System-of-systems framework for global infrastructure vulnerability assessments

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Abstract
Infrastructures such as energy, transport, water, waste and telecommunications are essential to the sustainability, social wellbeing and economic prosperity of nations. In meeting future infrastructure needs of a growing global population there is a need for creating resilient infrastructures, which can withstand large human induced or natural shocks. Understanding systemic vulnerabilities and risks to infrastructures goes a long way in meeting such challenges. There is a general lack of models and tools that provide such understanding in an easily interpretable and usable way. This paper addresses the need for a system-of-systems framework that applies to assess infrastructure vulnerabilities in a generalized sense. The system-of-systems framework present here outlines basic models and information on: (1) spatial hazards; (2) interdependent spatial infrastructure network assembly; (3) infrastructure customer service disruption; (4) macroeconomic loss estimation; and (5) simulation and generation of spatial vulnerability outcomes. Our aim is to create individual models and a coherent framework for regional or national scale vulnerability assessment that is replicable to multiple contexts globally. This builds on our previous studies developed for different infrastructure risk assessments for United Kingdom, China, and New Zealand. Here we present a demonstration of the framework for a case-study of the Gaza Strip, to show how electricity infrastructure failures induce direct and indirect vulnerabilities on dependent energy, water, waste water, health, banking, and education systems. The results highlight system-wide impacts of individual asset failures and concentrations of spatial vulnerabilities. Such knowledge helps in prioritising national-scale infrastructure risk management and resilience planning. We aim of apply such analyses to inform mitigation and adaptation challenges for developed and developing world contexts around the world.

Keywords
Vulnerability assessment, infrastructure networks, interdependencies

1. Introduction
Sustainable societies depend upon infrastructures such as flood defences (inland and coastal), energy (electricity, gas, liquid fuels), transport (road, rail, ports, airports), water (supply), waste (wastewater and solid waste), and ICT (fibre optics, digital communications and data storage or processing) systems. These infrastructures exist to provide essential services on which other systems and the broader society rely. From a national security perspective infrastructures are considered critical along with a broader class of relevant systems including, among others, emergency services, healthcare, education services, financial

services, food systems, and government (Cabinet Office 2010; DHS 2013). Globally the focus on infrastructure development is immense as an estimated US$ 5 trillion per year infrastructure investments are required by 2030 to support a future global population of 9 billion (WEF 2013). Advanced economies worldwide need such investments to upgrade their aging stock of infrastructures, while least-developed countries need investments as they struggle with the greatest deficit of infrastructure provisions (Hall et al. 2016). Promoting infrastructure investments is seen as beneficial in creating positive multiplier effects on socio-economic growth (S&P 2015), with estimated 5%-25% economic returns on every dollar spent on infrastructure developments (WEF 2013). While a strong case for infrastructure investments is clear there is a danger that poorly planned and built infrastructures will be detrimental to society. Especially during large-scale human induced and natural disaster events when social wellbeing and economic stability are at risk due to failed infrastructure provisions. As climate change increases the magnitudes and frequency of catastrophic natural hazard events (Schaller et al. 2016), the increasing incidents of infrastructure failures resulting in socio-economic losses could become common. Hence it is important that long-term infrastructure planning and investment is underpinned by a robust understanding of risks that could have major implications for sustainability and climate change impact adaptation.

This paper focuses on quantifying infrastructure vulnerabilities that lead to major disruptions to society and the economy. In particular the paper addresses the problem of understanding interdependencies that lead to large-scale cascading failures across multiple infrastructures and wider socio-economic systems. This requires a system-of-systems approach that integrates different hazards, infrastructures and socio-economic models into a coherent framework. Our aim here is to build a system-of-systems framework that is applicable for generalised scenarios of infrastructure risks globally. This framework answers key questions of interest to global development investors, governments, infrastructure owners and operators, and other relevant stakeholders – (1) Where are key vulnerabilities in infrastructures concentrated? (2) How do interdependencies magnify risks to other systems? (3) What are the wider consequences of infrastructure disruptions?

Infrastructures are large-scale spatially distributed systems with complex interactions. One major challenge facing modellers of infrastructures is the need to understand and represent the most salient features of such systems – providing a model that is able to capture important complexities, whilst at the same time, being robust enough to generalise different risk scenarios. Different approaches have been proposed to model infrastructure complexity including agent-based modelling (Brown et al. 2004), network science techniques (Strogatz 2001; Zio 2009), macroeconomics based models (Haimes et al. 2005), and empirical studies (McDaniels et al. 2007; Zimmerman 2001). For a comprehensive review and comparison of these approaches see Ouyang (2014). Each of these modelling approaches has aimed to quantify interdependencies, which represent the bi-directional relationship between different infrastructures (Rinaldi et al. 2001). While different types of interdependency definitions have been proposed (Ouyang 2014), physical, geographic, cyber and logical interdependencies are recognised as most relevant to infrastructures (Rinaldi et al. 2001). While there is consensus that no single model can answer all questions for even one infrastructure (Brown 2007), network science-based models, in particular, provide a powerful means to represent complexity at multiple scales. In comparison agent-based models are very data intensive, economic models are very high-level, and empirical models can be very context specific. In this study we adopt a network science-based modelling approach, to represent the infrastructure system-of-systems as a collection of interdependent geospatial networks that provide reliable flows of goods and services.

Infrastructure vulnerabilities here refer to the measures of negative consequences of failures of individual network components (called assets) at systemic scales (Pant et al. 2016). We particularly focus on quantifying vulnerabilities in terms of the numbers of customers of different infrastructures who potentially suffer service disruptions resulting from asset failures. When an individual asset fails it disrupts customers that are directly connected to it to derive service. Since this asset nests within a wider network, its failure cascades to connected assets, resulting in indirect customer disruptions from network failure effects. Hence the vulnerability of individual assets is characterised by calculating and comparing the potential direct and indirect disruptions that could result from their failures. The vulnerability of groups of assets is characterised by deriving geographic hotspots of critical assets, which highlight concentrations of critical infrastructures at a high level (Thacker et al. 2017b). The afore-mentioned vulnerability quantification is hazard invariant, as it is based on 'what if' scenarios consisting of individual assets failures. But, through integration with appropriate spatial hazard event maps, it can be used to create real multiple asset failure scenarios to quantify vulnerabilities and risks in terms of hazard probabilities or likelihoods and failure consequences.

The overall system-of-systems framework presented herein shows how the infrastructure vulnerability assessment can be generalised to provide useful insights for decision-making, for a range of different countries, globally. These insights provide decision-makers with evidence as to the systemic vulnerabilities and risks to infrastructures at national scales. We note that detailed understanding of vulnerabilities and risks requires details site-specific information that, is not consistently generalizable. As such the framework presented herein is useful for screening for potential systemic vulnerabilities of assets and locations that could be studied in further detail.

Components models and variants of the system-of-systems framework have been presented with demonstrable examples from different contexts around the world. These include, among others: (1) systemic vulnerability assessment of Great Britain's rail infrastructure (Pant et al. 2016a); (2) critical hotspot analysis of England and Wales' interconnected electricity, transport, water, waste, telecoms infrastructures (Pant et al. 2016b; Thacker et al. 2017b); (3) flood vulnerability assessment of electricity networks and depend water, wastewater, telecoms, and transport assets in the Thames catching in England (Pant et al. 2017); (4) vulnerability assessment of energy, transport, water, and waste networks in China (Hu et al. 2015); and (5) criticality analysis of interdependent electricity, fuels, transport networks in New Zealand (Zorn et al. 2017). In this paper we present analysis for Palestine focussing on the electricity network system within Gaza and its critical role in supporting not only direct consumers of electricity (i.e. domestic consumers), but also a range of indirect consumers from multiple critical infrastructure sectors (i.e. energy, water, waste water, health, banking and education).

The remainder of the paper is organised as following. Section 2 provides the overview of the system-of-systems framework where we discuss basic models and information required for implementing the framework. Section 3 presents a demonstration of the framework for Gaza showing the useful vulnerability outcomes. Section 4 concludes the study with discussion on the value of the methods and applicability to other contexts.

2. System-of-systems framework

Figure 1 graphically demonstrates the system-of-systems framework, which is employed for infrastructure vulnerability assessment, and can also be extended for risk assessment. As shown in the figure the framework consists of:

A. ***Hazards*** – A hazard signifies an external shock event that causes failure to infrastructures. We are interested spatially coherent probabilistic extreme natural hazards such as floods, extreme winds, heat and cold. While each of each hazard types requires specific modelling techniques, in the end, they generate similar outputs such as hazard extent, magnitude and frequency. For example, global, national or regional scale flood maps are typically generated with information on flood spatial extent, return-period, flood depth or flow (Ward et al. 2015). The current framework integrates such hazard information towards estimating infrastructure failure probabilities and likelihoods.

B. ***Interdependent infrastructure networks*** – All infrastructures we are interested in exist as networks that can be represented geospatially as collections of nodes and edges. The nodes signify point locations and assets such as electricity substations, water towers, telecom masts, ports, rail stations, junctions, etc. The edges signify linear elements that connect nodes, such as cables, pipes, fibre, rail tracks, road links, maritime routes, etc. By inferring how nodes of two different infrastructures are connected through edges we can quantify physical interdependency effects between different infrastructures, while spatial proximity of different assets helps quantify geographical interdependency effects. In addition to network topology we are interested in understanding the flows of services across and between infrastructures. Such flows are measured in terms of the amount of customers serviced by nodes and edges of the network contingent upon the capacities of nodes and connecting edges and the customer demands. We note that network flow modelling depends upon the characteristics of individual networks, and different approaches are required for flow estimation of utility and transport networks (Pant et al. 2016a,b; Thacker et al. 2017a,b). Representing these flows in terms of customer numbers creates a common metric across all infrastructures. Flows between different infrastructures measure the functional dependencies between assets (Thacker et al. 2017a). For vulnerability or risk assessment, the assembled geospatial interdependent networks are intersected with the spatial hazards to initiate failure conditions that trigger failure propagation across networks. As noted before, such failures can also be initiated assuming random failures of assets.

C. ***Service disruptions*** – The results of infrastructures failures are measured in terms of the numbers of customers who face service disruptions. As mentioned before, we estimate these service disruptions in terms of the direct and indirect customers disrupted due to assets failure and resulting network effects respectively. For estimating network disruptions we consider alternative flow route recalculation using capacity-constrained shortest or least cost paths, to explore diversionary network flow options. If no flow alternatives are available then customers are disrupted. The results of the service disruptions can be shown spatially in terms of the spatial locations and extent of disrupted customers (footprints) of failed assets. Multiple locations can be combined to show criticality hotspots where infrastructures with high disruption impacts are co-located (Thacker et al. 2017b; Hu et al. 2015; Zorn et al. 2017).

D. ***Macroeconomic losses*** – Infrastructures are part of a wider macroeconomic system of interacting sectors. Hence their service disruptions can be translated into economic flow losses that affect the wider economy. Using economic input-output models we are able to generalise the process of economic loss estimation. The infrastructure service disruptions are translated into direct exogenous demand losses corresponding to the infrastructure-based economic sectors. Using the demand driven Leontief economic input-output model (Leontief 1986) we can estimate the indirect economic losses to the rest of the economic sectors. Economic loss estimation provides the rationale for prioritising investments to reduce vulnerability and the basis for long term adaptation planning (Thacker et al. 2017c). It can be argued that infrastructure disruptions result in direct supply side losses, which requires supply-driven economic input-output models (Koks et al. 2015). These models can also be integrated into the overall framework.

E. ***Failure scenario generation*** – The models in components A – D above are assembled into a coherent workflow, with A being first, followed by B – D in order. We note that a hazard invariant vulnerability assessment can be completed without component A. Different failure scenarios can be generated by Monte-Carlo simulation methods to test failures for single or multiple assets. This can be repeated multiple times for different combinations of assets and hazard events. It can also be updated for current and future infrastructure network configurations and climate change driven hazard events to perform an exhaustive vulnerability and risk assessment in terms of probabilities and consequences.

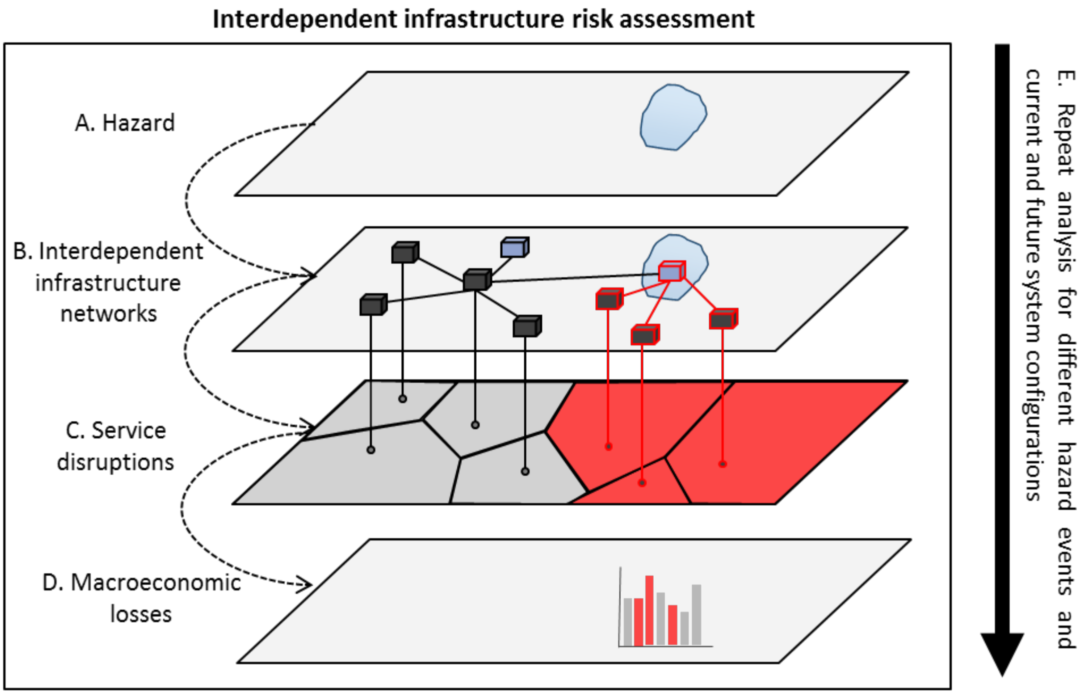

Figure 1: Graphical representation of infrastructure system-of-systems framework for infrastructure vulnerability and risk assessment (adapted from Thacker et al. 2017c).

3. Demonstration for Gaza

The systems-of-systems framework is demonstrated for the Gaza Strip, hence called Gaza, which is a self-governing Palestinian territory on the eastern coast of the Mediterranean Sea. This area has previously suffered large-scale infrastructure failures from geological, climate and manmade hazard types. Given this history, multiple organisations are interested in understanding systems infrastructure vulnerabilities due to infrastructure failures. Such knowledge is aimed at prioritising recovery planning in post-disaster environments and building systemic resilience through adaptation interventions. This section of the report provides details of the application of the vulnerability characterisation for Gaza, particularly focusing on Components B and C of the system-of-systems framework. Following an initial description of the scope of the application, results from the analysis are presented.

3.1. Scope of application and infrastructure network assembly

Our study focuses on the electricity network system within Gaza and its critical role in supporting not only direct consumers of electricity (i.e. domestic consumers), but also a range of indirect consumers from multiple critical infrastructure sectors (i.e. energy, water, waste water) and other sectors (health, banking and education). Table 1 gives a description of the data incorporated for Gaza; this includes the sector, function, type, number of assets and data source.

Table 1: Description of the datasets used in the analysis for Gaza

Sector	Function	Type	Number of assets	Source
Electricity	Supporting	Network	Sources: 14 Sinks: 24	Georeferenced from UN OCHA[1]

			Edges: 24	map
Water treatment facilities	Dependent	Point assets	7	Georeferenced from UN OCHA map
Waste water treatment facilities	Dependent	Point assets	3	Georeferenced from UN OCHA map
Building	Dependent	Polygon	167854	Open street map: tag 'building'[2]
Schools	Dependent	Point assets	59	Open street map: tag 'school'
Hospitals	Dependent	Point assets	18	Open street map: tag 'hospital'
Banks	Dependent	Point assets	31	Open street map: tag 'bank'
Fuel sites	Dependent	Point assets	28	Open street map: tag 'fuel site'

1 https://www.ochaopt.org/maps
2 https://www.openstreetmap.org/relation/1473938

The collected data on the location and interconnectivity of assets within Gaza's electricity sector are transformed into a directed network by classifying electricity assets as either a source node (electricity generator), a sink node (distribution substation) or an intermediate node (intermediate substation between source and sink). Edges (overhead lines and cables) define the connectivity between nodes and are classified as intermediate in their functionality. Edges are directed to represent the direction of flow and therefore the functional dependence between assets.

Data on the location of assets within Gaza's critical infrastructure and other sectors that are not from the electricity sector; for example, from the energy, water, waste water, health, banking and education sectors; are recorded as dependent nodes. These assets are connected to electricity distribution substation (sink) nodes to create the dependency edge that connects the dependent node and the supporting electricity sink node. These edges are also directed to represent their functional relationship. In the absence of real data on the nature and location of these dependencies, an edge has been created between the dependent asset and its geographically closest supporting asset (electricity sink). This is based on the assumption that dependent assets will be connected to its closest possible supporting asset – this assumption is based on the fact that during installation the costs associated with installation, operation and maintenance would be sought to be minimized.

Figure 2 shows a graphical demonstration of the network assembly explained above. The nodes depicted by circles represent electricity assets, while the square nodes depict asset of another infrastructure.

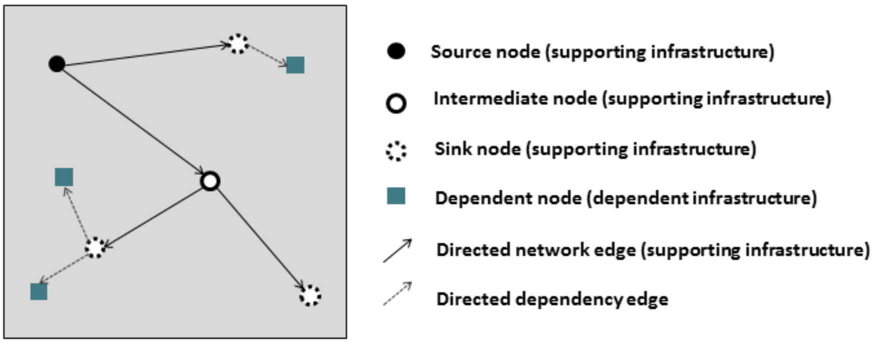

Figure 2: Network description for mapping assets and interdependencies.

The result of the network assembly is presented in Figure 3, which shows a hierarchical representation of electricity network system in Gaza. Generalised hierarchical network representations of infrastructures help us understand how these systems are spatially and functionally organised (Thacker et al. 2017a). The representation highlights the hierarchical nature of flows and therefore dependence that is established from the source asset layer (generation and interconnector assets) through lines to the sink asset layer (distribution substations). An example of dependence is shown on the figure by connecting buildings, through a dependency edge, to their supporting electricity distribution substation.

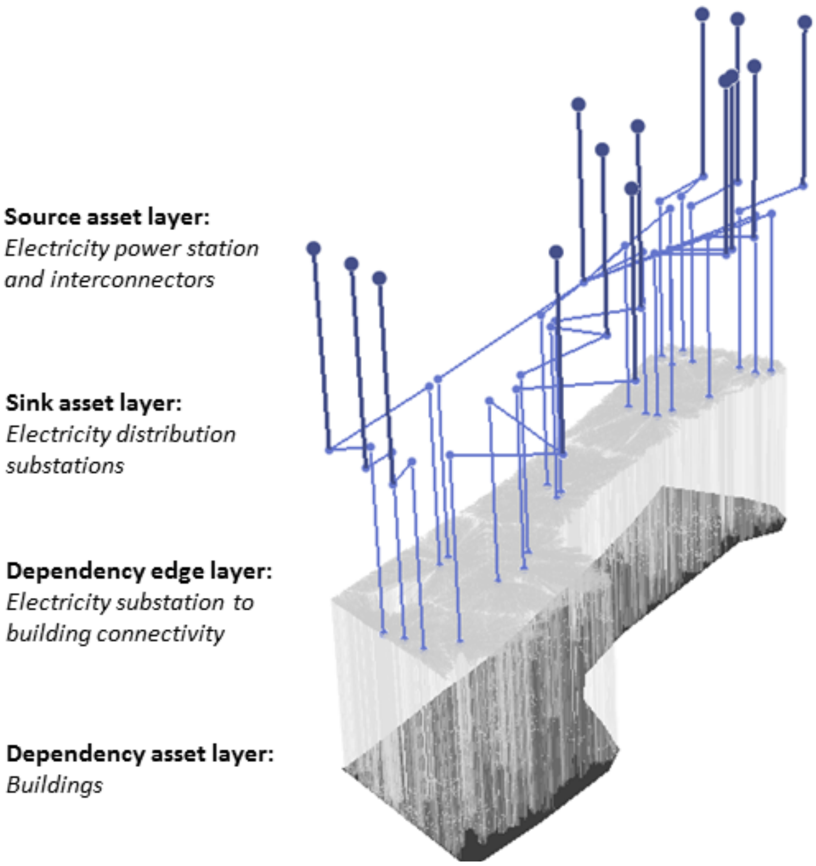

Figure 3: The electricity network hierarchy and dependent building assets for Gaza.

Figure 4 maps the entire infrastructure asset data used within the study and shows the number of assets in the corresponding legend item. The figure highlights the dependency links that are established between the supporting and dependent infrastructure.

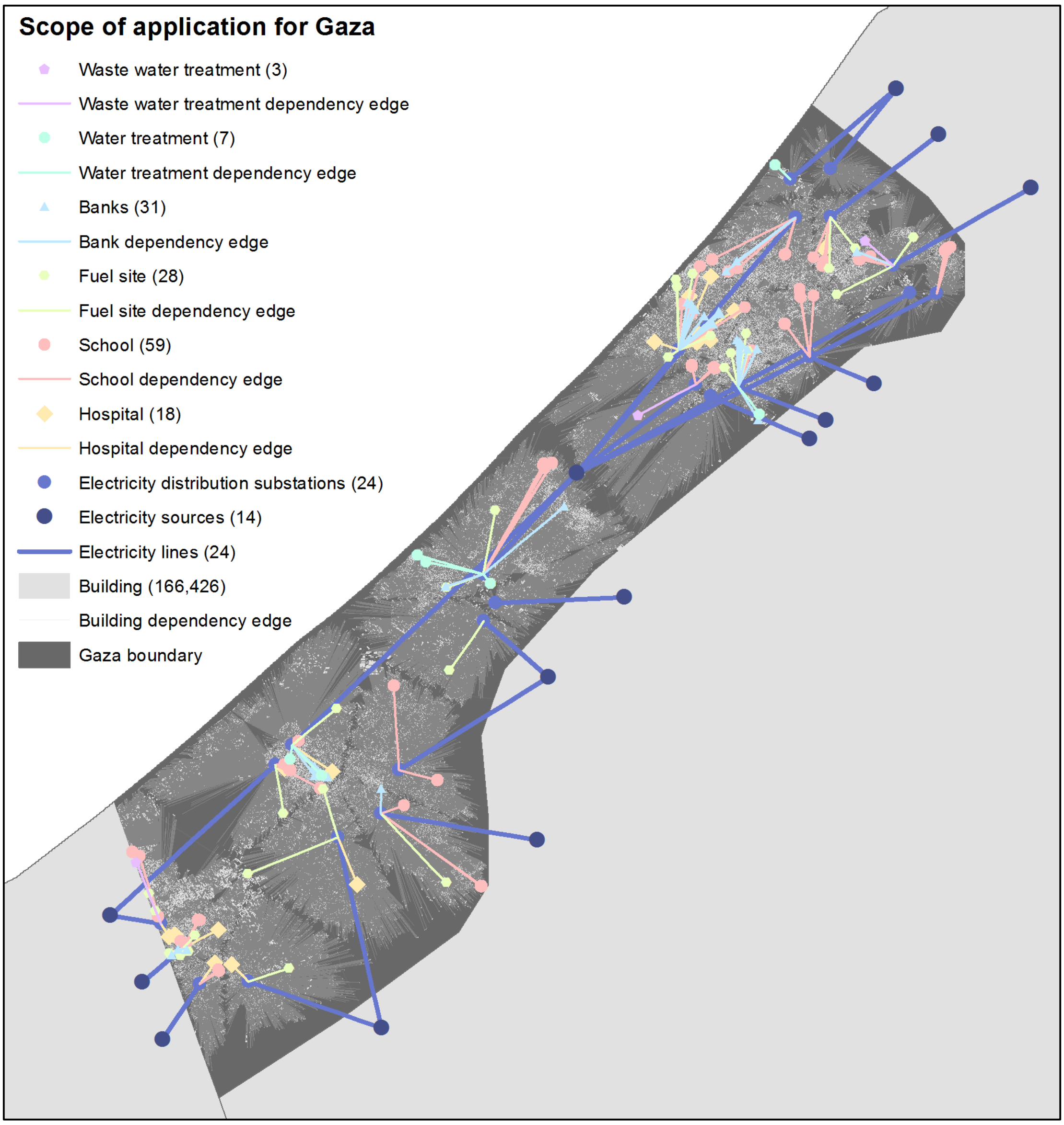

Figure 4: Scope of the application for Gaza, showing the electricity network and a range of dependent assets from the energy, water treatment, waste water treatment, health, banking and education sectors. The number of assets of each type is indicated in the figure legend.

3.2. Estimating direct and indirect service disruptions

Service demand attributes as number of consumers are assigned to all assets based on the amount of service that each asset directly supports. Figure 5 shows how this can be completed for the previously introduced example system of Figure 2. As highlighted in the figure, service demands are estimated by mapping geographic area coverage of nodes connected to customers. In the absence of the actual coverage of the geographic area we use Voronoi tessellation (Pant et al. 2017; Thacker et al., 2017b) methods, based on the assumption that a node serves its nearest population in space. Using population census maps which give population density estimates at different spatial disaggregation, we estimate the numbers of customers with the estimated service areas.

Following network assembly and service demand assignment, the consequences of failure of individual assets are evaluated systematically for all nodes within the system. This is done by removing each node individually from the network and calculating the direct and indirect service demands that are lost as a result of the disconnection. Figure 5 also depicts this process graphically, where the selected electricity asset fails to disrupt customers directly along the electricity network and also customers indirectly of the other sector.

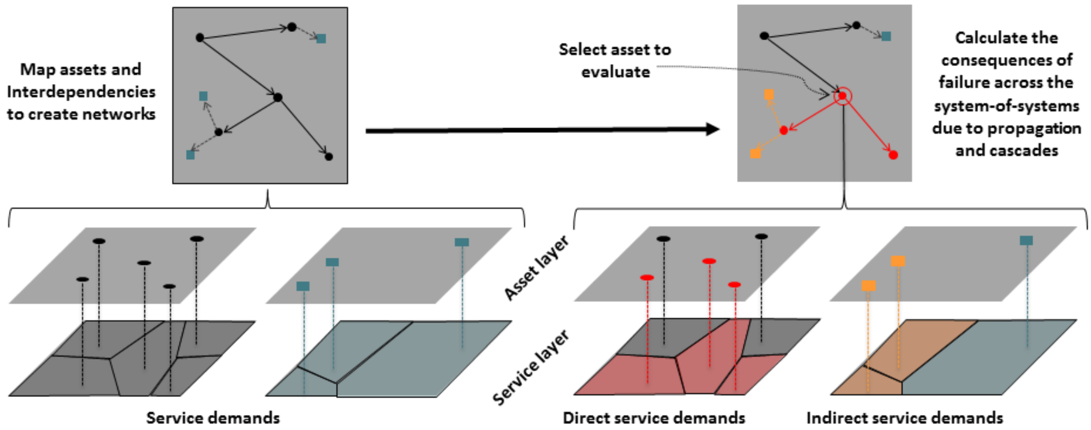

Figure 5: Framework for calculating direct and indirect failure impacts, (adapted from Thacker et al. 2017b).

3.3. Vulnerability results

The vulnerability of Gaza's electricity infrastructure is first evaluated at the asset level by comparing the direct and indirect service disruption consequences of failure of different electricity assets. This comparison can highlight assets that are characterised as 'critical' to multiple consumers from different sectors.

Figure 6 highlights the magnitude of potential disruptions (across multiple sectors) that can occur due to the failure of the 24-individual electricity distribution substation assets within Gaza. The analysis shows that the range of impacts for all sectors is heterogeneously distributed across assets. A number of substations can be seen to particularly important for the provision of different sectors, for example, substations [ID's: 23, 16, 10 and 13] are particularly important for the water treatment sector and substations [ID's 14, 20 and 5] are particularly important for waste water treatment sector. Substation [ID: 25] shows very large potential impacts across multiple sectors and can be classified as highly critical.

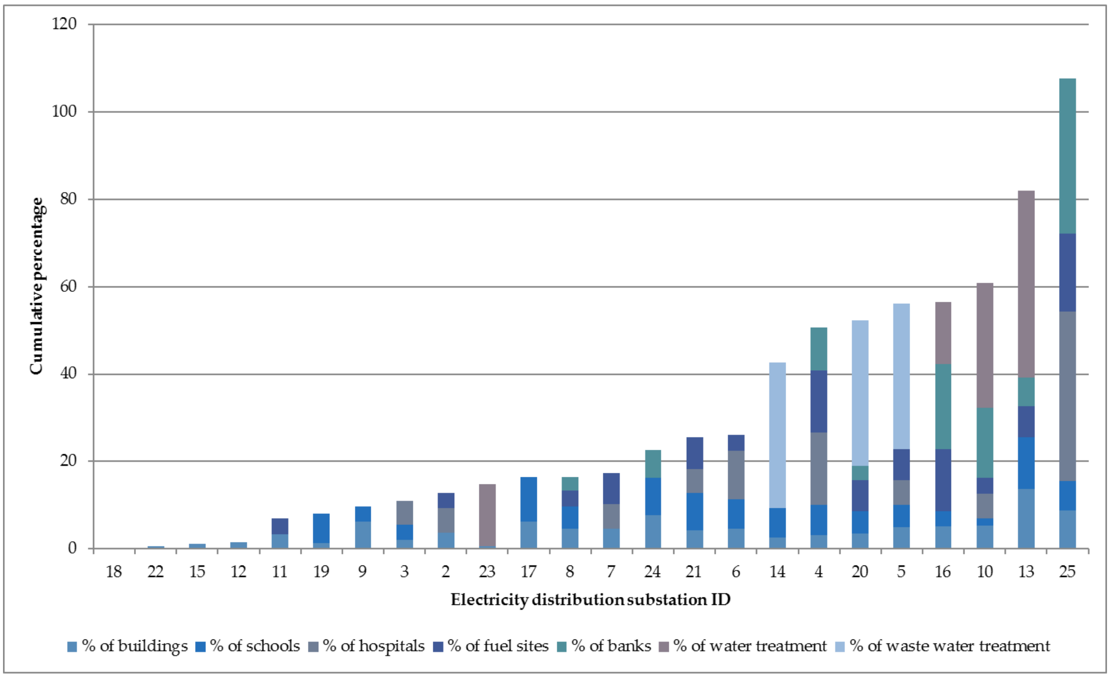

Figure 6: Vulnerability plot showing the magnitude of direct and indirect failure consequences for electricity distribution substation assets (sink assets).

The vulnerability of infrastructures can also be expressed above the level of individual assets – at the scale of multiple assets. This is achieved is by characterising the geographic interdependence of different assets through the derivation of infrastructure hotspots, which denote geographic concentrations of critical infrastructure. These hotspots are created by kernel density estimations that generate single continuous surface from discrete points, to integrate multiple critical assets within a certain distance using a specified kernel function. See details of the hotspot calculations see Thacker et al. (2017b), Hu et al. (2015). Figure 7 shows kernel density hotspot maps for the infrastructures previously introduced in this report. The plots highlight geographic concentrations of the different infrastructures and provide a means to compare the spatial distribution of assets from multiple sectors. The plots highlight the wide range of densities and heterogeneity in spatial distribution. Despite this, clear centres of density intuitively correlate to the most urbanised areas; this is most clearly demonstrated for the buildings density plot. The figure highlights that despite there being three distribution substations in the centre of Gaza; there is very little other critical infrastructure in this area. Conversely, there is no substation located centrally to Gaza city, though there are multiple other critical infrastructures located there.

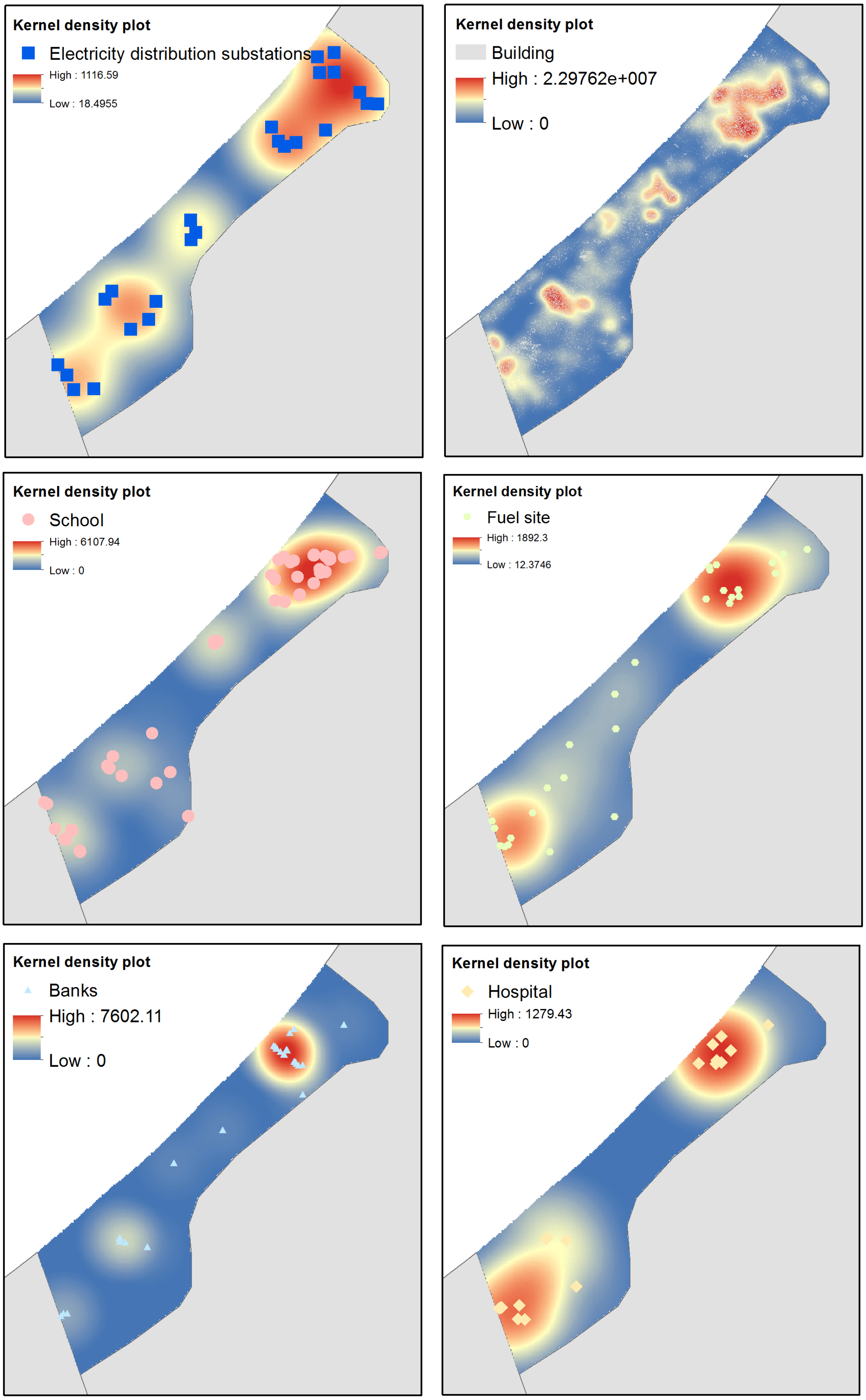

Figure 7: Kernel density plots showing relative geographic concentrations of critical infrastructure (classification of geographic co-location and interdependence).

3.4. Vulnerability for real hazard scenarios

We use a real spatial hazard scenario to estimate spatial concentrations of vulnerabilities of infrastructures. Figure 8 shows a kernel density plot highlighting the damage hotspots sustained during the 2014 conflict in Gaza. Damage estimates are taken from the UN's UNOSAT data (https://unitar.org/unosat/) derived from Pleiades satellite. The map shows that hotspots are typically found along the north-east to south-east of Gaza and are typically away from urban centres. Though a number of substations are located within high-damage zones, a number of critical substations are not.

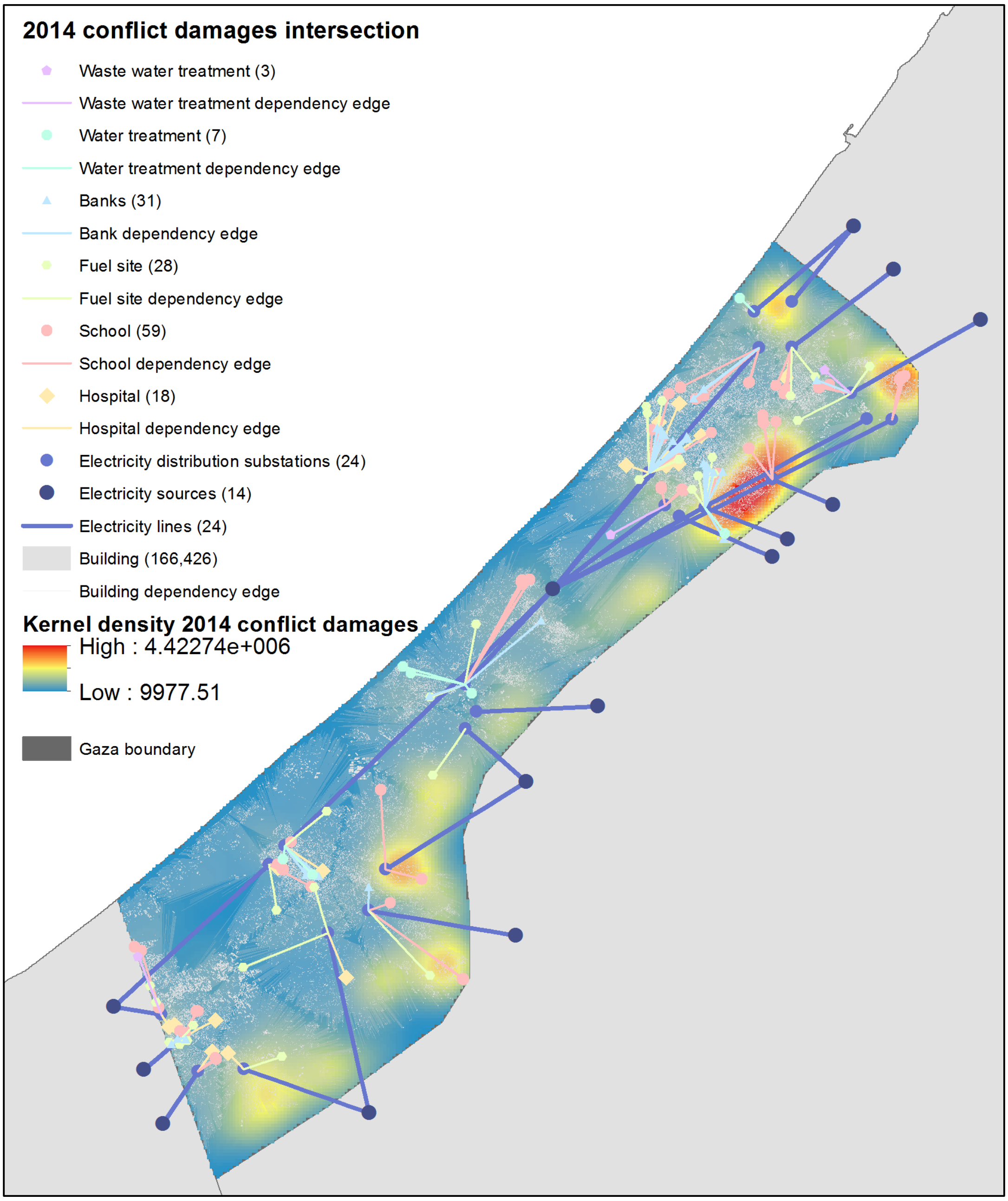

Figure 8: Kernel density map derived from satellite imagery representing damages sustained during the 2014 conflict in Gaza.

3.5. Usefulness of analyses for long-term vulnerability reduction interventions

Electricity is central to the functioning of multiple infrastructure sectors within Gaza. A small number of electricity distribution substations play a disproportionately large role in supporting large numbers of consumers from multiple sectors. A number of substations also play a relatively small role in supporting consumers from multiple sectors. The impacts of failure aggregate up layers of the electricity hierarchy from sink to source nodes.

Mapping assets and their associated density hotspots highlights the spatial heterogeneity of Gaza's infrastructure provision. Due to this, the location of dependent assets does not necessarily correlate with the location of electricity assets - this is most noticeable in the centre of Gaza and in Gaza city.

Intersection with the 2014 conflict damage kernel density map shows that although a number of substations are located within high damage areas, a selection of critical substations are not. Locating new assets within areas which have not previously been damaged (or have suffered relatively less damage) may provide an option for reducing expected future failures. One area for consideration may be the centre of Gaza city.

Locating new supply infrastructure such as substations and associated sources or interconnectors within areas of high density demand (for example in Gaza city) can help to alleviate the disproportionate failure consequences associated with highly critical assets in that area. Figure 9 shows a candidate location for a new electricity substation in Gaza city that could help reduce risks that manifest through these mechanisms.

Although locating new assets such as substations is a complex task, locating them close to demand centres from multiple-sectors is not only beneficial to reduce installation costs, but also reduces losses (which are particularly high in the Palestine) and also reduce the likelihood of failures that can occur due to electricity line failures (i.e. greater the cable length means a greater probability of failure due to increased risk of breakage due to natural or man-made events).

In addition to adding new substations, additional edges between different substations and substation and generation facilities and interconnectors can help build resilience by ensuring that, in the event of single asset failures, alternative supply options are available to maintain service delivery.

Distributed generation such as solar power installed on building roof tops can provide an alternative source of generation that not only supplements the overall generation portfolio, but is low carbon and is located geographically close to where demand is generated. The decentralised nature of this provision means that localised failures are likely to only have localised low-magnitude impacts.

Though in some instances back-up electricity generation may be available to provide support for assets, connection to a reliable grid infrastructure provides a more sustainable long-term alternative to support essential services and maintain social and economic wellbeing.

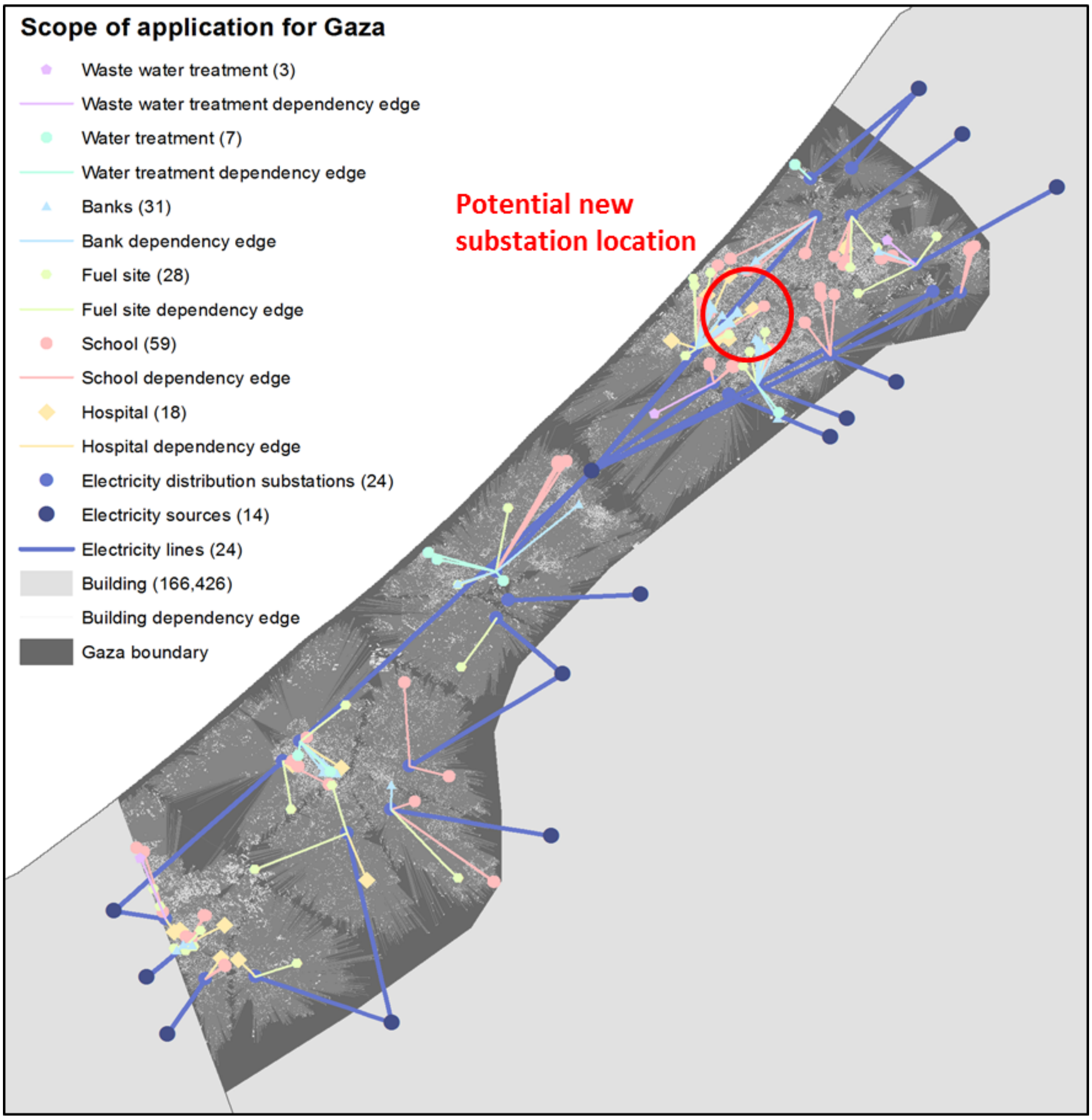

Figure 9: Map highlighting the potential location for a new electricity substation in Gaza city that would distribute the failure risks that currently emerge through the dependencies placed on substations located within the area. The location is also guided through knowledge derived from hazard and previous damage maps.

4. Conclusions and applicability to other contexts

This paper presents a system-of-systems framework for generic regional or national scale infrastructure vulnerability assessment. It integrates spatial hazards, interdependent infrastructure networks, spatial customer allocations, and macroeconomic loss models into a coherent workflow. The component models use generalizable parameters and information, making the overall framework applicable to a wide range of applications. These include case studies on infrastructure vulnerability and risk assessments for Great Britain, China and New Zealand from previous studies.

Here we present a case study of Gaza Strip in Palestine, which is a post-conflict area where infrastructure development is needed to meet current and future sustainability challenges. The study highlights the impacts of failure of electricity infrastructure assets on other systems such as energy, water, waste water, health, banking, and education systems. These impacts are estimated in terms of the numbers of direct customer disruptions on the electricity networks, and the numbers of indirect customer disruptions from other systems. For vulnerability outcomes are presented for individual assets to show their relative criticalities, and the groups of co-located assets to show spatial concentrations of systemic criticalities. This is a useful indicative analysis for identifying potential assets and locations that could be targeted for long-term risk reduction and resilience planning interventions.

For future analysis we are interested in applying the system-of-systems framework for understanding transport risks in Tanzania, which is a developing country. These risks will be analysed in the context of current and future transport networks subjected to present day and long-term climate change driven flooding scenarios. Several of the generalised models and knowledge from studies presented here will be applicable, while new knowledge will be created to update and adapt the framework to the Tanzania context. This enhances our understanding and approach towards creating an integrative system-of-systems approach for global infrastructure vulnerability and risk assessments.

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