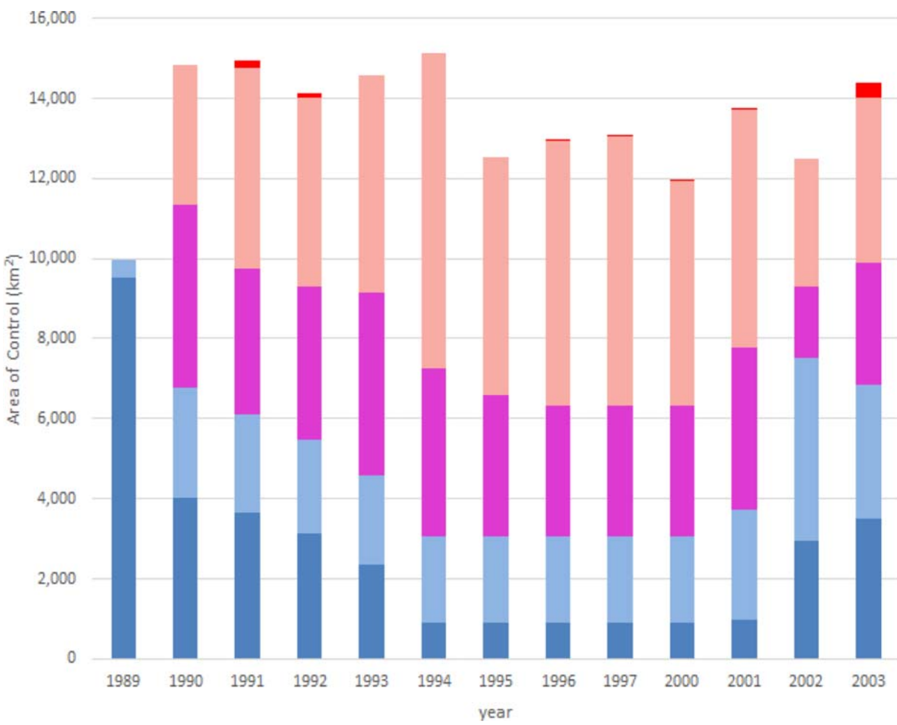

FIGURE 6 Temporal changes of area of control in Liberia

extended to other data sources or, indeed, entirely different research domains. For example, measuring territorial control in civil war requires knowledge of the date, location, warring parties, and outcome of individual conflict events. Such information could, in principle, be collected from other data sources in addition to the UCDP's GED on which we rely; examples might include the Armed Conflict Location and Event Dataset (Raleigh, Linke, Hegre, & Karlsen, 2010), the Integrated Crisis Early Warning System (ICEWS; see Boschee et al., 2015), and the Phoenix event data project (Schrodt, Beieler, & Idris, 2014). Note that these sources of data are updated monthly (or, in the case of the Phoenix data, daily), which with sufficient resources could permit the creation of a near real-time system of measuring territorial control during ongoing conflicts. Such a system could prove useful for forecasting policy-relevant events such as the location of terrorist attacks and violence against civilians, or the origins and direction of refugee flows. We applied this methodology to derive zones of varying degrees of territorial control in civil wars, basing the zones on information about specific conflict events. As suggested in the introduction, the resulting data should prove useful for addressing a number of outstanding questions about the role of territorial control in armed conflicts. At the same time, it is important to recognize that this approach has limitations that may restrict its ability to effectively address some of these research questions regarding civil war as well as its applicability in other domains. Validation of some of the assumptions of the methodology (such as drive times, speeds) against expert knowledge of specific conflict zones remains a priority. In that respect, sensitivity analysis may prove to be an important component of any future study of territorial control in situations involving armed conflicts.

NOTES

[1] We evaluated data from EUROPA Technologies (https://www.europa.uk.com/), Digital Charts of the World (http://www.diva-gis.org/gdata), NASA EarthData (https://earthdata.nasa.gov/), African Development Bank Group (http://www.infrastructureafrica.org/), and OpenStreetMap (https://www.openstreetmap.org/).

[2] We assume crossing a river does not influence the speed on road or railway if the original road/railway data are not interrupted at the intersection with rivers.

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