Using Network Analysis to Evaluate the Cascading Impacts of Crises on Service and Market Systems

Wetterwald Jeremy,

Country Coordinator, IMPACT Initiatives

Yaroslav Smirnov,

Senior Data and GIS Officer, REACH Initiative

Introduction

Risk assessments are a key component of disaster risk management and critical pillar of the United Nations Sendai Framework for Disaster Risk Reduction 2015 – 2030 under priority 1: understanding risk (United Nations, 2015). They enable decision makers to recognize risks and design effective mitigation strategies and are “a critical foundation for managing disaster risk across a wide range of sectors” (The World Bank, 2014, p.21). Risk is widely conceptualized as a factor of i) hazards, ii) exposure and iii) vulnerability (ibid). While there are slight differences in semantics in the literature, the underlying questions for analyzing risk are: understanding the hazards that threaten populations or assets, estimating exposure to these hazards and the capacities or vulnerabilities that influence negatively or positively the impact of hazards. Hazards refer to events that can cause harm such as floods, landslides, mines or fires. Exposure refers to the people and assets that can be harmed or damaged if the hazard occurs at a specific time or location, while vulnerability defines the specific characteristics of people and assets that can either increase or reduce their ability to cope with shocks.

One critical component of the risk equation is geography. The physical location of people and assets very much defines the likelihood and impact of a specific hazard which make geographic information systems (GIS) a critical tool of any risk assessment strategy. For example, the Global Risk Assessment Report (UNISDR, 2015) used a mix of open source data to create a global model of multi-hazard average annual loss. The increasing availability of open source GIS solutions and data is recognized as a key development in global efforts to understanding risk (The World Bank, 2014), with geospatial modelling of disaster risk is now being a key pillar of research in the sector (United Nations, 2015). On the hazard element of the risk equation there are multiple initiatives that seek to understand hazards both from a historical and probabilistic lens. For example, using remote sensing the United States National Aeronautics and Space Administration (NASA) currently maps high temperature events through its Fire Information for Resource Management System (FIRMS) which shares near real-time (NRT) active fire data through a mix of satellite imagery products (NASA, 2018) at a global scale. On floods the United Nations (UNISDR, 2018) has developed global riverine flooding model accurate at a level of 1 square kilometer. These initiatives have significantly improved the ability of disaster risk managers to understand where hazards have occurred historically and where they are the likely to happen in the future. On the exposure element of the risk equation similar progress has been made. Using remote sensing the Joint Research Centre (JRC) (European Commission, JRC, 2018) has created a global human settlement dataset that estimates population within a 250m area. Similar models have been made by other research entities notably the Gridded Population of the World (Center for International Earth Science Information Network, Columbia University, 2016) and the World Population Project (World Pop, 2018). Also, using somewhat comparable approaches UNISDR created a GDP exposure layer within a 1 square kilometer area. By overlaying hazard and exposure maps, estimating exposure to hazards has become increasingly accurate, reliable and comparable with different geographic lenses (national, regional or district).

A limitation of a static overlay of hazard and exposure GIS data is that is that it simplifies the dynamic nature of disasters and the complex networks of human settlements. Indeed, most disasters occur at a specific time and space. Riverine floods will affect river banks until water is drained, wildfires will affect forests and communities until they are controlled, landmines and unexploded ordinances of war will limit access to certain areas until they are cleared. Other phenomena such as desertification, climate change or nuclear disasters also lead over time to some areas being inaccessible. These physical geographies can be identified using various data collection methods including satellite imagery analysis, direct observations or key informant interviews with communities affected by a disaster amongst others. However, the complexity of human settlement networks also creates indirect consequences of disasters. An earthquake in a capital city that destroys a tertiary health facility will not only affect the residents of the city but the entire health system that depends on it for complex procedures or tests. Cities and smaller human settlements can be analyzed as complex systems organized around critical resources and basic infrastructure (Batty, 2008) that need to be better understood for adequate risk management strategies. Understanding the catchment areas of geographies both directly and indirectly affected by disasters; is critical to improve disaster response to all affected communities. To address this challenge this research presents how using network analysis and GIS can provide a dynamic understanding of risk for evidence-based disaster risk management. First the paper will explain some basic concepts of systems thinking and network analysis applied in urban environments as a background to the research. The methodology and limitations section will cover the main primary and secondary data used in the analysis which is followed by a case study of how network analysis was used to evaluate the cascading impacts of disasters in a densely built environment affected by conflict.

Systems thinking and Network Analysis Applied to Urban Environments

Systems theory is a field of research focused on the understanding of systems. Systems can be defined as 'an interconnected set of elements that [are] coherently organized in a way that achieves something' (Meadows, 2009). It seeks to better understand the interaction between different elements of a system to estimate how changes in one component will affect the others due to interlinkages between its parts (ibid). The internet, cities, climate and social relationships can all be analyzed using systems thinking. There are varying degrees of complexity of systems that researchers can study: simple systems abide to certain easily measurable laws while chaotic systems have less obvious linkages that produce less predictable outcomes (Rickles, 2007). Using the example of a healthcare Rickles (ibid) explains how the removal of a nurse in a healthcare system will have limited impact on the overall quality of health services and inversely how increasing the number of nurses might not lead to better outcomes. A tool to understand complex systems such as cities are networks (Newman, 2010; 31). In general networks can be broken down in two components: nodes and edges. Nodes are points through which information, people, interactions and goods transit. Edges are the connections that link nodes in a network. The internet is probably the world's most popular network which connects billions of people through telecommunication infrastructure. Network analysis is useful given that studying relations between the components of the network will enable a better understanding of how the system will react to a certain event (ibid; 2). For example, a node that connects a dozen of edges will likely be more critical the one that connects only three. Using transport infrastructure as an example, a railway station that connects ten cities will be more critical than one that connects three (assuming comparable city sizes).

The use of network analysis in urban environments has been used to describe and analyze geospatial patterns of built environments: from transport, shelter density to utility planning (Sevtsuk & Mekonnen, 2012). While these tools have successfully been applied in improving the design of modern cities, its use in disaster risk assessments has been limited. Jones & Faas (2016) studied how social networks play an important role in disaster response and recovery from a crisis affected and insititutional point of view, but the use of network analysis for understanding the dynamic nature of how communities access goods and services in post-crisis settings has been seldom explored. Nonetheless, agglomerations, cities or villages are complex network systems connected by infrastructure. By applying this to human settlements and depending on the level observation, a highway can be the edge that connects two urban centers of more than 50,000, while a single road will be the edge that connects two villages of a few hundred people. The impact of a disruption on a highway will be far greater than that on a single road as the flow of goods and people that transit through this 'edge' is much greater. As a result, the entire urban network that was dependent on this flow for supplies of goods or labor will be affected. A clear example of the cascading consequences of disasters is the Fukushima Daiichi nuclear disaster in March 2011. After a 9.1

magnitude earthquake hit the eastern coast of Japan, a 15m tsunami reached one of the nuclear power plants of Japan causing a failure of its cooling system and the largest nuclear incident ever recorded after the Chernobyl accident. Some 140,000 people had to be initially evacuated and as of March 2018 close to 50,000 are considered evacuees. The total area of ‘evacuation designated zones’ is of 371 km^2 or 2.7% of the total area of the Fukushima prefecture. The cascading consequences impact of this disaster were i) the disconnection from the Japanese grid, and ii) the displacement of more than 100,000 people which had to integrate new communities that should provide shelter, food, water, utilities and employment with a residual displaced population of 50,000. By using network analysis, it is possible to try and better understand how disaster affected communities adapt to the complete disruption of their historical geographical connections to new ones. This can be conceptualized through the term of ‘reorganized communities. This paper presents an attempt at trying to model connections between areas to better understand the impact of disasters on urban systems.

A key concept in describing ‘reorganized communities’ is the notion of catchment areas. Historically cities and human settlements have developed around access to critical resources and within constraints from natural geography to form organic areas (Rose, 2018). Rivers, mountain ranges or forests have significantly shaped the human settlements of today and the communities that inhabit them (Marshall, 2015). Apart for a few of cities built in areas with no geographical feature, geography is a key factor that explains the location, size and outline of modern cities. The mostly organic nature of cities and settlements entail that the administrative boundaries that define them will be closely aligned with their organic boundaries. Disasters significantly disrupt this historic and organic environment by destroying the critical infrastructure and social connections that link human societies. Thus, disasters force communities to organize in new ways until these organic structures are restored. Using network analysis enables risk assessments to better understanding and map these dynamics by i) mapping catchment areas ii) describing these areas and iii) understanding changes to these networks.

Methodology and Limitations

This paper capitalizes on research conducted in eastern Ukraine by REACH[1] and funded by the Office of the US Foreign Disaster Assistance (OFDA). The conflict in eastern Ukraine has been ongoing for more than 4 years and killed more than 10,000 people (UNOCHA, 2018). After negotiations between the Ukrainian Government and the separatist areas of Donetsk and Luhansk the conflict is now concentrated a 467km contact line which has effectively separated the major urban centers of the region from their core urban peripheries. Up to 1 million people cross this line via five checkpoints, however this remains a high risk and long procedure including a 7-hour waiting time for crossing (ibid). The restriction on the movement of people in goods has led to the reorganization of the socio-economic fabric of the Donbas due to disruptions of access to basic services and employment networks (REACH, 2017). While the original research focused on conflict related hazards and restrictions of movement the approach can be replicated in other types of crisis.

This assessment was designed in close consultation with the main providers of humanitarian aid active in Ukraine. As the Ukrainian crises entered its 4th year, research priorities shifted from humanitarian needs to understanding local capacities. Capitalizing on the area-based assessment (REACH, 2017), REACH (2018) published the capacity and vulnerability assessment for the district of Yasynuvata. The main research question of the study was the following: How have changes in demand and supply for goods and services in conflict affected area impacted the quality of basic services and markets?

To map catchment areas REACH used a household survey representative at a 95% confidence interval and 7% margin of error randomly selected through a two stage, stratified random sampling method. Using a combination of different population figures from the Ukrainian state statistics service, REACH used ArcGIS to draw random points based on a precise sampling frame. Enumerators collected data in person at the household level to

[1] REACH is an initiative of ACTED, IMPACT and the UNOSAT that seeks to inform more effective humanitarian action through assessments, capacity building and GIS

collect information on where people accessed basic services before and after the conflict. This data was cleaned and processed through within a R programming environment and QGIS and mapped using ArcGIS.

The main limitations to this study revolve around limited availability of accurate population data due to conflict induced displacement. Nonetheless, the network data was weighted for population estimations to better understand the role of each node within the network using a combination of household and key informant data to improve accuracy of the responses. This was sufficient for the purpose of the approach which is to identify how communities have reorganized and where are the new centers for accessing goods and services following a crisis. While the example focuses on a conflict setting the approach can be easily replicated in other contexts related to both technological disasters such as nuclear disaster or to large-scale natural hazards such as wildfires or earthquakes. It could also be useful in slow onset crises like desertification or droughts which create long term and mass displacement from rural areas to urban centers.

Defining Services of Interest – A Simple Taxonomy

To map catchment areas requires a simple framework that defines essential services and places for exchange of goods and services. This section presents a basic taxonomy of service infrastructure.

The size of service and market networks depends on their complexity. The table below shows the main categories of services and markets that can be studied using network analysis and their relative size.

Table 1. Taxonomy of basic services

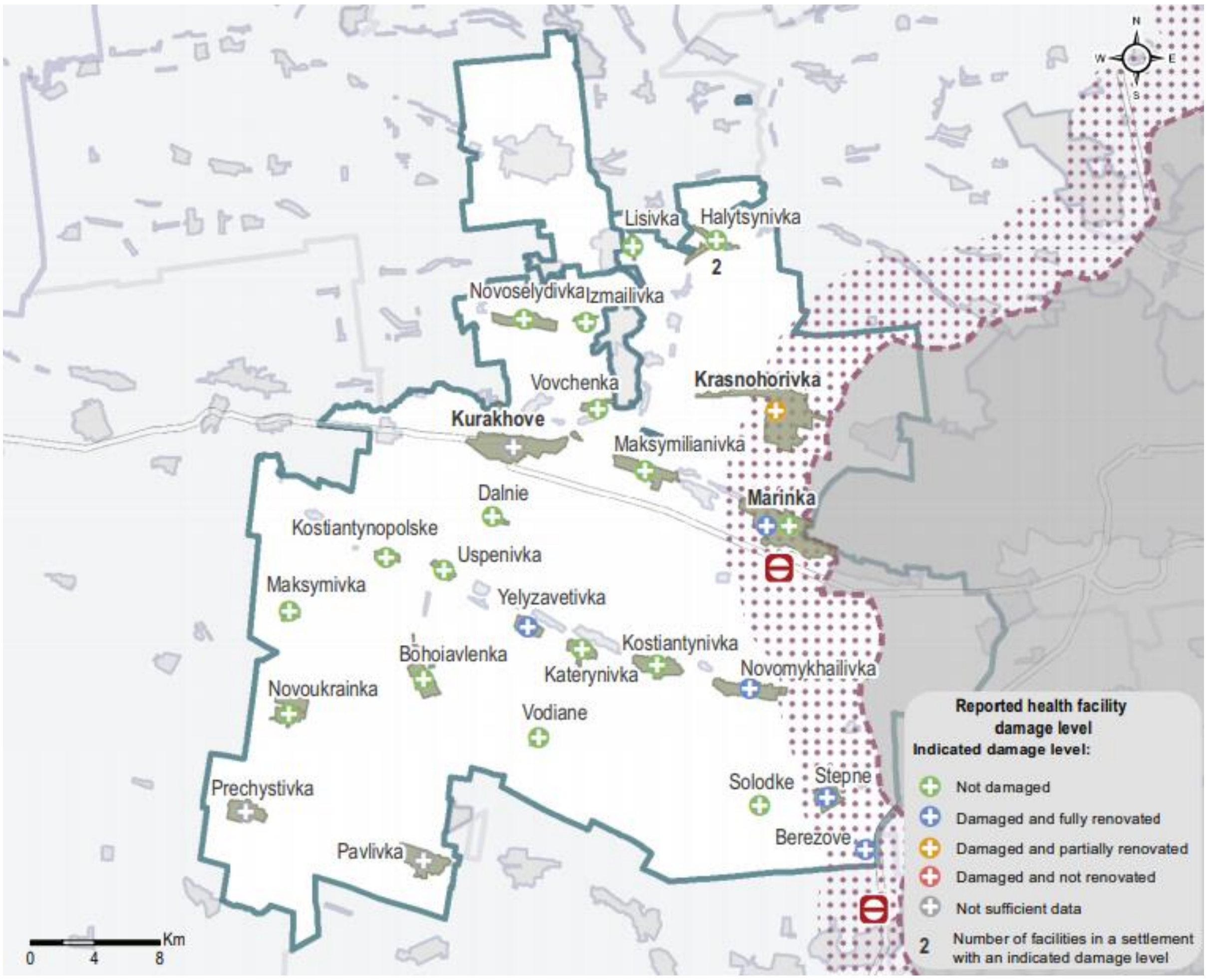
Category	Description	Size of network
Transport	Includes roads, railways and all related transport infrastructure such as train stations or airports	Wide depending on the type of infrastructure. Highway will have typically large catchment areas while smaller roads will cover smaller populations
Power	Includes electricity production facilities and power networks	Wide usually a regional and national level

Healthcare	Includes health facilities, pharmacies, cemeteries and morgues	Dependent on the type of facility. Tertiary level healthcare will have wide networks while primary will cover smaller populations
Heating	Includes all facilities related to the production of centralized heating	Wide and linked to water and electricity infrastructure
Water and Sewage	Includes infrastructure related to the provision of water and evacuation of sewage	Wide with regards to centralized water provision systems
Education	Includes all facilities related to the provision of education	Small for kindergarten and primary schools, wide for university education
Markets	Relates to any facilities that connect sellers and buyers of either goods or services	Small for local food sellers, wide for complex and heavily specialized goods
Police, fire and other emergency services	Includes all infrastructure for protecting civilians against crime and disasters	Small for local policing and wide for more complex services such as national security or disaster response
Waste management	Includes all infrastructure related to the collection, treatment and storage of waste	Small for communal garbage, large for complex waste such as medical or nuclear
Employment	Includes the physical location of employment providers at the city or neighborhood level	Small for unspecialized jobs, wide for highly skilled professions

Mapping service infrastructure requires a solid base of geospatial data. Most GIS data is proprietary, however open-source alternatives such as Open Street Map (OSM) provide easily available ‘point of interest’ accessible through open software such as QGIS using an application programming interface. The global file that holds all GIS files for OSM is more than 40 GB and is easily accessible online. By using such tools risk assessment specialists can conduct secondary data reviews of geo-data that can be complemented with locally available datasets (from ministries, statistical institutes or mapping institutes). Unfortunately, in low income economies, isolated areas or in the case of rapid onset crises this data is often missing, a problem REACH and other actors try to address through some of their humanitarian programs. By acquiring the geospatial features of infrastructure defined in table 1 it becomes possible to start mapping service and market catchment areas. The output of this geo-spatial process produces a variety of vector layer (such as shapefiles) representing point (facilities), lines (roads, electricity or water lines) or polygons (administrative units, water bodies).

Using a mix of open street map and data available from the Ukrainian Ministry of Education, REACH was able to map some of the core infrastructure for health service delivery amongst others. Enumerators were then able to visit each of these facilities to assess damages and main service delivery challenges. The map output of this process is shown in the map above (map 1).

Map 1. Health Infrastructure by Damage Status



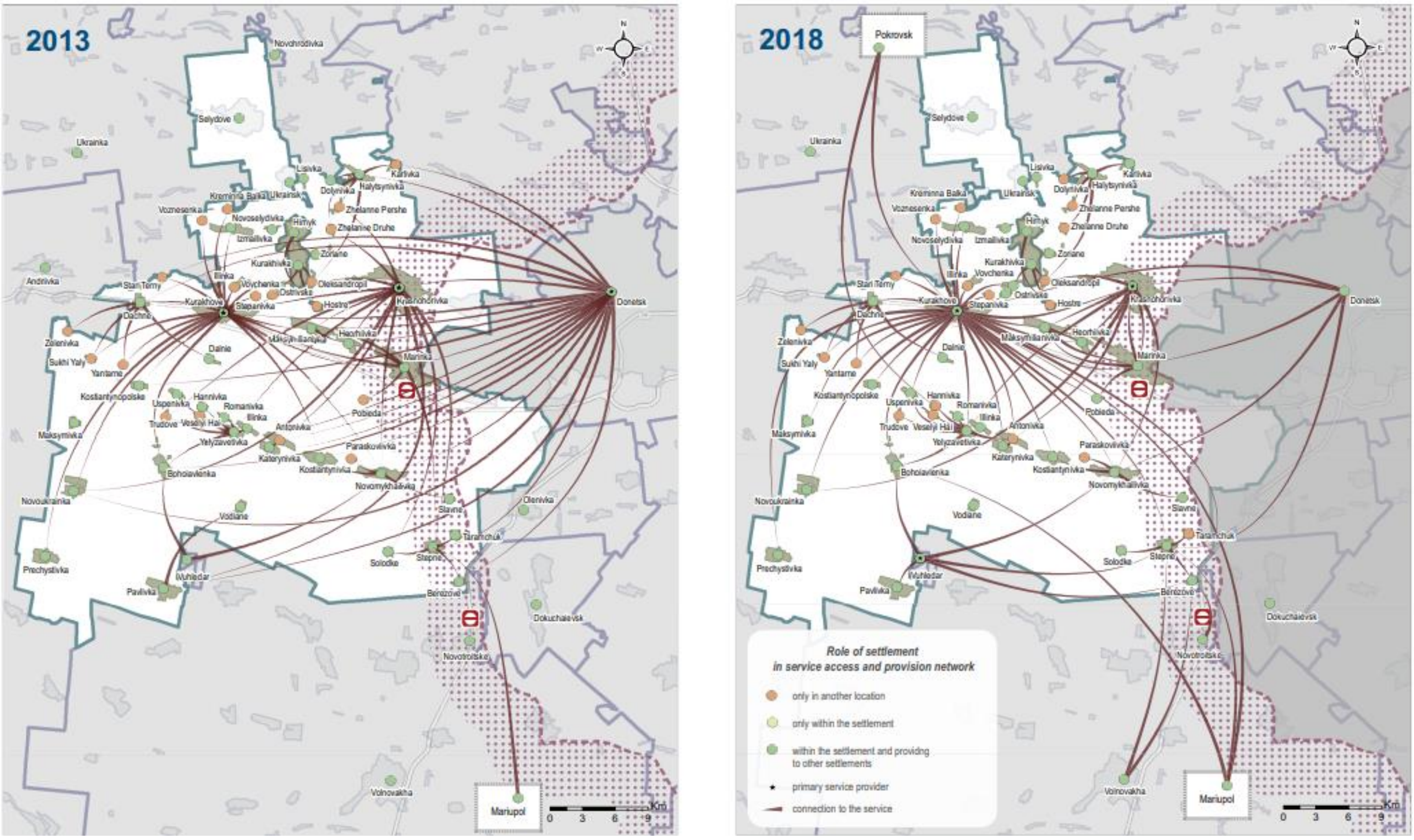
Defining Catchment Areas

This section describes the process of mapping catchment areas. Mapping infrastructure and location of service nodes identifies hubs in which communities access key services and goods. The next step of the catchment area mapping is to identify the cities that are net demanders of services and goods against the ones that are net suppliers. The next section presents a community level of analysis as used in Ukraine, but a facility level could technically follow the same approach albeit at a higher cost.

Through the household survey REACH collected data on where residents accessed key services including health, education, social, administrative and financial services but also food, non-food, construction and employment markets. The information was collected through a mobile data collection application (Kobo toolbox) and processed in R. Using a mix of R, QGIS and ArcGIS, REACH produced a dataset which connected the settlement in which the survey was collected to the area in which the respondent accesses a service. For this paper we will use healthcare as it is a critical facility during a disaster and employment due to its importance on household economic security. However, by using the taxonomy of services presented in the section above a similar approach could be implemented for other sectors. The output of this process is presented below for health networks and employment networks (map 2)[2].

[2] The maps presented in the paper were developed using ArcGIS, R, and Adobe InDesign by the REACH team in Ukraine (Anton Vasyliev, Yaroslav Smirnov and Galyna Uvarova) for publication purposes.

Map 2. Location of Where Residents of Marinka Raion Accessed Healthcare Services in 2013 and 2018



The network maps provide the foundation for identifying of a 'catchment area' by outlining all the communities connected to the main hubs (city) that provide health services. This approach can be replicated for any other service (education) or market (food or employment).

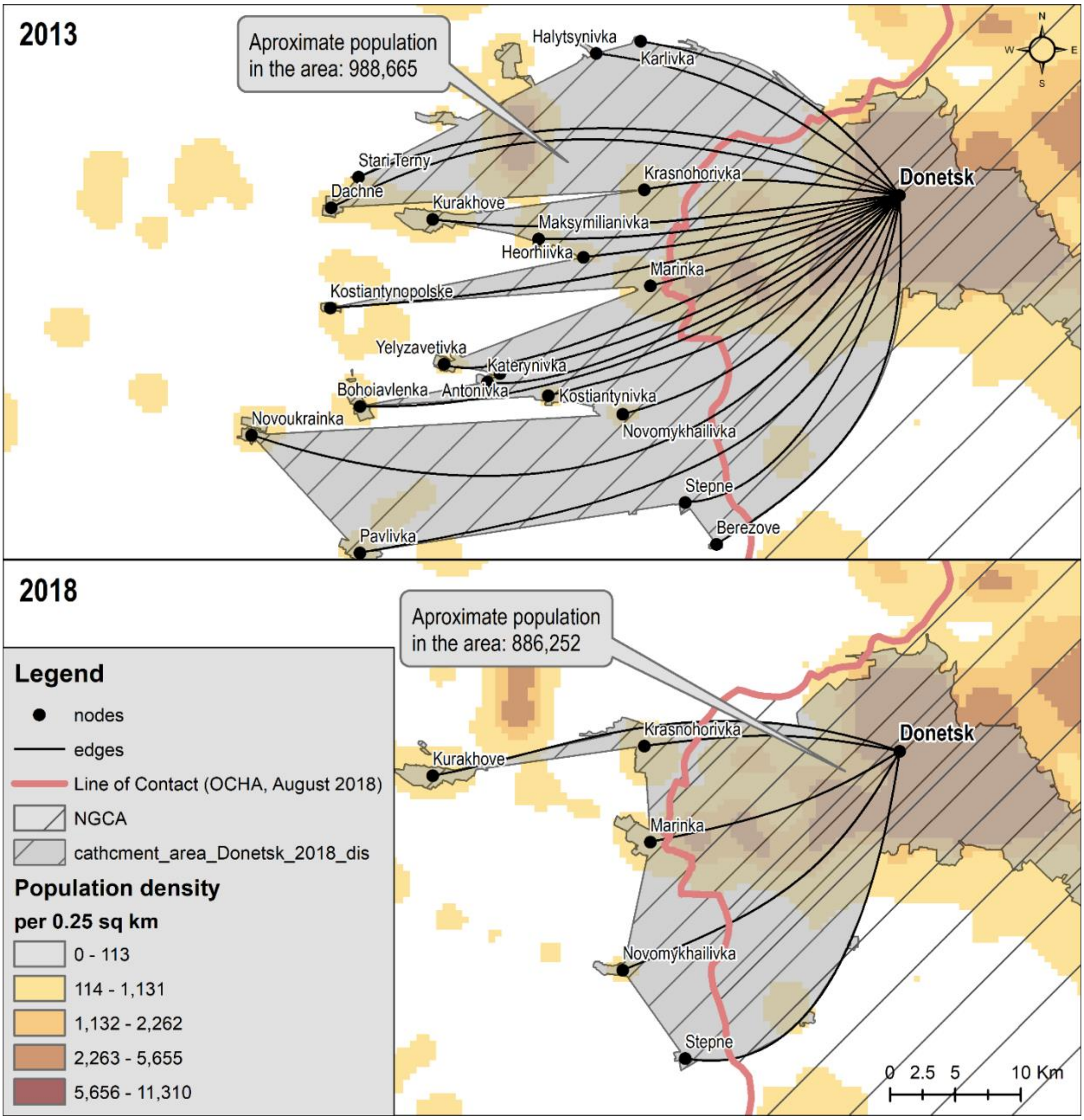
Mapping Changes in Catchment Area Dynamics

Catchment areas are useful levels of analysis because they provide an estimate of the population that would be affected if a city or a critical infrastructure were to fail or become inaccessible. It is an analysis that enables a more detailed understanding of the cascading consequences of disasters on communities.

Using the Global Human Settlement (GHS) dataset provided by the European Joint Research (European Commission, JRC, 2018) it is possible to estimate population numbers of non-administrative boundaries. The GHS uses a mix of census data and remote sensing to allocate population data into built areas. The remote sensing component estimates the built area of a 250 square meter raster and divides it by the total built area of an administrative boundary with census data. By applying this percentage to the census information each raster represents an accurate picture of population distribution within a 250m square. The main advantage of using raster population data in risk assessments is that it enables planners to look beyond administrative boundaries. Disasters rarely confined to national, regional and communal boundaries. Crisis affected populations will move in areas where they can find suitable water, shelter and food regardless of boundaries. While the response is often coordinated by national and international entities the way people will access goods and services will revolve overtime on the availability of good and services. This entails that assessments need to better understand where and how crisis affected populations are likely to move and access services should their current communities be disrupted by conflict or disasters.

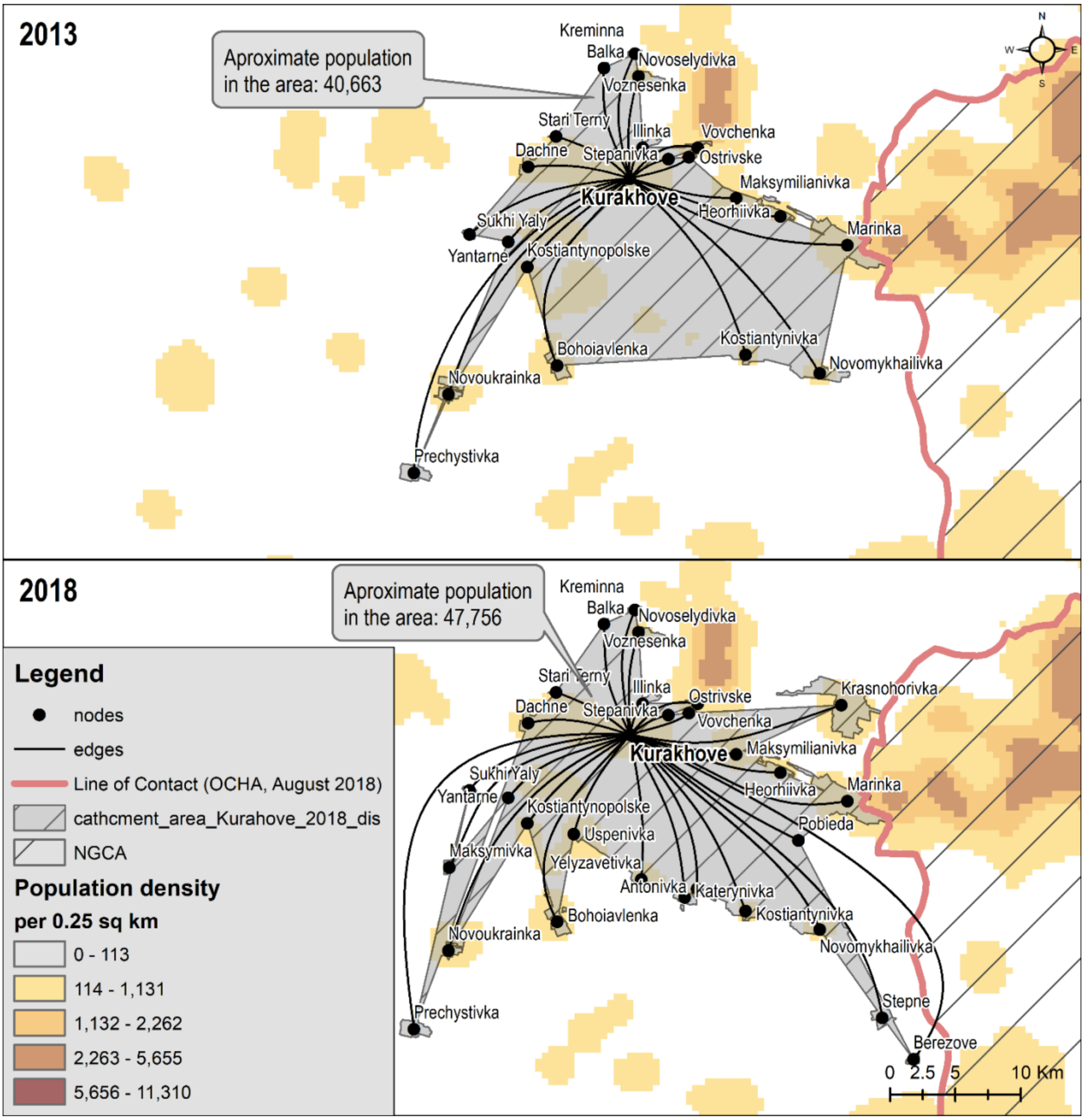
The network maps developed through the methodology described in the previous it is possible to define a geography that can calculate the estimated populations within catchment areas established through network analysis. This is done by drawing the catchment area in QGIS by creating polygons that incorporate all the nodes of the network. Combining this to the GHS raster it is possible to calculate the estimated populations within a catchment area. Zonal statistics tools can achieve this and are available on the open source GIS software QGIS. This tool can compute the sum of all 250 square meter raster cells within the drawn catchment area as shown below compared to most population figures that are aggregated to administrative boundaries. Map 3 shows on an example of a catchment area defined using a network analysis of communities accessing health services in Donetsk (largest node in map), which is now inaccessible due to the contact line along.

Map 3. Change in the Catchment Area of Donetsk City from 2013 to 2018



In the example above an estimated 102,000 people are unable to access healthcare in Donetsk as a result of the crisis, a drop of more than 10% in the overall caseload for the city. Using the current areas of service access, it is possible to map the new healthcare network map.

Map 4. Change in the Catchment Area of Kurakhove from 2013 to 2018



The maps above show the new healthcare map of the raion of Marinka. The network map above shows the disconnect of Marinka raion peripheries from its urban core in Donetsk city. Using the zonal statistics this disconnection potentially affects access to health services for some 102,000 people in catchment area of Donetsk city. The 2018 network map shows that populations in the former periphery now go to other hubs of healthcare in Kurakhove which now has to service an estimated 47,000 people against a 40,000 pre-conflict caseload, a 17.5% increase. Therefore, the network analysis shows a clear dual tension affecting healthcare networks in eastern Ukraine: i) a reduction of caseloads in the pre-crisis hub of Donetsk and ii) an increase of caseloads in the post crisis hub of Kurakhove. This has major implications on the allocation of resources of aid organizations that should prioritize nodes in the system that are unable to cope with changes in demand and capacity to deliver quality services.

This type of analysis enables aid planners to look at service delivery not only as an infrastructure point rehabilitated but as a holistic network that serves neighboring populations. Any changes in these networks will create a change in demand and supply of services that can be quantified through catchment area mapping and a population density raster.

Conclusions

Network analysis of areas and communities enables risk assessment to better understand the dynamic nature of how crisis affected communities' access critical services and goods. The networks that enable populations to meet their needs are systems that should to be understood to increase their resilience. A highly centralized network will be much more vulnerable to shocks than a decentralized one. By identifying primary and secondary nodes risk management planners can focus their activities in the areas that are critical to the sustainable functioning of human settlement clusters. In the context of protracted crisis with lasting infrastructure damage and changes in the structure of communities, relying on administrative boundaries as a unit of planning will omit the complexity human networks. Strategies for recovery need to adapt to the organic ways in which communities organize after crises until the infrastructure and social relationships that connect communities to urban areas are fully restored.

The use of mapping and geospatial data provides a valuable tool to understand these relationships. It allows risk assessment managers to better understand the geographies and communities in which disasters happen to better anticipate their capacities to meet their needs.

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