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CRITICAL INFRASTRUCTURE SYSTEMS: A CASE STUDY OF THE INTERCONNECTEDNESS OF RISKS POSED BY HURRICANE SANDY FOR NEW YORK CITY

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Abstract

The goal of this paper is to investigate the impact of Hurricane Sandy from the perspective of interdependence among different sectors of critical infrastructure in New York City and to assess the interconnected nature of risks posed by such a hurricane. Critical areas and sectors where interdependent risks led to a catastrophic cascading effect are identified. This study uses indirect damages of each sector to estimate the degree of interdependence among the sectors. The study examines the impact of the hurricane on different critical infrastructures by combining hazard maps of actual inundation areas with maps of critical infrastructure. The direct damages of each sector are calculated from the inundation areas in the flood map. The indirect damages are estimated by considering the areas that were not inundated but affected by Sandy through the interconnected infrastructure. The electricity sector was the key sector to propagate risks to other sectors. The examination of new initiatives to increase the resilience of critical infrastructures in New York City after Sandy reveals that these initiatives focus primarily on building hard infrastructures to decrease direct damages. They understate the importance of interdependent risk across sectors. Future disaster risk reduction strategies must address interdependent infrastructures to reduce indirect damages.

1. Introduction

At the end of October 2012, Hurricane Sandy caused enormous damages from the Caribbean Sea to the northeastern coast of the United States. Sandy caused more than 200 fatalities along its track (Kunz et al., 2013). Even though Sandy was not the most severe storm event in terms of wind speed and precipitation, it produced tremendous economic damage, particularly in the United States. Kunz et al. (2013) concluded that the total damage might exceed USD 100 billion, estimating direct damage to be between USD 78 and 97 billion and indirect damage to be between USD 10 to 16 billion primarily due to business interruption.

Many storms hit New York with higher winds than Sandy's 80-mile-per-hour peak wind gusts and many storms have brought more rain than the half inch that Sandy dropped in parts of New York. However, Sandy's storm surge was unlike anything seen before (New York City Government, 2013). Its arrival on the evening of October 29 coincided almost exactly with high tide and generated a massive surge on the Atlantic Ocean and in New York Harbor. The storm surge caused flooding that exceeded the 100-year floodplain boundaries by 53% citywide (New York City Government, 2013). Though both wind and storm surge by hurricanes produce damages in many cases, specifically the most damage resulted from storm surge in New York City during Sandy.

The indirect damage due to business interruption resulted primarily from interconnected risks within infrastructures. The concept of interdependence of risks is very important to formulate a strategy to reduce disaster risks. The interconnected risks of critical system failures may relate to catastrophic cascade effects due to functional interdependence or physical proximity. Heterogeneous networks, in general, are particularly vulnerable to attacks in that a large-scale cascade may be triggered by disabling a single key node (Motter & Lai, 2002). Therefore, national disaster risk management strategies must address interdependence between different sectors of critical infrastructure. This interdependence is also enhanced by an increasing degree of economic integration. Mapping and modelling of complex risks enable policy makers to address hazards and their economic cascading effects that do not travel linear pathways(Radisch, 2013). The concept of interconnected risks is not explicitly included in Indicator in Hyogo Framework for Action (HFA). Yet, several indicators 4.2, 4.3, 4.6, and 5.3 are relevant to interconnected risks (Table 1).

Indicator	Descriptions of indicator
Indicator 4.2	Social development policies and plans are being implemented to reduce the vulnerability of populations most at risk
Indicator 4.3	Economic and productive sectorial policies and plans have been implemented to reduce the vulnerability of economic activities
Indicator 4.6	Procedures are in place to assess the disaster risk impacts of major development projects, especially infrastructure
Indicator 5.3	Financial reserves and contingency mechanisms are in place to support effective response and recovery when required.

Table 1 : Relevant indicators in HFA to Interconnected and interdependent risks

In the HFA progress reports to review the progress of the HFA, some countries such as the United States, Germany, Bulgaria, and Australia, have recognized the importance of the interconnected risks of critical system failures. Government operations and business activities heavily depend on reliable public infrastructures and utilities, efficient urban systems, an educated workforce and reliable public service. Therefore, reducing disaster risks in critical infrastructures produces favorable outcomes for both the public and private sectors.

Hurricane Sandy is a very important example of examining interconnected risks posed by disasters because it caused extensive damage to electric transmission and distribution infrastructures in the Northeast and Mid-Atlantic region of the United States. Both electric and petroleum infrastructures are critically interdependent with other infrastructures such as water, communication, transportation, food supply and private sector supply chains. For example, approximately 8,500,000 customers lost power at peak during Sandy (U.S. Department of Energy, 2013). The hurricane also damaged the region's petroleum infrastructures. As of November 6 2012, two refineries in the path of Sandy, i.e. Hess Port Reading Refinery in Port Reading, New Jersey and Bayway Refinery Phillips 66 in Linden, New Jersey, were shut down. This resulted in the loss of 26.3% of the total operating capacity of 1,170,200 Barrels Per Day (U.S. Department of Energy, 2012). The loss of the electricity and fuel sectors propagated to other sectors. Gas stations in NJ could not operate because of the outage. Three health care facilities in Manhattan and Brooklyn had to emergently evacuate all patients due to the outage.

The goal of this paper is to investigate the impact of Hurricane Sandy from the perspective of interdependence between different sectors of critical infrastructure and identify interconnectedness of risks posed by the natural hazard. The collapse of power utilities and petroleum infrastructures triggered failures in other infrastructure systems such as health care facilities, public transportation systems, the supply of necessities, and emergency facilities in the New York metropolitan area. The study examines the impact of the hurricane on different critical infrastructures such as utility, transport, and healthcare by combining hazard maps of actual inundation areas with maps of critical infrastructure. Areas and sectors where interdependent risks exist are identified. Maps that identify vulnerable sectors which tend to increase interconnected risks are developed. A scenario that produced domino effects in the case of Hurricane Sandy is also developed.

2. Literature Review

Methodology of previous studies

There are several ways to estimate the direct and indirect economic losses induced by interdependent risks. Satumtira and Dueñas-Osorio (2010) review research in the field of infrastructure interdependence from the 1980's to 2010. They categorize four methodologies under mathematical models in the field: Agent-based, input-output, network or graph theory, and all other emerging models. One of the main approaches is to use the input-output model proposed by Leontief (1986). Indirect economic losses are usually quantified in terms of production losses in the affected region with the help of input-output models (Okuyama, 2007). For example, Wei, Dong, and Sun (2010) deploy the inoperability Input-Output Model (IIM) to assess the impacts of supply chain disruptions. Wei et al. (2010) formulate an Ordered Weighted Averaging Operator to evaluate the interdependency matrix, which is a key component of the IIM. Furthermore, Kajitani and Tatano (2014) investigate a method for estimating the production capacity loss rate (PCLR) of industrial sectors damaged by a disaster. They propose a method of PCLR estimation that considers the two main causes of capacity losses, namely damage to production facilities and disruption of lifeline systems. This study utilizes indirect damages of each sector to estimate the degree of interdependence between each sector. To estimate indirect damages of each sector, this study uses GIS mapping and compares the hypothetical damages calculated from the inundation areas with actual damages reported by government agencies.

Economic Losses through Interdependent Infrastructures

Some studies have investigated the damage of Sandy through direct and indirect economic losses. Kunz et al. (2013) concludes that Hurricane Sandy is the second costliest hurricane in the history of the United States next to Hurricane Katrina. The direct economic losses are estimated between USD 78 and 97 billion in the US (Kunz et al., 2013) while the direct economic losses in New York City are estimated between USD 15 billion (Cuomo, 2012) and USD 19 billion (DeStefano, 2012). By comparing Sandy with similar past events, Kunz et al. (2013) calculate the value of power outage disruption to be USD 16.3 billion. Using the input-output approach and modeling sector-specific dependencies, Kunz et al. (2013) quantify total business interruption losses to be between USD 10.8 and 15.5 billion.

Descriptions of the Damages for Each Sector

New York City Government (2013) summarizes the damages to various critical infrastructure: buildings, utilities, liquid fuels, healthcare, telecommunications, transportation, water and wastewater, and other critical networks. This section of the study encapsulates the damages outlined in a report by New York City Government (2013) while demonstrating interdependent features of critical infrastructures in various parts of damages. It also demonstrates the electricity sector played a crucial role in citywide critical infrastructures during Sandy.

In the building sector, Sandy flooded approximately 88,700 buildings, or 9% of the city's building stock. These buildings encompassed 662 million square feet of space that included more than 300,000 housing units and 23,400 businesses. More than 100 of these impacted homes and businesses were destroyed by storm-related fires. Because of damages to electrical equipment in their buildings, 55,000 electricity customers lost power.

Within the utility sector, the most damage was suffered by the electric system. The total number of New York electric customers who lost power as a result of Sandy eventually reached 800,000, which is equivalent to more than 2 million people. Damages to substations produced especially large losses. In total, about 370,000 electric customers in New York City were left without power due to network shutdowns and substation flooding in Manhattan, Brooklyn, Queens, and Staten Island. The vulnerability of substations in networks was reported by various past studies that examined cascading failures in the power grid (Albert, Albert, & Nakarado, 2004; Kinney, Crucitti, Albert, & Latora, 2005). Damaged substations also led to stresses within the city's transmission system, which became another cause of power outages. As a result, 140,000 customers lost power. As an example of interdependent infrastructure, the vulnerability of building structures caused approximately 55,000 customers to lose power because of damage to electrical equipment in their buildings. Electric systems needed up to 14 days to be restored. The natural gas sector was generally resilient compared to the electric system. Approximately 84,000 natural gas customers ultimately lost service.

The fuel sector also became the source of propagating risks to different sectors. Regional refineries were partially shut down before the storm to minimize damage to equipment. This eliminated 35 to 40% of the region's total supply capacity preemptively. Storm surge damaged electrical equipment at two of the six refineries, further reducing regional refining capacity by 26%. Damage to storage tanks at several terminals resulted in spills into area waterways. In addition, the large amount of storm-related debris in the harbor immediately following Sandy prevented tanker and barge shipments, which reduced supply capacity by an additional 20 to 25%. Major pipelines were also closed for four days due to extensive power outages in New Jersey. This reduced total supply in the region by another 35 to 40%.

The waste management sector experienced fewer damages partly because the facilities housed vehicles that were moved out of the storm surge inundation area. Nonetheless, 44 heavy-duty and 31 light- and medium-duty vehicles were damaged or destroyed by floodwaters. In contrast, the larger waste disposal system was affected by Sandy. The Essex County Resource Recovery Facility preemptively shut down its boilers, and could not operate for a subsequent two weeks due to significant floods. Eventually, over 10% of its disposal capacity was lost.

Sandy's impact on the health sector was significant. Five acute care hospitals and one psychiatric hospital closed. This caused the emergency evacuation of nearly 2,000 patients. Of these, three hospitals—New York Downtown (Manhattan), the Veterans Affairs New York Harbor Hospital (Manhattan), and South Beach Psychiatric Center (Staten Island)—closed preemptively. Three other hospitals—New York University's Langone Medical Center (Manhattan), Bellevue Hospital (Manhattan), and Coney Island Hospital (Brooklyn)— shut down due to the failure of electrical and mechanical systems including emergency power systems. In addition, residential providers also had significant damages. Sixty-one nursing homes and adult care facilities were in areas impacted by power outages and/or flooding. This resulted in reducing bed capacity by 8% citywide. In addition, due to utility outages and damage to building electrical equipment, 26 nursing homes and adult care facilities had to shut down, and another five partially evacuated, decreasing residential capacity by 4,600 beds citywide. 500 community-based providers (5% of total providers) were located in inundated areas while 1200 providers (12% of total providers) were in areas that experienced power outages only. The impact of failures in the electricity sector on the health sector, one of the examples of interdependent critical infrastructure, was significant.

Sandy also enormously affected every transportation system. Six vehicular tunnels went out of service. All six of the subway tunnels connecting Brooklyn to Manhattan, one tunnel from Queens to Manhattan, and one tunnel from Long Island City to Greenpoint were flooded (Table 2 and Figure 1). In addition, The PATH tunnels under the Hudson River and the railroad tunnels under the East River also were flooded. Because many tunnels were inundated for days, water and corrosion damages to delicate equipment were exacerbated. This shutdown of various transportation systems impacted about 8.6 million daily public transit riders, 4.2 million drivers, and 1 million airport passengers (Table 2).

Name of Crossings (Year of Construction)	**Transpor-tation Line**	**Number of Users**	**Causes of Damage**	**Impacted Periods**
Harlem River Lift Bridge (1955)	N/A	275,000 daily riders	The facility houses for the bridge were damaged by saltwater.	Closed for trains 3 days Unable to open Bridge for ships 10 weeks
53 Street Tube (1933)	E Line & M Line	275,000 daily riders	500,000 gallons of saltwater	Closed 7 days
Steinway Tube (1910's)	7 Line	200,000 daily riders	1 million gallons of saltwater	Closed 6 days
Queens-Midtown Tunnel (1940)	N/A	81,000 daily vehicles and 1,100 buses	12 million gallons of saltwater	10 days to fully open
LIRR East River Tunnels (1910)	LIRR+Amtrak	226,000 daily riders	13.6 million gallons of saltwater	12 days to fully open
Greenpoint Tube (1930's)	G Line	55,000 daily riders	3 million gallons of saltwater	Closed 10 days
Canarsie Tube (1920's)	L Line	200,000 daily riders	7 million gallons of saltwater	Closed 11 days
Rutgers Tube (1930's)	F Line	130,000 daily riders	1.5 million gallons of saltwater	Closed 7 days
Cranberry Tube (1930's)	A Line & C Line	230,000 daily riders	1.5 million gallons of saltwater	Closed 7 days
Clark Tube (1910's)	2 Line & 3 Line	145,000 daily riders	.5 million gallons of saltwater	Closed 6 days
Montague Tube (1920's)	R Line	65,000 (pre-storm) daily riders	27 million gallons of saltwater	Closed 53 days
Joralemon Tube (1908)	4 Line & 5 Line	185,000 daily riders	No long-term flooding	Closed 6 days
Brooklyn-Battery Tunnel/ Hugh L.	N/A	47,700 daily vehicles and	60 million gallons of saltwater	21 days to fully open

Carey Tunnel (1950)		3,100 buses		
Rockaway Line (1950's)	A Line	31,000 daily riders (pre-Sandy)	High winds and the heavy tidal surge destroyed the line (3.5 miles long).	Closed 7 months

Source : *Metropolitan Transportation Authority (2013)*

Table 2 : Metropolitan Transportation Authority (MTA) River Crossings Damaged by Sandy

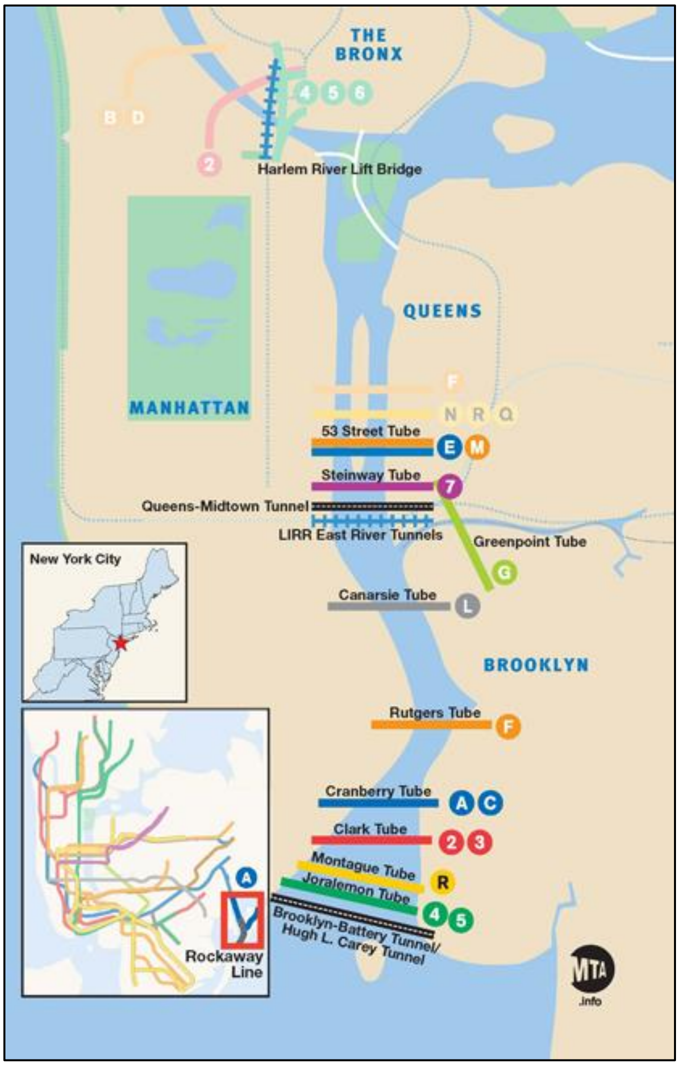

Figure 1 : MTA River Crossings Damaged by Sandy (Metropolitan Transportation Authority, 2013)

3. Methodology and Data

The damage to the critical infrastructures depends on the type of disaster and its temporal and spatial characteristics. From among these, the most critical factor affecting cascading infrastructure failure is a spatial characteristic of each sector. Therefore, this paper focuses on estimating the direct and indirect damages caused by Hurricane Sandy to each sector using GIS techniques.

The total coastal areas of NYC inundated by Sandy were about 216.4 square kilometers. Since many parts of the city's critical infrastructures were within the inundated areas, the critical infrastructures were damaged directly by storm surge and wind. In addition, due to the cascading effects, the infrastructures were indirectly damaged. The sectors affected by

Sandy were identified as building, utility, fuel, health care, telecommunication, transportation, water and wastewater, food, and waste. The direct and indirect damages in each sector were defined in Table 3.

Sector	Direct Damage	Indirect Damage
Building	Physical damage	•Loss of utility, access to transportation, water, waste water, waste
Food	Physical damages to facilities	•Stopped operations due to electrical outage, the lack of access to water, transportation
Liquid fuel	Physical Damages to refineries, pipelines, gas stations	•Stopped operations due to electrical outage, the lack of access to water, wastewater, transportation, and licensing issues
Health care	Physical damages to buildings	•Stopped operations due to electrical outage, the lack of access to water, wastewater, transportation
Telecommunication	Physical damages to facilities	•Stopped operations due to electrical outage
Transportation	Physical damages to tunnels, subway lines, closure of bridges	•Lack of fuels •Stopped operations due to electrical outage
Utility (electricity)	Physical damages to substations, distribution and transmission lines	•Preemptive closure, lack of supply from New Jersey, adjustment due to the overload
Water and waste water	Physical damages to facilities	•Stopped operations due to electrical outage
Waste	Physical damages to facilities and trucks	•Stopped operations due to electrical outage

Table 3 : Direct and indirect damage in each sector

We define direct damages as the physical damages caused by Sandy in each sector. The indirect damages were caused by functional problems such as power outage, overload, and impacts of failures in other sectors. The direct and indirect relationship of each sector based on Table 3 is shown in Figure 2. The directly destroyed parts of an infrastructure indirectly damaged other parts of the infrastructure as well as other infrastructures. For example, due to the electric outage, gas stations could not provide fuels even if they have sufficient gas supply. This paper defines the cascading effect as the process in which critical infrastructures were wrecked continuously as shown symbolically in Figure 2. The most critical infrastructure in NYC's case was the electricity sector because it indirectly affected other sectors such as transportation, telecommunication, and healthcare sectors; there is no specific alternative to overcome the problem. The degree of interdependency between each sector determines indirect damages triggered by a sector. The other way, if indirect damages of each sector are calculated, they could provide a guideline to estimate the degree of interdependency between each sector.

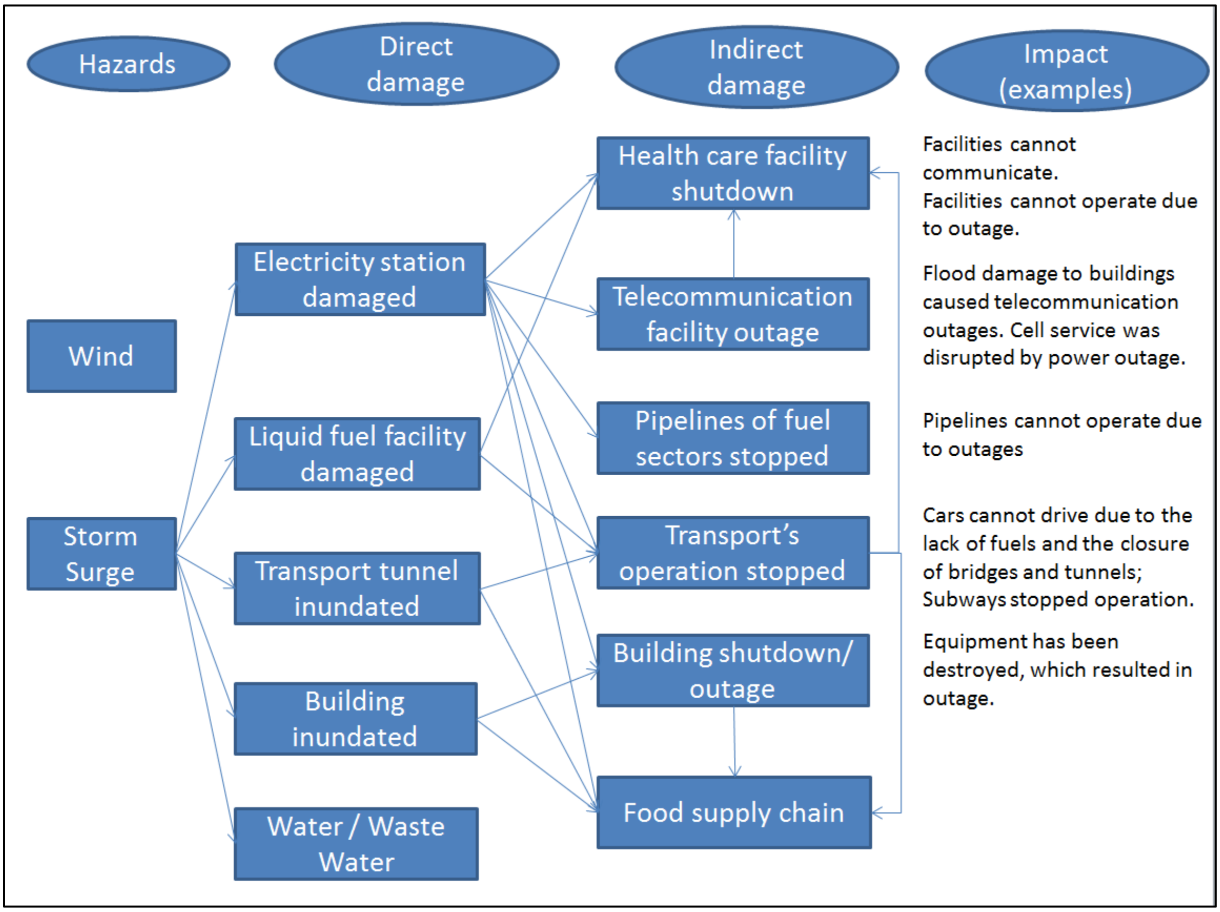

Figure 2 : Schematic Features of Interdependent Infrastructures

In this study, the spatial information of each sector is used to estimate the damage. The areas that experienced direct and indirect damage in the electricity sector are estimated based on the causes of the electricity outage reported by New York City Government (2013). Directly damaged area is defined as one that lost power due to flooded transmission substation, flooded area substation, or preemptive shutdown. Areas that preemptively shut down facilities are considered directly damaged areas because they were flooded after the landing of Sandy. In contrast, indirectly damaged area is defined as one that lost electricity due to the transmission system overload. This study considers other sectors (not electricity) to be directly damaged if they are located in inundated areas on the flood map. Damages to other sectors are considered indirect if they were not inundated but affected by Sandy through interconnected infrastructures. For example, if a building is not inundated but it cannot pump drinking water up to higher floors without power, the damage is indirect. An electricity outage map is used to estimate the indirect damages to other affected sectors. The concept diagram is shown in Figure 3. The collected GIS data was summarized in Table 4.

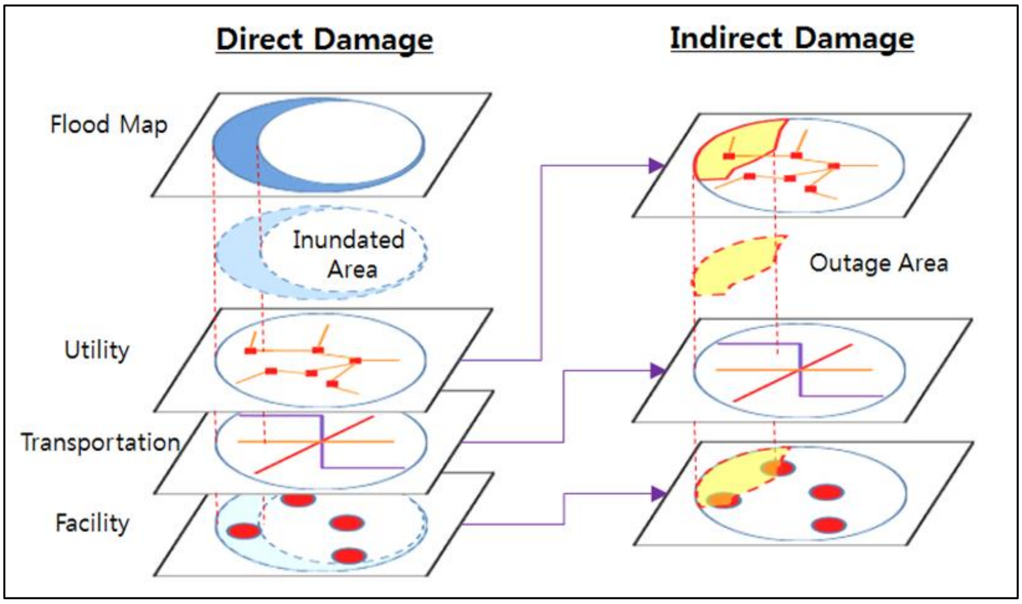

Figure 3 : Concept diagram to estimate the direct and indirect damages

GIS Data	Data sources
Inundated area	• FEMA Modeling Task Force(MOTF) (2013a)
Damaged building	• FEMA Modeling Task Force(MOTF) (2013b)
Electricity outage territory	• New York City Government (2013)
Healthcare location	• New York City Government (2012)
Transportation routes (truck, bus, and subway)	• NYS GIS Clearinghouse (2013)

Table 4 : GIS data sources

4. Result of the Analysis

4.1 Estimation of direct and indirect damages

This study assumes the infrastructure within inundated areas to be directly damaged. We consider the infrastructure elements which were not flooded but lost power to be indirectly damaged. The direct and indirect damages are estimated using the spatial information of each sector (Figure 3). The estimated damages are summarized in Table 5 and mapped in Figure 4.The area of 173 square kilometers, which was about 12.7% of NYC, was affected by electricity outage or overload, including both the direct (9.9% of NYC) and indirect damages (2.8% of NYC). In the transportation sector, 10.7% of the total transportation mileage was directly damaged while 19.4% was indirectly damaged. In the health care sector, the direct damage was about 7.5% of the total number of facilities while the indirect damage was 2.4% of the total number of health care facilities. 7.0% of the number of buildings was built in the directly damaged areas while 16.8% were built in the indirectly damaged areas. Thus, in these sectors, the direct damage ranged from 7.0 to 10.7% and the indirect damage ranged from 2.4 to 19.4%. The variance of the direct damage in each sector is relatively small, while the variance of the indirect damage is large. This means that the degree to which one sector affects other sectors depends on the degree of interdependence among each sector. As a result, the transportation sector experienced direct damage by the storm surge the most, followed by electricity, health care, and building sectors. The most severely indirectly damaged sector by the electricity outage was transportation, which is followed by building, and health care sectors.

Sectors	Direct damage	Indirect damage
Electricity	9.9%	2.8%
Transportation	10.7%	19.4%
Health care	7.5%	2.4%

Building	7.0%	16.8%

Table 5 : Direct and indirect damages in each sector

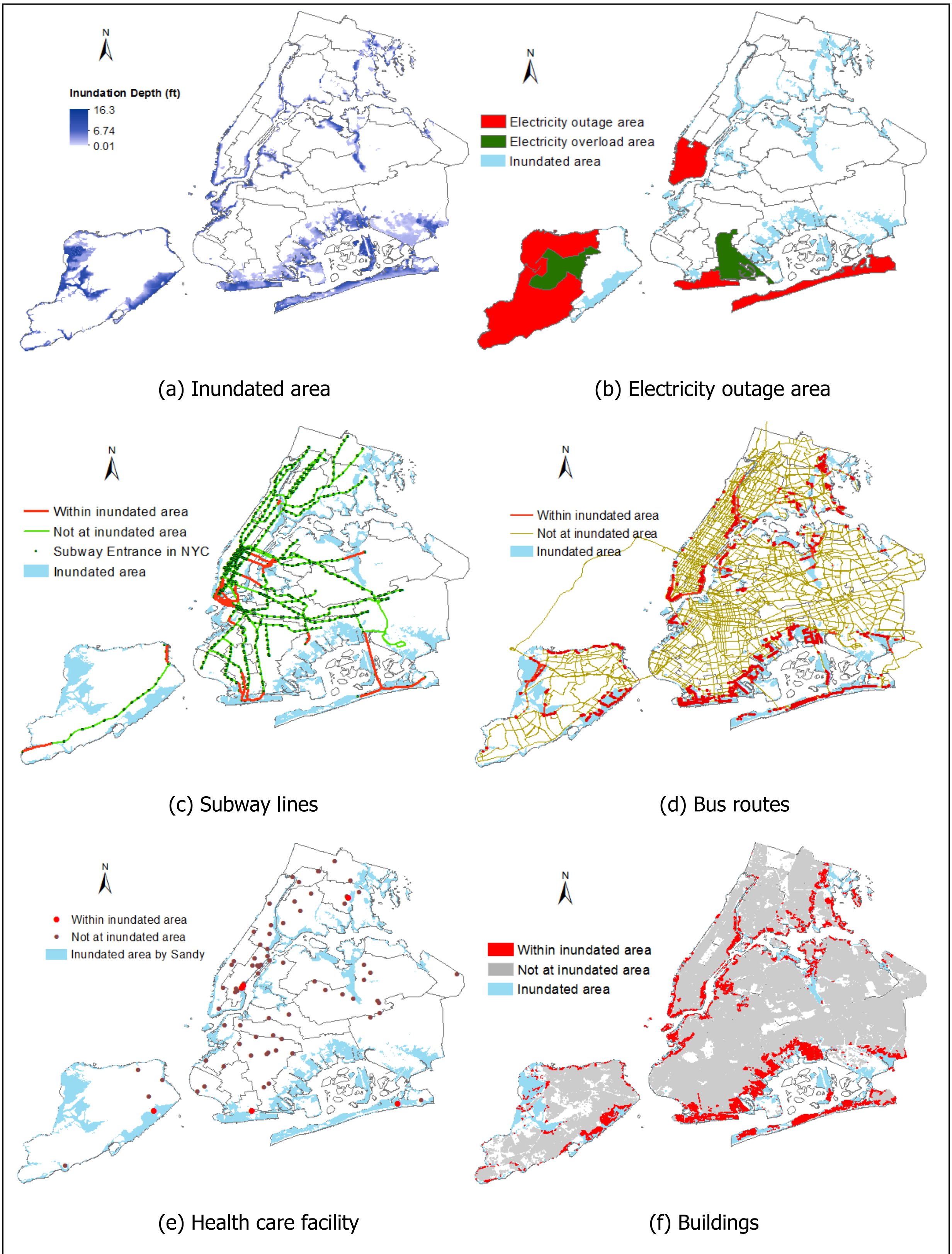

Figure 4 : The spatial information of each sector affected by the storm surge in the NYC

4.2 Comparing damages calculated based on inundation areas with actual changes in service reported in government's reports

We compare the damaged calculated in Section 4.1 with numbers reported in New York City Government (2013). This paper estimates 7.0% and 16.8% in direct and indirect damages in the building sector. New York City Government (2013) reported 9% of the city's building stock was flooded, which is between our estimates of direct and indirect damages. In the healthcare sector, 8% of bed capacity and 17% of buildings of housing community-based providers are reported in New York City Government (2013). The percentage of affected bed capacity (8%) is close to 7.5%, which is our estimate in the direct damage of the health sector. New York City Government (2013) describes that east river crossing reduced by 86.8% on October 31, which is two days after Sandy. This number is not similar to our estimates, which are 10.7% for the direct damages and 19.4% for the indirect damage. Comparing our estimates with impacts in the transportation sector is not straightforward because the impact on the transportation sector includes various factors related to indirect damages. For example, New York City Government (2013) measures the impacts in the sector by referring to data such as changes in high way travel speeds and river crossings in addition to the number of impacted passengers, drivers and public transit riders. Therefore, it is essential to improve the methodology to estimate the impact in the transportation sector.

5. Initiatives to Prepare for Future Disasters

New York City government and public-benefit corporations have already started new initiatives to increase the resilience of infrastructure. In December 2012, New York City started the Special Initiative for Rebuilding and Resiliency (SIRR) to create a stronger New York City, with a long-term focus on preparing for and protecting against the impacts of climate change. SIRR released a final report in June 2013 to propose 250 actionable recommendations. The city's proposals, if they are all enacted, would cost approximately $ 20 billion (Kia Gregory, 2013). In addition, our study shows that the electricity sector played a central role in critical infrastructures. Thus, Con-Edison, which provides electric service in New York City, has already spent about $105 million on resiliency measures in 2013, and proposes to spend more than $1 billion in all through 2016 (Fleming, 2014). To make sure that their system is less susceptible to similar storms, Con-Edison has embarked on a long-term plan, focusing on the following three areas: fortifying the electric, gas, and steam systems against future storms; decreasing time to restore power, and enhancing storm planning and restoration processes; and improving the flow of information to customers and other stakeholders (Table 6).

The U.S. Department of Transportation awarded approximately $886 million to help the New York Metropolitan Transportation Authority (MTA) continue rebuilding and replacing transportation equipment and facilities damaged by Sandy (U.S. Department of Transportation, 2014). Of $886 million, about 60% ($535 million) is for critical repairs primarily to three damaged under-river tunnels—Greenpoint, Montague, and Steinway. About 16% ($138.9 million), the second largest portion, will be spent for repairing damaged substations and power infrastructure for the Long Island Rail Road (LIRR) and Metro-North Railroad.

Focused Areas	Proposed Plans
Fortifying the electric, gas, and steam systems against future	• Redesigning underground networks • Flood-proofing vulnerable facilities • Investing in more smart-grid technologies

storms	• Upgrading overhead systems • Burying select overhead lines • Protecting the gas systems from flooding • Protecting our generating facilities • Reinforcing critical tunnels • Hardening internal communications infrastructure • Benchmarking and evaluating new capabilities and technology solutions
Improving estimated times of restoration, and enhancing storm planning and restoration processes	• Storm planning • Securing external workforce and resources • More effective restoration and accurate Estimated Times of Restoration
Improving the flow of information to customers and other stakeholders	• Strengthening community relations • Collaborating with government (e.g. An enhanced Municipal (Muni) Liaison Program, new feeder maps for individual municipalities, and annual exercises) • Expanding and enhancing customer information flow (e.g. Apps for iPhone and Android phones, an opt-in text message service, and additional call-center agents)

Source: Consolidated Edison Co. of New York (2013)

Table 6 : Focused areas by Consolidated Edison Co. to prepare for future similar storms

6. Summary

Hurricane Sandy caused enormous economic damages because of the interdependent infrastructure systems in New York City. This study shows that the electricity sector plays a central role in citywide critical infrastructures, particularly in the healthcare, transportation, and liquid fuel sectors. This study also estimates direct and indirect damages by combining inundation maps with maps of each critical infrastructure. This study's estimates of damages are close to the damages reported by New York City Government (2013) in the building and health care sectors. In contrast, the direct and indirect damages in the transportation sector are not estimated well by our study because the damages in the sector are influenced by other external factors and are not easily measured.

The current plans proposed by New York City Government and relevant public-benefit corporations focus more on reducing direct damages than indirect damages. For example, New York City's building sector initiatives in New York City Government (2013) contain various methods to construct new buildings and retrofit old buildings in the floodplain to the highest resiliency standards. Considering the result of this study that the indirect damages to the building sector were larger than direct damages, new plans must reduce indirect damages with a focus on interdependence between sectors. For example, the electricity sector must reduce feeder segment size.

Studies that examine interdependent infrastructures face data collecting challenges because they require data from different sectors, which are sometimes spread over different jurisdictions. Rinaldi, Peerenboom, and Kelly (2001) point out the lack of data in interdependent infrastructure studies. Also, future studies must estimate the economic damages caused by interdependent infrastructure risks. For example, in the transportation sector, approximately 8.6 million daily public transit riders, 4.2 million drivers, and 1 million airport passengers were impacted by the shutdown of not only the transportation system but also other sectors such as building and telecommunication sectors (New York City Government, 2013). Future studies about Sandy must improve their methodology to estimate damages in the transportation sector caused by interdependent risks, for example, damages due to power outages. They also must address economic damages.

Bibliography

Albert, Réka, Albert, István, & Nakarado, Gary L. 2004. Structural vulnerability of the North American power grid. *Physical review E,* Vol. 69, Issue 2: 025103.

Consolidated Edison Co. of New York, Orange and Rockland Utilities. 2013. *Post Sandy Enhancement Plan*. New York, USA.

Cuomo, Andrew M. 2012. *Governor Cuomo holds meeting with New York's congressional delegation, Mayor Bloomberg and regional county executives to review damage assessment for the State in the wake of Hurricane Sandy*. Retrieved March 14th, 2014, from http://www.governor.ny.gov/press/11262012-damageassessment.

DeStefano, Anthony M. November 26, 2012. Bloomberg: Sandy Losses Total $19 billion. Retrieved March 14th, 2014, from http://www.newsday.com/bloomberg-sandy-losses-total-19-billion-1.4262746.

FEMA Modeling Task Force(MOTF). 2013a. *GIS Data/MOTF/Hurricane Sandy*. Retrieved March 14th, 2014, from: http://184.72.33.183/GISData/MOTF/Hurricane%20Sandy/.

FEMA Modeling Task Force(MOTF). 2013b. *GISData Imagery-Based_Assessments*. Retrieved March 14th, 2014, from: http://184.72.33.183/GISData/Imagery-Based_Assessments/.

Fleming, Wilder. January 22, 2014. Con Ed gets a post-Sandy reboot, *The New York World*. Retrieved from March 14th, 2014, http://www.thenewyorkworld.com/2014/01/22/con-ed-sandy/.

Kajitani, Yoshio, & Tatano, Hirokazu. 2014. Estimation Of Production Capacity Loss Rate After The Great East Japan Earthquake And Tsunami In 2011. *Economic Systems Research,* Vol. 26, Issue 1: 13-38. doi: 10.1080/09535314.2013.872081

Kia Gregory, Marc Santora. June 11, 2013. Bloomberg Outlines $20 Billion Storm Protection Plan, *New York Times*. Retrieved March 14th, 2014, from http://www.nytimes.com/2013/06/12/nyregion/bloomberg-outlines-20-billion-plan-to-protect-city-from-future-storms.html.

Kinney, R., Crucitti, P., Albert, R., & Latora, V. 2005. Modeling cascading failures in the North American power grid. *The European Physical Journal B - Condensed Matter and Complex Systems,* Vol. 46, Issue 1:101-107. doi: 10.1140/epjb/e2005-00237-9

Kunz, M., Mühr, B., Kunz-Plapp, T., Daniell, J. E., Khazai, B., Wenzel, F., . . . Zschau, J. (2013). Investigation of superstorm Sandy 2012 in a multi-disciplinary approach. *Nat. Hazards Earth Syst. Sci. Discuss.,* Vol. 1, Issue 2:625-679. doi: 10.5194/nhessd-1-625-2013

Leontief, Wassily (1986). *Input output economics*. New York, USA. Oxford University Press.

Metropolitan Transportation Authority. 2013. MTA River Crossings Damaged by Sandy. *Superstorm Sandy: One Year Later.* Retrieved February 7th, 2014, from http://web.mta.info/sandy/river_crossings.htm

Motter, Adilson E., & Lai, Ying-Cheng. 2002. Cascade-based attacks on complex networks. *Physical Review E,* Vol. 66, Issue 6:065102.

New York City Government. 2012. *New York City Selected Facilities and Program Sites 2005*. Retrieved March 14th, 2014, from: http://www.nyc.gov/html/dcp/html/bytes/applbyte.shtml

New York City Government. 2013. NYC PlaNYC: A Stronger, More resilient New York. New York, USA.

NYS GIS Clearinghouse. 2013. Retrieved March 14th, 2014, from: http://gis.ny.gov/index.cfm

Okuyama, Yasuhide. 2007. Economic modeling for disaster impact analysis: past, present, and future. *Economic Systems Research,* Vol. 19, Issue 2:115-124.

Radisch, Jack; Gamper, Catherine. 2013. *Interconnected, inter-dependent risk: Input paper for Thematic Research Area 16*. Retrieved March 14th, 2014, from http://www.preventionweb.net/english/professional/networks/private/hfa-thematic-review/documents/concept/GAR15_Concept_Note_RA16.docx.

Rinaldi, Steven M, Peerenboom, James P, & Kelly, Terrence K. 2001. Identifying, understanding, and analyzing critical infrastructure interdependencies. *Control Systems, IEEE,* Vol. 21, Issue 6:11-25.

Satumtira, Gesara, & Dueñas-Osorio, Leonardo. 2010. Synthesis of modeling and simulation methods on critical infrastructure interdependencies research *Sustainable and Resilient Critical Infrastructure Systems* (pp. 1-51): Berlin, Germany: Springer.

U.S. Department of Energy. 2012. *Hurricane Sandy Situation Report # 19* Retrieved March 14th, 2014, from http://www.oe.netl.doe.gov/docs/2012_SitRep19_Sandy_11062012_300PM.pdf.

U.S. Department of Energy. 2013. *Comparing the Impacts of Northeast Hurricanes on Energy Infrastructure*. Retrieved March 14th, 2014, from http://www.oe.netl.doe.gov/docs/Northeast%20Storm%20Comparison_FINAL_041513c.pdf.

U.S. Department of Transportation. 2014. *U.S. Department of Transportation Awards $886 Million to New York MTA for Ongoing Hurricane Sandy Recovery Efforts*. Retrieved March 14th, 2014, from http://www.dot.gov/briefing-room/us-department-transportation-awards-886-million-new-york-mta-ongoing-hurricane-sandy.

Wei, Hairui, Dong, Ming, & Sun, Shuyu. (2010). Inoperability input-output modeling (IIM) of disruptions to supply chain networks. *Systems Engineering,* Vol. 13, Issue 4:324-339.