Center for Disaster Management and Risk Reduction Technology

CEDIM FDA-Report on Hurricane *Sandy* 22-30 October 2012

- 2nd Report: Information as of 08 November 2012, 18 UTC -

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1 Hazard Information

1.1 Summary

"Sandy", an Extraordinary Hurricane
➢ ***Low probability of occurrence over the U.S. East Coast, but high impact!*** ➢ ***Record breaking spatial extent: 1700 km!*** ➢ ***Record breaking high water levels at the East Coast: ~3 m!*** ➢ ***Unusual track: due to blocking by high pressure system!*** ➢ ***Unusually high sea surface temperature along the track: It provided additional energy!*** ➢ ***Extratropical transition during landfall: It further strengthened the storm system!*** ➢ ***Interaction with a huge upper level trough: It increased the hurricane's severity!*** ➢ ***Time of occurrence end of October, which is outside the peak hurricane season!***

From October 22 until October 29, 2012, Hurricane *Sandy* made its way from the Caribbean Sea into the Atlantic Ocean and finally entered the United States on the morning of October 30, not far from New York. According to the Saffir-Simpson Hurricane Wind Scale with a 1 to 5 rating, *Sandy* was a category 2 Hurricane (154-177 km/h). Along its path *Sandy* caused many fatalities on Jamaica, Haiti and Cuba and left many people homeless (see section 2). The interaction between *Sandy* and an extra-tropical weather system created a huge storm that made landfall in the U.S. and affected large areas; it was associated with high impact weather as far as the Great Lakes and even beyond in southern and southeastern Canada. Because *Sandy* showed characteristics of both tropical and extratropical systems, it was termed *Frankenstorm* by some media outlets. Due to the huge spatial extension and intensity *Sandy* caused massive damage and losses in the densely populated East Coast states.

1.2 Evolution of Hurricane *Sandy*

Sandy was added to the list of 2012 hurricanes on October 22; it was tropical storm system #18 so far this year in the North Atlantic region. Huge convective cloud structures began to organize 250 kilometers north of Panama. With further strengthening, *Sandy* was classified as a category 1 hurricane on October 24, just before crossing the island of Jamaica. Heading north, the hurricane approached Cuba, where the storm center arrived 24 hours later. Associated with heavy rain *Sandy* crossed the eastern parts of Cuba and reached its maximum intensity. Between 06 and 12 UTC on October 25, the hurricane had 1min-sustained winds of 95 kt (176 km/h) and gusts around 110 kt (204 km/h) making *Sandy* a category 2 hurricane.

Constant in intensity, *Sandy* passed the Bahamas on October 26. The following day the hurricane made a right turn towards the northeast and started to lose strength. More and more forecast models began to predict a scenario where *Sandy* was expected to make landfall at the East Coast of the U.S. Even time and location of landfall turned out to be quite consistent between the models, the hurricane was expected to arrive in the night October 29/30 somewhere along the Delaware/New Jersey Atlantic coast.

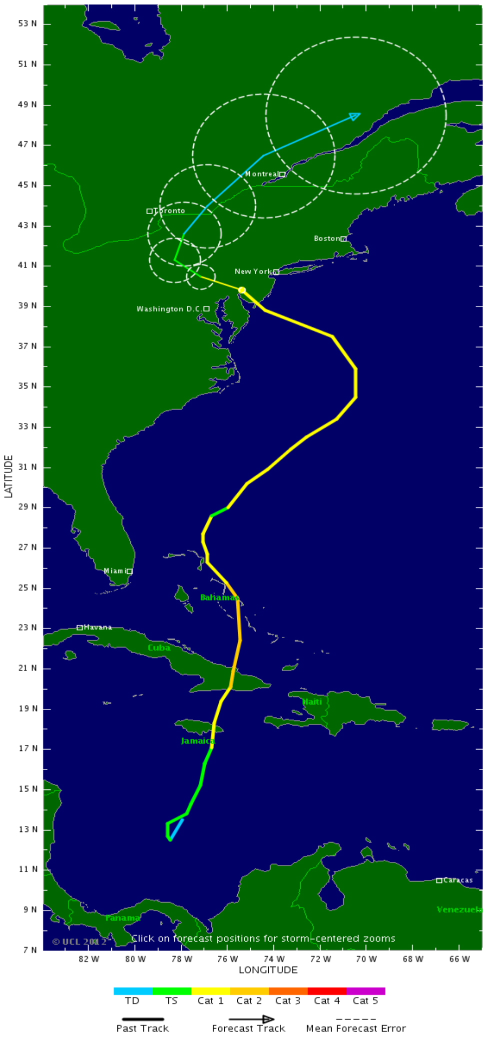

Figure 1: Track of Hurricane *Sandy*
Image Credit: tropicalstormrisk.com

Some hours before entering the U.S. mainland, the hurricane intensified again and showed mean wind speeds of 80 kt (148 km/h). The storm center itself crossed the coastline around 00 UTC on Oct 30. On Oct 30 and 31 *Sandy* slowly travelled northward and finally weakened.

1.3 Affected areas and precipitation in the Caribbean and on the Bahamas

Over the eastern parts of Jamaica (which were affected first), more than 200 mm rainfall was recorded, while the western parts did not receive significant rainfall. Also the southwest of Haiti was affected by heavy convective rain with near to 200 mm rainfall. *Sandy* further moved over Cuba, but rainfall exceeded 200 mm only in some easterly and central provinces. Obtained from satellite sensors, the precipitation signals showed values around 250 mm in the vicinity of the Bahamas. Furthermore, widespread flooding occurred in the Dominican Republic and Puerto Rico.

1.4 Affected areas, wind and precipitation in the U.S.

Cloud and precipitation areas covered most of the northeastern parts of the U.S. from October 29 afternoon onwards. Many locations between the Atlantic coast and the Great Lakes experienced wind gusts of 75 km/h or more (Figure 2). Strongest winds exceeding 100 km/h occurred along and near the coastlines of Virginia, Delaware, New Jersey and parts of New York; the JFK airport at New York recorded a wind gust of 128 km/h.

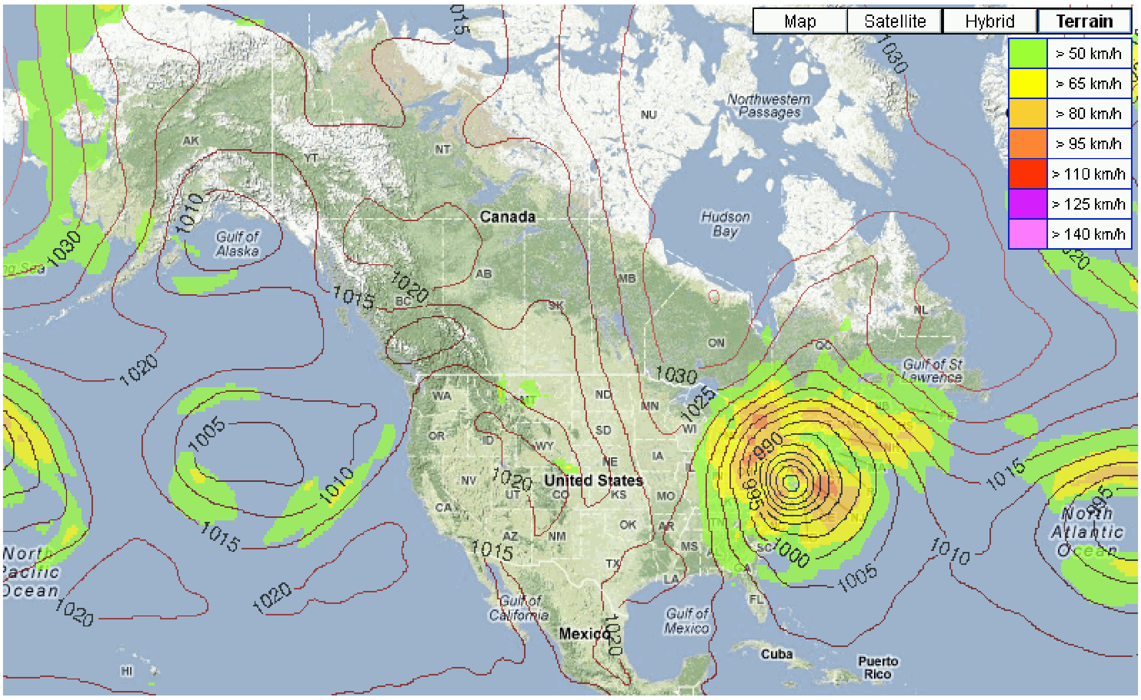

Figure 2: Wind peak gusts on October 30, 2012, 06 UTC (GFS-model run)
Image Credit: wettergefahren-fruehwarnung.de

While strong storm surge (see section 1.7) along the coastlines of Virginia, Delaware, New Jersey and New York caused severe problems to coastal highways and other kinds of infrastructure, heavy precipitation was responsible for some flooding and high river levels elsewhere. Pennsylvania, Maryland, New Jersey, Delaware and Virginia received rain amounts between 100 and 200 mm. Wallops Island (Virginia) recorded a total of 214 mm within 48 hours, Baltimore/Washington Int. Airport recorded 150 mm. Most rainfall occurred in the vicinity of the Chesapeake Bay (Easton, MD, 319 mm).

The intrusion of cold air near the surface from the northwest led to heavy snowfall especially in the southern and central Appalachian Mountains. In mountainous areas of Tennessee, Kentucky, North Carolina, West Virginia and Virginia, people experienced blizzard-like conditions and snow depths of up to 1 meter in the area between Elkins and Beckley (West Virginia).

Table 1: Selected recordings of peak wind gusts and precipitation amounts during *Sandy*, October 29 and 30, 2012. Data source: NOAA Global Summary of the Day / Ogimet.com

Station	Oct 29	Oct 30	Oct 29	Octo 30
	peak wind gusts [km/h]		precipitation [mm]	
Atlantic City Intl Airport, NJ	94.6	90.7	58.9	88.4
Baltimore/Washington Intl Airport	77.8	94.6	31.5	133.9
New York JFK Intl Airport, NY	127.8	109.5	0.5	13.0
New York La Guardia Intl Airport, NY	109.5	114.8	0.0	13.7
Philadelphia Intl Airport, NJ	85.2	87.0	24.4	55.9
Lakehurst, NJ	92.4	114.8	---	---
Wallops Island, VA	109.5	70.6	111.8	102.1
Patuxent River, MD	90.7	77.8	84.8	123.2
Newark Intl Airport, NJ	125.9	120.6	1.5	25.7
Teterboro Airport NJ	116.5	105.4	0.0	18.8

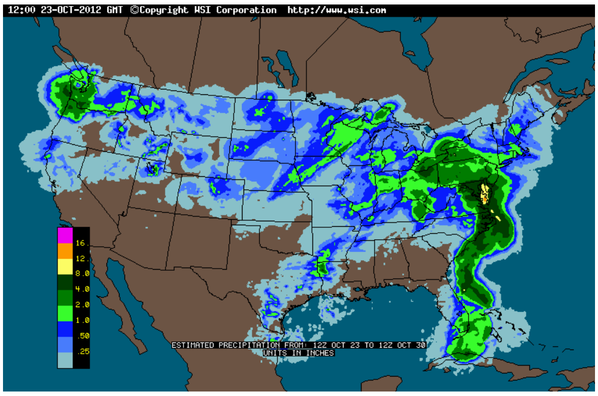

Figure 3: Precipitation estimates from radar, Oct 23-30, 12UTC
Image Credit: intellicast.com

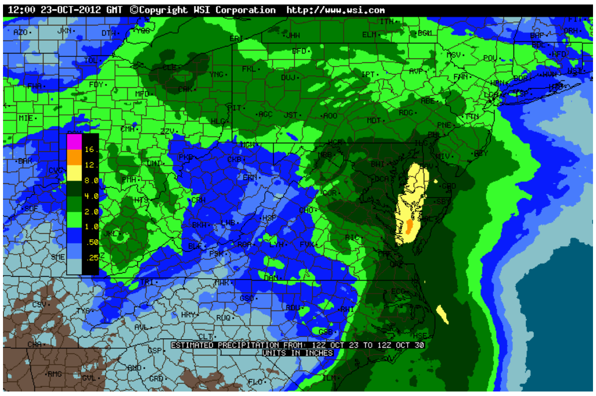

Figure 4: Precipitation estimates from radar, Oct 23-30, 12UTC
Image Credit: intellicast.com

Table 2: Snow depth on October 31, 2012. Data source: NOAA HPC

Gatlinburg	Tennessee	86 cm
Clayton	West Virginia	84 cm
Redhouse	Maryland	74 cm
Quinwood	West Virginia	74 cm
Davis	West Virginia	71 cm
Deep Creek Lake	Maryland	66 cm
Cove Creek	North Carolina	61 cm
Norton	Virginia	71 cm
Whitesburg	Kentucky	46 cm

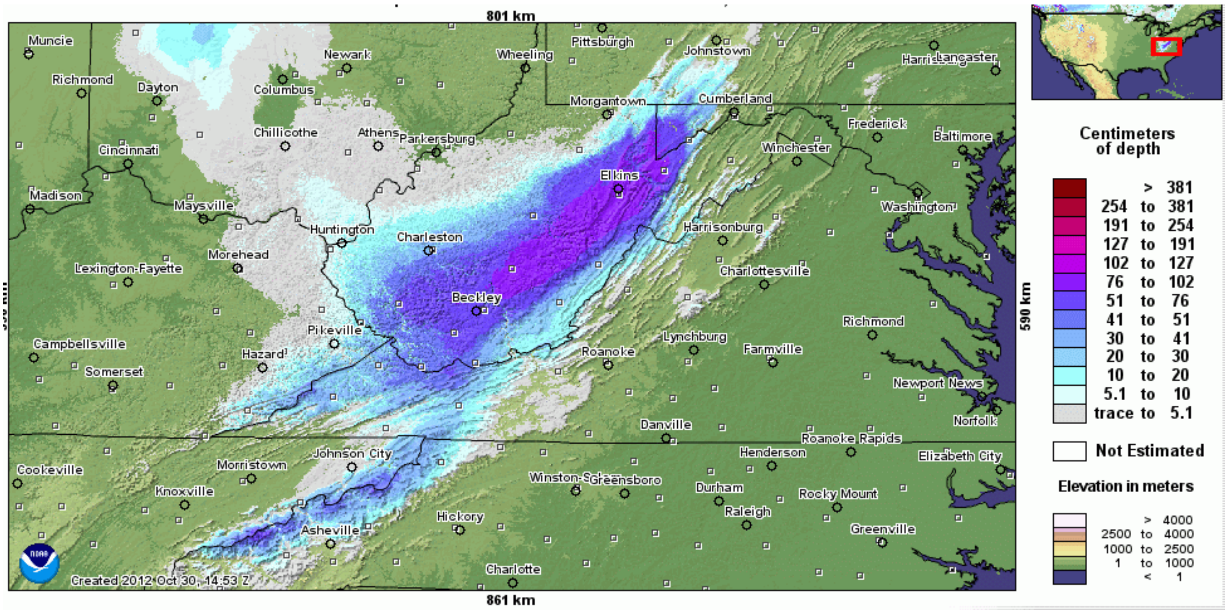

Figure 5: Snow depth in the Appalachian mountains measured in cm, October 30, 2012, 21 UTC, Image Credit: NASA NOHRSC

1.5 The extratropical transition of *Sandy*

Figure 6 shows the satellite image showing *Sandy* just crossing Jamaica. At this time, *Sandy* was a category 1 hurricane. Figure 7, four days later, shows *Sandy* with its storm center well off the coast. A huge shield of mainly high level clouds covered most of the northeastern parts of the U.S., indicating the beginning of the interaction with an upper level trough (low pressure at higher levels in the troposphere) located to the west.

Figure 6: Satellite image, October 24, 2012, 18:15 UTC, Image Credit: NASA GOES Project

Figure 7: Satellite image, October 28, 2012, 17:45 UTC Image Credit: NASA GOES Project

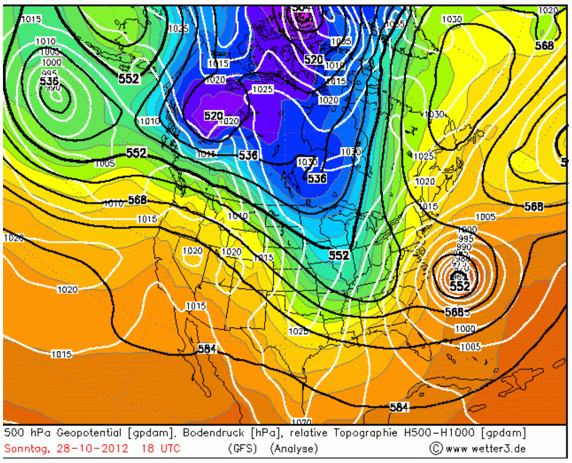

Figure 8: 500 hPa Geopotential and Sea Level Pressure, Oct 28, 18 UTC
Image Credit: wetter3.de

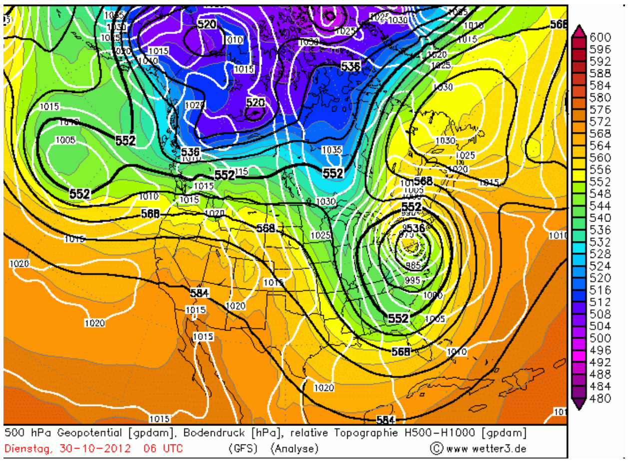

Figure 9: 500 hPa Geopotential and Sea Level Pressure, Oct 30, 06 UTC
Image Credit: wetter3.de

A perfect timing just before landfall initiated the transition from a tropical into an extratropical cyclone. By this transition, the system continuously loses the characteristics of a tropical storm, whereas it adapts to that of an extratropical low. On October 29, *Sandy* started to interact with an upper-air low causing an inflow of cold air beneath. Tropical storms are characterized by a symmetrical and concentrically arranged warm core. With the inflow of cold air into the circulation of the hurricane, the horizontal temperature field gets more and more asymmetric and the air in the center becomes colder. The inflow of colder air continuously weakens the horizontal pressure gradient and, thus, the wind speed.
On October 28, 18 UTC, the storm still showed an approximately symmetric warm core (Fig. 8). Within the next 36 hours, the intrusion of cold air begun to evolve warm and cold fronts, whereas the core becomes colder and asymmetric. Shortly after landfall, *Sandy* turned into a cold-core-low and completed the extratropical transition.

1.6 What made *Sandy* extraordinary?

Flood and storm surge

While approaching the U.S. coastline, the winds at the northern flank of the hurricane shifted from northerly to south-easterly directions. Wind gusts of up to 130 km/h lashed the waters against the coasts of New Jersey, New York, Connecticut, Massachusetts and Rhode Island, causing tremendous damage. The fact that the peak of the storm surge in many areas coincided with the flood tide enhanced the effect and led to record-breaking high water levels.

Area affected

Sandy hit a region that has rarely been plagued by hurricanes in the past. Since recording, *Sandy* was only the third hurricane that made landfall in New Jersey. According to the Hurricane Probability Project, the probability of landfall in New Jersey is only 1% during the hurricane season (for comparison only: Florida is 51%).

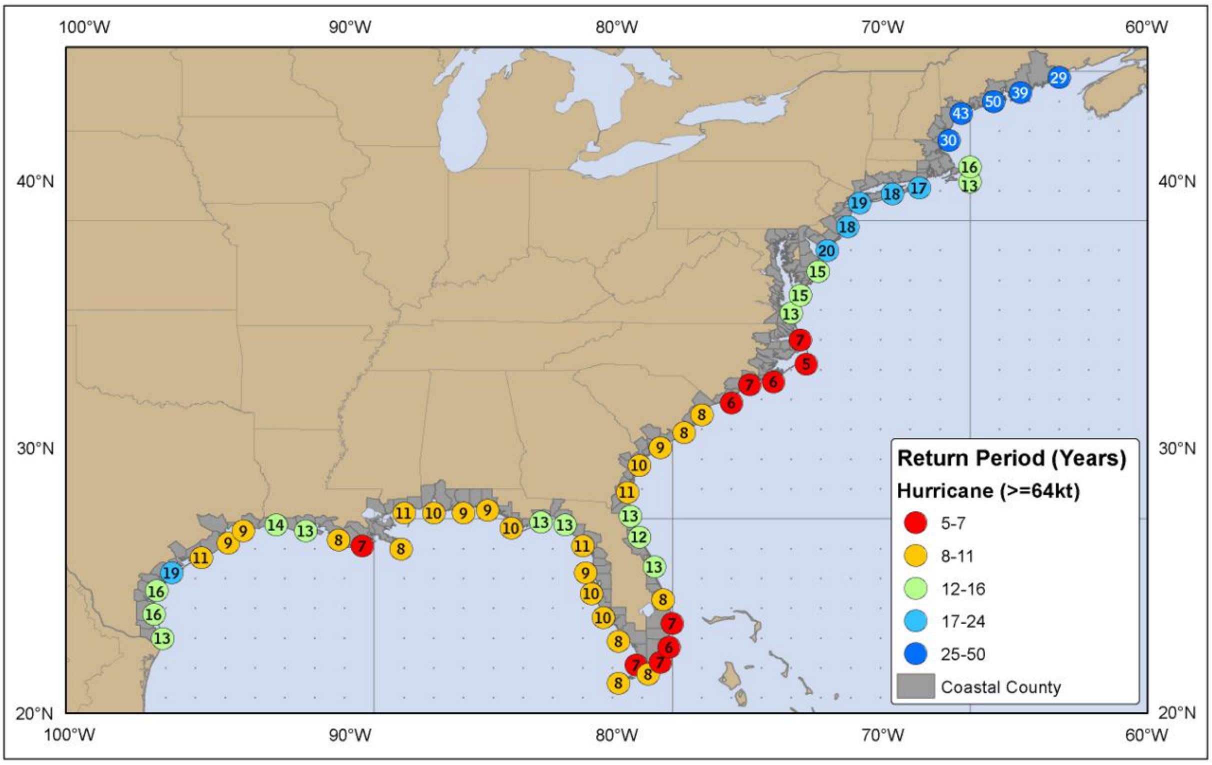

Figure 10: Estimated return periods in years for hurricanes passing within 50 nautical miles of various locations on the U.S. Coast
Image credit: NOAA National Hurricane Center

For other states that have been affected, the probability is between 1 and 8%.

In the past, hurricanes not directly hitting the Atlantic coastline caused significant damage. For example, the NOAA National Hurricane Center calculated a return period of 20 years for a hurricane that approaches New York to at least 92 km and causes sustained winds of >64 kt (>119 km/h).

Positive Anomalies of Sea Surface Temperature

High sea surface temperatures (SST) well above the mean along the track of *Sandy* helped to keep their intensity over a long period of time. The deviation from the long-term mean SST was 2-4 K on October 27 off the East Coast of the U.S. The warm water provided more latent heat, which is the source of energy for hurricanes, and intensified the tropical low, while there was no or only little wind shear, which is destructive for those systems.

Time of occurrence and blizzard-like conditions

The date, where *Sandy* made landfall, is well outside the peak hurricane season, especially as far north as New York. Cold air from Canada that was included into *Sandy*'s circulation provided a high potential for blizzard-like weather conditions in parts of the Appalachians (snow accumulation was nearly 1 meter, see Table 2) .

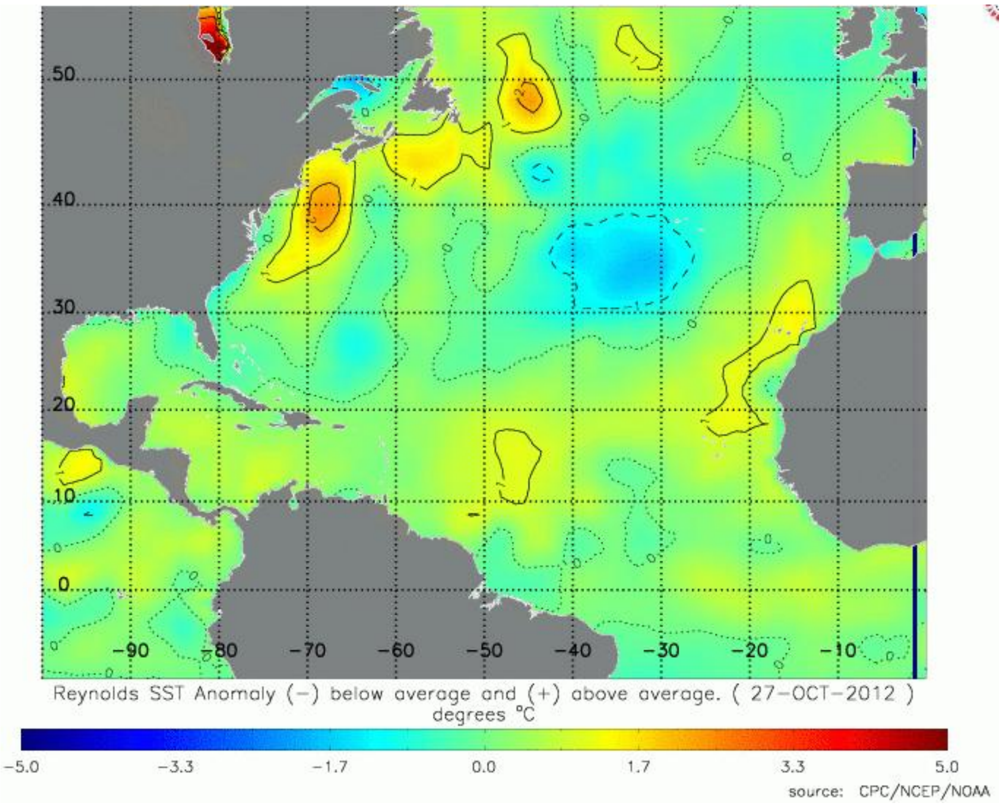

Figure 11: Sea Surface Temperature anomaly on October 27, 2012
Image credit: NOAA National Hurricane Center

Extratropical transition while making landfall

When the extratropical transition started, *Sandy* approached the East Coast of the U.S. as a category 1 hurricane (see Section 1.5). With both tropical and extratropical characteristics, the storm became somewhat capricious and dangerous.

Additional lifting by an upper level trough and huge spatial extension

Sandy began to interact with a huge upper level trough that stretched across the central parts of the U.S. and moved into an easterly direction. At its eastern edge, the trough provided additional forcing and extra lifting, which resulted in further strengthening of the storm system. The extension of *Sandy* grew rapidly; temporarily the storm had a horizontal extension of record breaking 1700 km. Even far from the center, storm force winds occurred.

Unusual track

Nearly all tropical cyclones in the North Atlantic turn onto an east-northeasterly track before they get anywhere close to the mainland U.S. Then they usually travel towards Europe as extratropical cyclones. However, the particular meteorological situation over the North American continent and the Atlantic Ocean from October 28 onwards led to a significant shift of Hurricane *Sandy*. By the end of October, an unusually well-pronounced upper air ridge (high pressure at higher levels in the troposphere) established over eastern Canada. In cooperation with a north Atlantic low pressure system, the ridge had a blocking effect to *Sandy* that was on the way from the southwest. The usual right turn of most hurricanes, referred to as recurvature, was not possible for *Sandy*. The storm was forced towards the west-northwest and targeted for New Jersey and New York.

Conclusions

The U.S. and even the New England States have seen much more intense tropical storms in the past (e.g., Hurricane Gloria in 1985). Both the rain amounts and wind speeds associated with *Sandy* did not exceed highest values from the past in nearly all parameters. However, the combination and interaction of particular circumstances (time of occurrence, sea surface temperature, extratropical transition and interaction with upper level trough, location of landfall, blocking by high pressure system) made *Sandy* extraordinary; the storm affected a very large area and therefore *Sandy* became a dangerous storm event.

1.7 Secondary hazards

Wind speed and extreme precipitation associated with hurricanes can cause secondary hazards whose impacts may exceed those caused by the meteorological constituents of the hurricane. Flooding is the most relevant of these secondary hazards. It can occur in different forms: Coastal flooding is generally caused by water masses that are driven into the coastlines by strong winds, called storm surge. Fluvial floods result from heavy precipitation after landfall. Rivers that drain the affected catchments can show extreme discharge in the aftermath of heavy precipitation.

1.7.1 Storm surge

Shoreline characterization

The shoreline of the affected region consists of *Sandy* barrier islands with dunes that are often densely settled and connected to the actual coast by bridges that span the wetlands and marches behind the barrier. A clear distinction between land and sea is lacking. The shoreline is interrupted by inlets and huge bays (Chesapeake Bay, Delaware Bay, Lower and Upper Bay, Long Island Sound). The major rivers discharge into these bays and their geographical settings showed aggravating (Lower and Upper Bay, Long Island Sound) as well as mitigating (Chesapeake Bay) effects on the storm surge due to the complex interaction with the tidal activity and the meteorological characteristics of *Sandy*. The aerial of Atlantic Beach and Long Beach on Long Island shown in Figure 12 exemplify the characteristics of long stretches of the Atlantic coast and clearly demonstrates the extreme susceptibility to flooding.

The whole coastline is extremely prone to coastal change by erosion and undergoes significant changes when hit by a hurricane or tropical storm (see USGS: http://coastal.er.usgs.gov/hurricanes/*Sandy*/).

Figure 12: Atlantic Beach, New York
Image credit: Wikimedia Commons

Storm surge: Definition

The National Oceanic and Atmospheric Administration (NOAA) gives exact definitions of Storm Tide, the actual maximum water level caused by a cyclone in combination with the astronomical tide and Storm Surge, the abnormal rise in sea level caused by the cyclone (NOAA: Tide and Current Glossary, Silver Spring MD, 2000. http://tidesandcurrents.noaa.gov/publications/glossary2.pdf). Storm Tide is given in feet above MHHW (Mean Higher High Water).

Affected Area and Regional patterns

The selected Tide gauges (given in Fig. 14 as green circles) are located along the affected coastlines of Rhode Island, Connecticut, New York, New Jersey, Delaware, and Virginia. At these gauges, storm tides up to 8.83 ft (2.69 m) were observed (see Table 3) documenting the high level of the storm surge As mentioned in the previous sections, the center of Hurricane Sandy made landfall at the New Jersey coastline around Atlantic City. Higher winds north of the center of the Hurricane drove water into the coasts from New Jersey to Massachusetts, causing extreme water levels. This is confirmed by the gauge measurements in Table 3.

The highest levels, corresponding to a >200-year event, occurred at “The Battery” on the southern tip of Manhattan, where water levels unprecedented in the record occurred. This was due to the astronomical tide and storm surge reaching maxima at the same time (see b in Table 3 and Figure 14), a situation that did not happen to full effect at other sections of the affected coast. At Kings Point (c) in the Long Island Sound for example, the effect of the storm tide maximum was pronouncedly lowered by the low astronomical tide but still reached record or near record levels. Similar levels occurred in Providence (a) where the influence of the astronomical tide was between the extremes of The Battery and Kings Point.

Geographical characteristics of The Battery gauge, namely the location at the confluence of Hudson and East River at the northern end of Upper Bay may also have contributed to the record water level.

Table 3: Tide Gauges along the Mid-Atlantic coast and maximum water levels caused by Hurricane Sandy

	Tide Gauge, Gauge ID	State	Storm Tide [Feet above MHHW]	Peak time and date [GMT]	Return Period [years] (GEV, 95% Confidence Intervals)	Start of Record [year]	Rank in Record
a	Providence, 8454000	Rhode Island	4.52	20121029 23:30	10 (6-20)	1938	4
b	The Battery, 8518750	New York	8.83	20121030 01:24	> 200 (200-)	1920	1
c	Kings Point, 8516945	New York	6.51	20121030 02:00	30 (10-100)	1998	1
d	Atlantic City, 8534720	New Jersey	4.29	20121030 00:24	20 (10-50)	1911	2
e	Chesapeake Bay Bridge Tunnel, 8638863	Virginia	4.20	20121029 12:36	30 (10-100)	1975	5

Source: NOAA - Center for Operational Oceanographic Products and Services (http://tidesandcurrents.noaa.gov/)

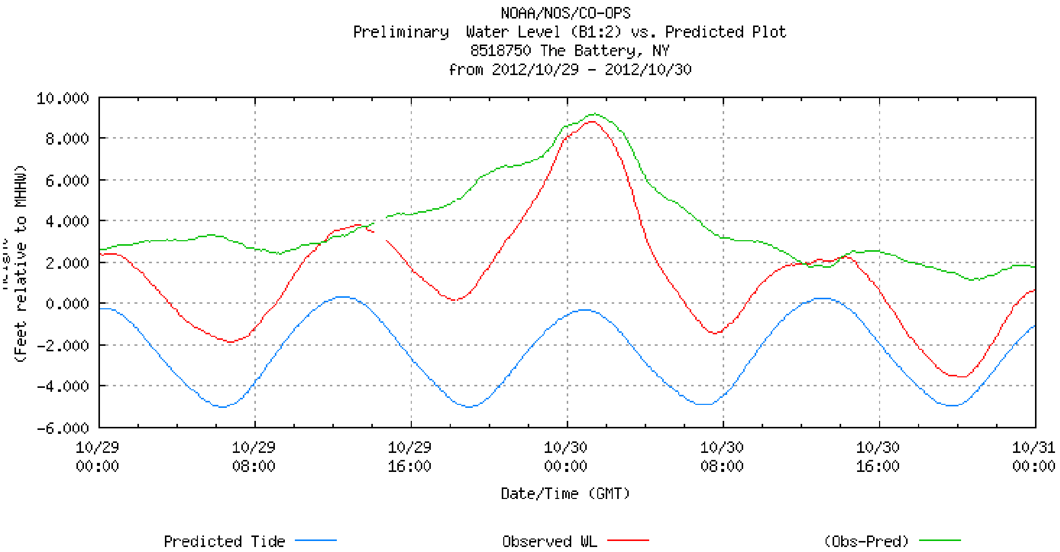

Figure 13: Coastal flooding (Storm tide) situation during *Sandy* from 29 to 30 October at gauge Battery Park, New York. Green Line: Storm surge. Red Line: Water level measurements. Blue line: Astronomic tide; from NOAA

The tide gauge of Washington DC (point B in Figure 14) showed a different picture as it is situated remote from the coast at the Potomac River. The maximum water levels during this event were reached 36 hours after the high tide at the Chesapeake Bay Bridge Tunnel gauge. At this location, the storm surge contributed only moderately to the high water levels. Those were reached by the superimposition of the tidal activity and the fluvial discharge from the Potomac caused by heavy precipitation.

1.7.2 River floods

The area affected by heavy precipitation mostly belongs to the Mid-Atlantic region which drains into the Atlantic. For details of sub-regions and on the diverse river systems it is referred to http://water.usgs.gov/GIS/huc_name.html#Region02. Major river basins in this region are the Hudson, Delaware, Susquehanna and Potomac.

The observations from 913 operational USGS river gauges in the Mid-Atlantic region give a comprehensive picture of the flood situation in the course of and after the landfall of Hurricane *Sandy* on October 30. The map in Figure 14 summarizes the flood and high flow conditions from October 28 to November 5.

In total, 39 gauges reported flood conditions, from which 24 gauges were in the state of minor flooding, 10 gauges reported moderate flooding and the level of major flooding was exceeded at five gauges. Table 4 summarizes the flood and high flow conditions for selected gauges in the Mid-Atlantic region.

Explanation

- USGS streamgages above major flood stage as defined by the **National Weather Service**
- USGS streamgages above moderate flood stage as defined by the **National Weather Service**
- USGS streamgages above flood stage as defined by the **National Weather Service**

Figure 14: Summary of Flood and High Flow Conditions from October 28 to November 5 in the Mid-Atlantic region
Image credit: www.waterwatch.usgs.gov

Regional patterns

The location of the gauges in the map shows a spatial clustering in the Potomac River basin (Maryland, Virginia and Pennsylvania), in the upper Susquehanna river basin (Pennsylvania) as well as for diverse tributaries of the Delaware river (Pennsylvania and New Jersey). Furthermore, two gauges at the Hudson River (New York state) reported flooding.

Table 4: Summary of flood and high flow conditions between October 28 and November 5 at selected gauges in the Mid-Atlantic region. For location of gauges see Figure 14. Based on: USGS Water Watch (waterwatch.usgs.gov/index.php?id=ww_flood)

Map reference	USGS station number	USGS station name	Drain. Area [mi²]	NWS Flood Class	No. of days above major flood stage	Highest Peak from 2012-10-28 to 2012-11-05							Historical Peaks	
						Peak streamflow [date]	Peak streamflow [ft³/s]	Peak stage [date]	Peak stage [ft]	Rank (1 = highest value)	among total number of peaks	return period Tn [years] acc. to Hazen[1)]	maximum peak observed	year of maximum peak
A	1372058	HUDSON RIVER BELOW POUGHKEEPSIE NY	11740	major	1	-	-	30.10.2012	9.5	-	-	-	-	-
B	1647600	POTOMAC RIVER AT WISCONSIN AVE, WASHINGTON, DC	-	moderate	0	-	-	31.10.2012	7.6	-	-		-	-
C	1643000	MONOCACY RIVER AT JUG BRIDGE NEAR FREDERICK, MD	817	major	2	30.10.2012	29700	30.10.2012	21.77	11	83	7	81600	1972
D	1480870	East Branch Brandywine Creek below Downingtown, PA	89.9	major	1	29.10.2012	4500	29.10.2012	11.12	13	40	3	8160	1972

1) Tn = N / (N + 0.5 - m); with N = number of records, m = rank (rank = 1 for the smallest value)

Sources of Flooding

Numerous gauges are located at the lower reaches of the rivers or in estuaries near the Atlantic. At these locations, tidal currents and storm tides superpose with river stream flow to form the water levels. Therefore, the source of flooding at these gauges cannot be attributed completely to a single triggering factor. Inland, the source of flooding in the period considered can be attributed solely to precipitation and resulting runoff.

Flood event evolution

The evolution of the inland flood is illustrated by means of hydrographs observed at selected gauges reporting flooding. Figure 15 exemplarily shows the water stage hydrographs of the Monocacy River at Jug Bridge (map reference C in Figure 14). In response to the large areal precipitation (from October 23 to 30), the recorded time series shows a pronounced peak in water levels and stream flow on October 30. The National Weather Service (NWS) flood stages were exceeded during two days.

The influences of the tidal dynamics and the storm surge are clearly visible in the records. For the Hudson River (see Figure 16), the superposition of the tidal high water and the storm surge – as it has been observed also at the gauge the Battery – results in maximum water levels in the early morning of October 30. During the second high tide on the same day the storm surge has already declined significantly.

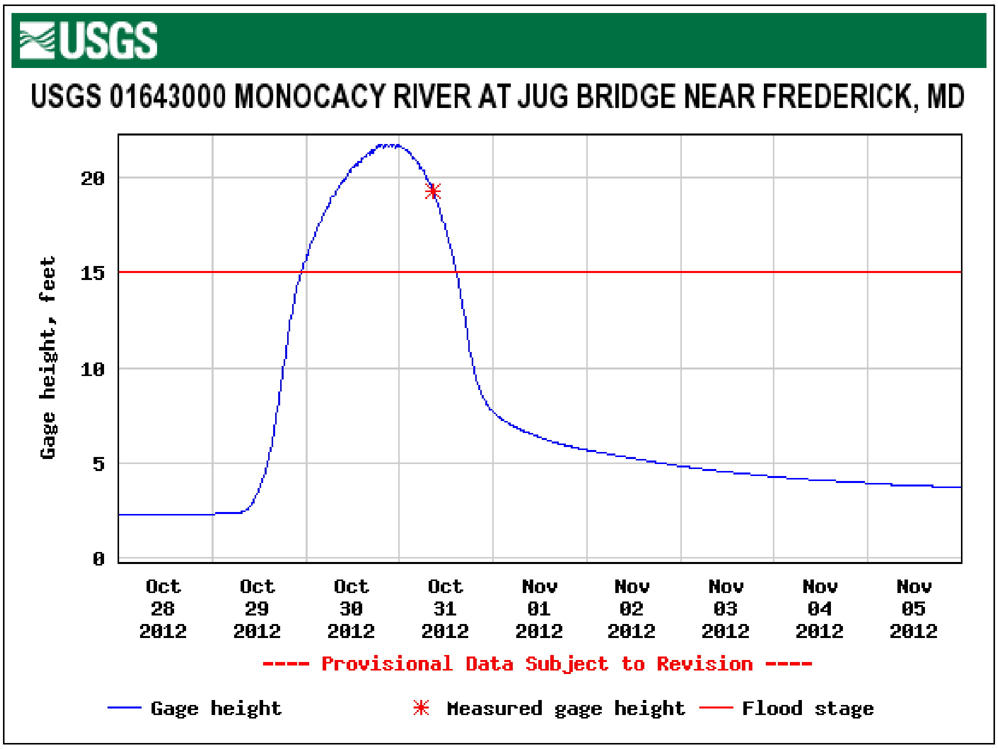

Figure 15: Gauge Monocay River at Jug Bridge near Frederick (MD)
Image credit: www.waterwatch.usgs.gov

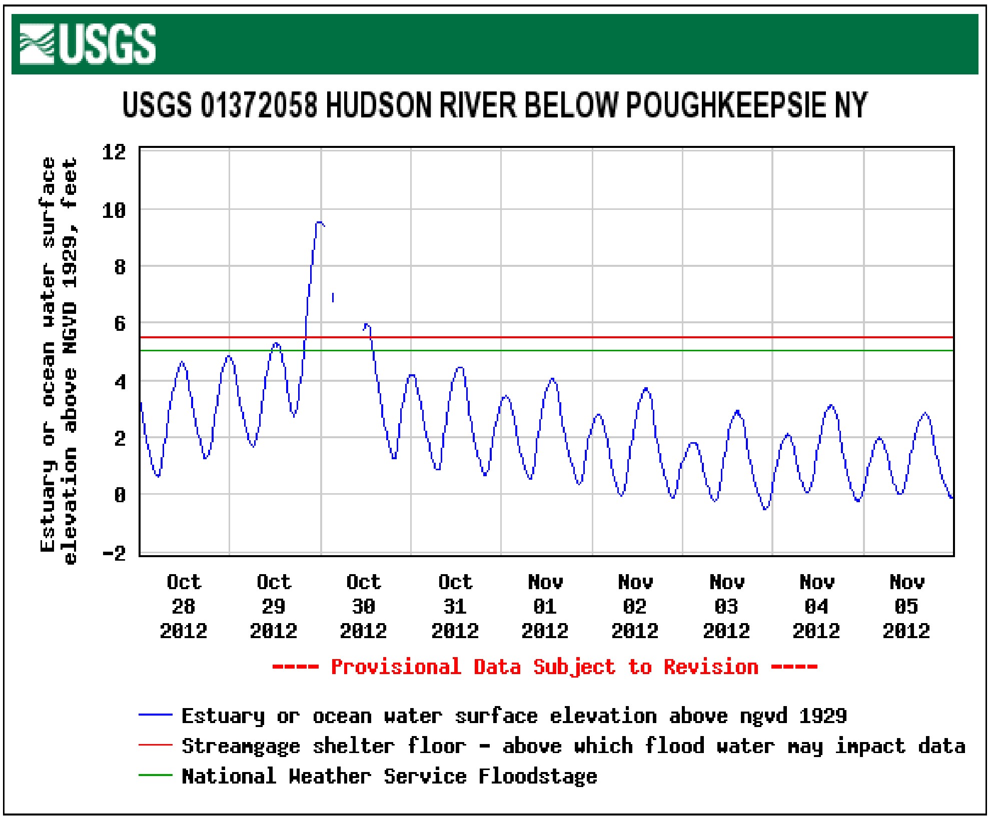

Figure 16: Gauge Hudson River Below Poughkeepsie, NY,
Image credit: USGS National Water Information System

Magnitude of impact

The impact of the inland flood can be qualitatively assessed on the basis of the alert levels predefined by the NWS. This classification is based on the occurrence of property damage and public threat at the different gauge locations. The following implications are attached to the different flood levels:

- Minor flooding: minimal or no property damage, but possibly some public threat or inconvenience,
- Moderate flooding: some inundation of structures and roads near streams. Some evacuations of people and/or transfer of property to higher elevations are necessary,
- Major flooding: extensive inundation of structures and roads. Significant evacuations of people and/or transfer of property to higher elevations.

Considering this background, the adverse consequences of inland flooding in the region affected by Hurricane *Sandy* were of minor importance. This assessment is supported by a preliminary evaluation of the return periods of the flood peaks at the different gauges. The observed discharges mainly correspond to frequent flood events with return periods between 1.01 and 5 years. The estimated return period for the observed discharge at the gauge Goose Creek near Leesburg (Virginia) in the Potomac River basin corresponds to 9 years and represents the least frequent flood discharge observed during this event in the region. The discharge observed at the Monocacy River at Monocacy Blvd. at Frederik (Maryland) in the Potomac River basin has been the highest value observed within the last eight years.

2 Impact Analysis

With high wind speeds, precipitation, flooding and storm surges, *Sandy* has impacted a wide region from the Caribbean to the East Coast of the U.S. In total, more than 190 people lost their lives (see section 2.1). In the Caribbean, more than 250,000 houses were damaged and almost 40,000 people were displaced[1]. Critical infrastructure (roads, hospitals) was either destroyed or its function interrupted, and agricultural crops destroyed over large regions. In the U.S., more than 10 States were directly impacted by *Sandy*. According to estimates of the companies Eqecat and Moody's Analytics, the economic loss in the U.S. could be up to $50 billion, thereof at least $12 billion in the New York Metropolitan Area.[2] Power outages (section 2.4) and interruption of transportation lines in Metropolitan Areas of New York are expected to accumulate further indirect damages (see section 2.5). In total, 8.4-8.7 million customers or 20-22 million people have been reported having no electricity supply.

2.1 Fatalities/casualties

As of November 4th, 2012, more than 190 people have lost their lives during *Sandy* (Table 5). In the Caribbean, 76 people have been killed, with highest death tolls in Haiti. In the U.S., 113 *Sandy*-related fatalities have been reported, most of them in the States of New York, New Jersey, and Pennsylvania.

Table 5: Number of fatalities from storm *Sandy*

Country	Deaths
Jamaica	1
Haiti	60
Dominican Republic	2
Cuba	11
Puerto Rico	1
Bahamas	2
USA	113
Canada	2
Total	**192**

Sources: Reliefweb, CDEMA, OCHA, LA Times, CNN[3]

[1] OCHA-Report 2 Nov 2012: UN relief agency estimates 1.8 million Haitians have been affected by Hurricane *Sandy*: http://reliefweb.int/report/haiti/un-relief-agency-estimates-18-million-haitians-have-been-affected-hurricane-*Sandy*

[2] NY Times, 2 Nov 2012: Estimate of Economic Losses Now Up to $50 Billion, 2 Nov 2012: http://www.nytimes.com/2012/11/02/business/estimate-of-economic-losses-now-up-to-50-billion.html?_r=0

[3] Reliefweb, overview map 31 Oct 2012: Impact of Tropical Storm *Sandy*,

2.1.1 Haiti

In terms of fatalities, Haiti is the country worst hit by *Sandy* in the Caribbean. According to UN OCHA estimations, some 1.8 Mio Haitians have been affected by Hurricane *Sandy*[4], thus almost one fifth of the estimated overall population of 9.7 Mio. Even if *Sandy* historically is not the deadliest hurricane of all time affecting Haiti (see Table 6), there are some factors that aggravate *Sandy*'s impact in Haiti.

Table 6: The deadliest hurricanes affecting Haiti

Name of hurricane	Approximate Dates	Deaths
Flora	Aug. 1963	5000+
Jeanne	18-19 Sep. 2004	3006
Unnamed	19-25 Oct. 1935	2000+
Hazel	5-13 Oct. 1954	1000+
Hanna	28 Aug. 2008	529
Allen	4-7 Aug. 1980	250+
Cleo	24-25 Aug. 1964	192
Georges	23 Sep. 1998	187
Unnamed	9-13 Nov. 1909	150+
Haiti	1816	100s
Gustav	25 Aug. 2008	85
Sandy	*Oct. 2012*	*60*

Source: CATDAT (see www.cedim.de or www.earthquake-report.com) built from historical sources

Firstly, Hurricane *Sandy* struck a country that is still recovering from the devastating earthquake in 2010. As a result of this, nearly 350,000 people are still living in camps for internally displaced persons[5]. Secondly, after the passage of tropical Storm Isaac

http://reliefweb.int/sites/reliefweb.int/files/resources/*Sandy*map.pdf
CDEMA, 27 Oct 2012: Caribbean Disaster Emergency Management Agendy Situation Report #3 - Hurricane *Sandy*, http://reliefweb.int/report/jamaica/cdema-situation-report-3-hurricane-*Sandy*
OCHA, 2 Nov 2012: http://reliefweb.int/report/haiti/un-relief-agency-estimates-18-million-haitians-have-been-affected-hurricane-*Sandy*
LA Times, 4.11.2012: http://www.latimes.com/news/nation/nationnow/la-na-nn-hurricane-*Sandy*-deaths-climb-20121103,0,6945430.story
CNN, 2.11.2012: http://edition.cnn.com/2012/11/01/us/tropical-weather-*Sandy*/index.html

4 http://reliefweb.int/report/haiti/un-relief-agency-estimates-18-million-haitians-have-been-affected-hurricane-*Sandy*

5 OCHA, 2 Nov 2012: http://reliefweb.int/report/haiti/un-relief-agency-estimates-18-million-haitians-

(August 2012) and Hurricane *Sandy* (October 2012) resulting in destruction of agricultural crops, the food security is affected "with up to two million people at risk of malnutrition"[6]. Thirdly, damage to hospitals and limited access to health services and to restocking supplies because of impassable rivers and obstructed roads have also aggravated the health situation. The WHO warned that poor sanitary conditions could increase the risk of water-borne diseases such as cholera, which is still endemic in the country.[7] As of November 6th 2012, 21 cholera deaths have been reported in Haiti in the 10 days after the passage of *Sandy*, and more than 2000 people are infected.[8] In the Dominican Republic, some 250 people are reported to be affected from Cholera. The Pan American Health Organization has issued an epidemiological alert for the Caribbean countries affected by Hurricane *Sandy*.[9]

2.1.2 Fatalities in the Eastern U.S. from hurricanes

In the Eastern U.S., more than 110 people died because of *Sandy*, most of them in New York, New Jersey and Pennsylvania (see Table 7). Of the 48 fatalities in the State of New York, 40 occurred in New York City, 20 of them on Staten Island[10].

Comparing the hurricane fatalities in the States New York, New Jersey and Pennsylvania with historic events it can be seen (Table 8) that *Sandy* has in the top 3 in terms of deaths through recorded history of hurricane deaths per event, with it being the deadliest single event in New Jersey history.

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have-been-affected-hurricane-*Sandy*

6 OCHA, 2 Nov 2012: http://reliefweb.int/report/haiti/un-relief-agency-estimates-18-million-haitians-have-been-affected-hurricane-*Sandy*

7 OCHA, 2 Nov 2012: http://reliefweb.int/report/haiti/un-relief-agency-estimates-18-million-haitians-have-been-affected-hurricane-*Sandy*

8 Agence France-Presse, 6 Nov 2012: Recrudescence des cas de choléra après l'ouragan *Sandy*: http://reliefweb.int/report/haiti/recrudescence-des-cas-de-chol%C3%A9ra-apr%C3%A8s-louragan-*Sandy*

9 REDLAC (Risk Emergency Disaster Working Group for Latin America and the Caribbean) Situation Report 6 Nov. 2012, http://reliefweb.int/sites/reliefweb.int/files/resources/Situation_Report_284.pdf

10 Tagesspiegel, 2 Nov 2012, http://www.tagesspiegel.de/weltspiegel/folgen-des-hurricans-*Sandy*-drueckt-preis-fuer-us-erdgas/7335684.html

Table 7: Number of fatalities in the Eastern U.S. from *Sandy*

U.S. State	No. of fatalities
Connecticut	4
New Jersey	24
New York	48
Maryland	11
North Carolina	2
Pennsylvania	14
Virginia	2
West Virginia	7
New Hampshire	1
Total	**113**

Source: LA Times, 4 November 2012[11]

Table 8: Number of fatalities in the States New York, New Jersey and Pennsylvania from historic events

	New York		New Jersey		Pennsylvania	
Rank	Storm Name, Year	Deaths	Storm Name, Year	Deaths	Storm Name, Year	Deaths
1	New England, 1938	60	**Sandy, 2012**	**24**	Diane/Connie 1955	75-90
2	***Sandy*, 2012**	**48**	Unnamed, 1806	21	Agnes, 1972	50
3	Edna, 1954	29	Irene, 2011	10	***Sandy*, 2012**	**14**
4	Norfolk/Long Is. 1821	17	Unnamed, 1944	9	Floyd, 1999	6-13
5	Hurricane Five, 1894	10	Unnamed, 1878	8	Gale of 1878	10
6	Agnes, 1972	6	Floyd, 1999	6	TC Allison	7

[11] http://www.latimes.com/news/nation/nationnow/la-na-nn-hurricane-*Sandy*-deaths-climb-20121103,0,6945430.story

2.2 Fatality causes

From media reports various circumstances and causes for the fatalities in the Caribbean and U.S. are reported which are directly or indirectly related to *Sandy*:

- falling off the roof while preparing shutters for the hurricane
- drowning in flood or swollen rivers, being swept away by the storm surge
- being crushed by debris
- killed by falling tree(s)
- killed in car accident
- fire, electrocution
- heart attack
- carbon monoxide poisoning

As there are no exact numbers on the causes of fatalities and on the socio-demographic characteristics of victims available at the moment, a comparison to fatality patterns of other past hurricanes in the U.S. is not yet possible. At this moment, however, it can be said that the above mentioned causes for death are conform to other findings of research on causes of fatalities from other hurricanes in the U.S. such as Hurricane Katrina (Jonkman et al. 2009, Brunkard et al. 2008) or Hurricane Andrew (Combs et al. 1996). A more detailed investigation and critical analysis of circumstances of fatalities during *Sandy* of live could be helpful to identify the main drivers for loss of life and to prevent loss of life in future disasters.

2.3 Evacuation and shelter - Preparation for the disaster

During the days before the expected landfall of *Sandy*, evacuation orders were issued, and shelter was prepared and provided throughout the potentially affected area. More than 500,000 people were told to evacuate from their homes in low lying areas (approx. 375,000 from New York, 66,000 from Atlantic City/ New Jersey and 66,000 from coastal communities in Delaware). In most cases, the evacuation orders were mandatory.

It has been reported that in some places people did not follow evacuation orders. It is known from past disasters that people do not response appropriately to evacuation orders, stay in their homes and expose their lives to the physical forces and impacts - despite the fact that evacuation measures and shelter significantly reduce fatalities from hurricanes (for a first overview see Shultz et al. 2005). In their study on evacuation behavior during the 2004 Florida Hurricane season, Smith and McCarthy (2009) identified the following factors that contribute to not evacuating and which could contribute also to explaining the non-response-behavior during *Sandy*:

- The thought of being able “to ride out” the storm
- Storm was predicted to hit elsewhere
- Concerned about leaving house
- Concerned about leaving pets

- Job did not permit leaving
- Medical condition prevented evacuation
- Had no place to go
- Had no transportation
- Did not have enough time

The experience of an “unnecessary evacuation” is also often mentioned as a reason why people do not evacuate. It has also been reported for Hurricane Sandy in the media that people did not follow the evacuation orders referring to the experience of a “false alarm” from Hurricane “Irene” in 2011 which hit the coasts with less severe impacts than expected by the forecast[12]. An analysis of evacuation behavior in the 1996 hurricane season in South Carolina by Dow and Cutter (1998), however, showed that prior “false alarms” seemed to have no large influence on overall evacuation behavior during a sequence of hurricanes, but had some influence on those who had not developed their personal basic response option to “principally evacuate or not” and who showed changing evacuation behavior during two hurricanes in one season with voluntary and mandatory evacuation measures in place.

Thus, a conclusion on driving factors for loss of life from evacuation response behavior during *Sandy* would be premature at this point. As with the circumstances of fatalities, it would be very helpful to further investigate the factors that hampered appropriate response behavior during *Sandy* and to identify the implications for disaster mitigation.

2.4 Electric power outage

2.4.1 Power outages as of November 6, 2012

In the most of the Hurricane *Sandy* affected regions, where the electricity broke down, the power supply was successfully restored after multiple blackouts. According to Table 9 on November 6, 2012 a huge amount of customers are still affected by an extended power outage in New Jersey (app. 150,000 customers) and New York (app. 174,000 customers in the regions Nassau, Suffolk and Westchester and app. 28,000 customers in New York City). Both hotspots are also affected by the new winter storms. The storm stresses both the power utilities in their restoration schedules as well the people who are living in the regions without power.

Single hotspots of more than 1,000 customers without power are reported from single areas of Pennsylvania, Michigan, North Carolina, South Carolina and West Virginia.

[12] For example here: Hurricane's Blog: How Irene Affected Sandy Evacuations, 1 Nov. 2012: http://www.nbcphiladelphia.com/weather/stories/Sandy-Blog-Hurricane-Evacuations-176864221.html

Table 9: Power outages with more than 1,000 affected customers/region reported by different utility companies in Northeast States/ Status November

State	Area/Region/County	Reported Estimates	Sourced by Utility Companies
New York	Nassau	86604	Long Island Power Authority
	Suffolk	83766	
	Westchester	3291	NYSEG
New York City	Bronx	4013	Consolidated edison company of New York
	Brooklyn	8395	
	Queens	12684	
	Staten Island	3221	
Pennsylvania	Lackawanna	1754	PPL Electric Utilities
New Jersey	Sussex	9616	FirstEnergy Corp.
	Warren	8874	
	Hunterdon	13853	
	Somerset	11189	
	Passiac	2422	
	Essex	2633	
	Morris	41921	
	Union	6355	
	Middlesex	8819	
	Monmouth	42716	
Michigan	Clarkston/Waterford	3044	DTE Energy
North Carolina	Stokes	1282	Duke Energy
South Carolina		1531	Duke Energy
West Virginia	Preston	5524	FirstEnergy Corp.
	Tucker	1583	
	Barbour	3414	
	Randolph	4092	
	Upshur	2933	
	Webster	1781	

2.4.2 Dependency on electric power supply

Figure 17 displays a flow chart/causal map with the main issues of how the affected people rely on electricity and how this impact the satisfaction of human basic needs. Some affected regions have been out of power for eight days. That may reach the limits of the citizens' self-helping capacities. Furthermore, the approaching new winter storm again stresses the main power outage hotspots. The longer the outages take, the more aspects like water and food shortages, food poisoning from refrigeration not working, disease outbreaks from not working sewage systems/drinking water supply and deficits in health care can become serious issues (see Bayleyegn et al., 2006). Additionally, carbon monoxide poisoning and a rising number of flat fires from people using unconventional heating in their homes can occur. This is known from former comparable incidents (see Platz et al. 2007).

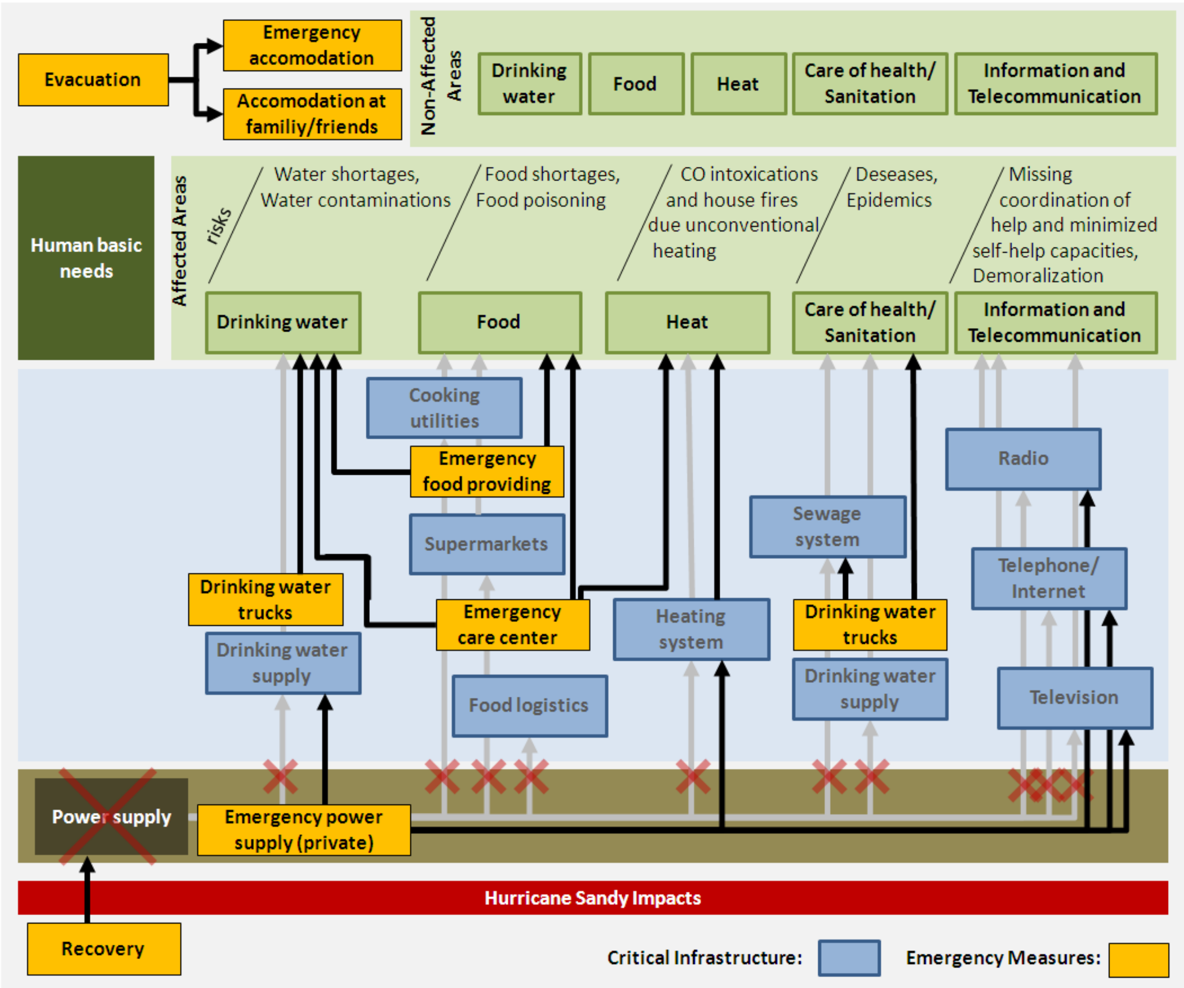

Figure 17: Very soft casual map/**flow chart to capture main effects of extended power outages for human basic needs and possible emergency measures to avoid further risks**
Image Credit: CEDIM

2.4.3 Historic events and power outages

The 2003 Northeast blackout spread through eight states and affected more than 50 million people (see Table 10) but was not caused by a storm and did not involve downed power lines, broken trees and flooding. It lasted less than 24 hours for most people and was considered the second most widespread blackout in history.

Sandy's impact is expected to be less (on the order of 22 million people affected), however, power outages may last longer and linger on for days.

In comparison to other hurricanes, the power outages from *Sandy* have set records (see Table 11).

Table 10: List of historic events

Event	Number of people affected	Duration of Blackout
Opal (1995)	More than 5 million	Few days
Isabel (2003)	10 million	Few days
Katrina (2005).	More than 6 million	Repair lasted several weeks
Irene (2011)	13-19 million	Repair lasted several days to weeks in some places
2003 Northeast Power Blackout	55 million	Less than 24 hours
July 2012 India blackout	670 million	2 days

*List of power outages (Source: Wikipedia)

Table 11: List of historic hurricane/tropical storm events by customers without power.

Name	Year	Number of Customers without power
Sandy	**2012**	**8,767,000**
Irene	**2011**	**6,000,000**
Isabel	**2003**	**4,300,000**
Ike	**2008**	**3,900,000**
Wilma	**2005**	**3,500,000**
Katrina	**2005**	**2,700,000**
Gloria	**1985**	**2,277,000**
Bob	**1991**	**2,100,000**
Opal	**1995**	**2,000,000**
Floyd	**1999**	**1,760,000**
Rita	**2005**	**1,500,000**
Gustav	**2008**	**1,100,000**

*Note: There are 125.7 million residential customers in the U.S. (2.51 people per residential customer)

2.4.4 Use of twitter messages for rapid assessment

To get local, detailed, and up-to-date information about the behavior of the storm and its impact, Twitter messages (tweets) with various keywords such as hurricane, sandy, shelter, winter storm or power outage have been recorded. Figure 18 shows distribution and frequency of localized tweets with the keywords hurricane (blue) and power outage (red) from October 27 to November 2. The number of tweets increased slowly before the event and decreased abruptly after the event. The day Sandy arrived at the East coast of the USA (30.10.2012), more than 7600 localized tweets from the East coast referring to the keyword hurricane were sent. The day after the event (31.10.2012), the number of sent tweets from the affected area decreased to 2800. Two assumptions can be derived from the data: A decrease of the tweets may indicate the breakdown of supply networks (electricity and communications); after event tweets indicate working communication networks. Examples of tweets describing intact power networks are given in Table 12.

Table 12: Two examples of twitter messages concerning the storm.

user	date	tweet
Davis Boyle	Oct 30, 2012 13:08 UTC	"(…) not bad here. low 40s. rain stopped for now. no power outages near (…)"
Kathy Warren	Oct 30, 2012 13:01 UTC	"(…) we are all ok here.. lots of flickering power but no long outages"

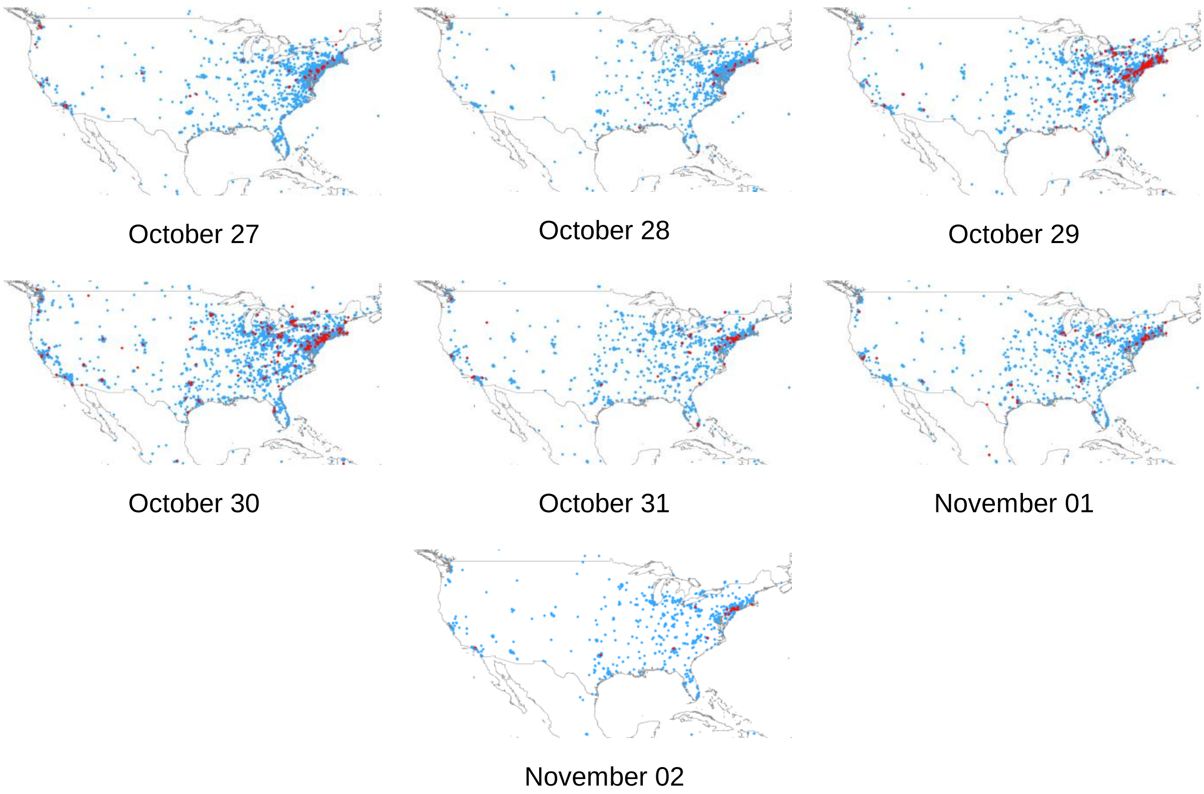

Figure 18: Located tweets with the keywords *hurricane* (blue dots) and *power outage* (red dots) for a time line of seven days
Image Credit: CEDIM

2.5 Indirect losses

Besides direct costs due to damage to buildings and infrastructures, natural disasters generate important indirect economic losses. Due to the growing interconnectedness of modern supply chains and the dependency on critical infrastructures, the world-wide vulnerability to natural disasters has increased considerably (Perrow 1984), and business interruptions propagate through various industrial sectors. Particularly the interruption of the most essential infrastructures such as electric power and water supply or transportation can cause ripple effects throughout other infrastructure systems (Rinaldi et al. 2001). It has been shown that the impact of the disruptions on the industrial sector and associated supply chains disruptions are most prominent (Zimmerman 2004; Zimmerman and Restrepo 2006) .

2.5.1 Cost of power outages

Due to *Sandy*, power outages have been reported on Monday October 29 and Tuesday October 30 in 14 Northeastern States, leaving an estimated 8.7 million customers (approx. 2.51 people per residential customer) without power (see section 2.4.1 and Table 9). A week after the storm, on Monday, November 5, around 1.3 million people were still affected by the outage.

The (direct and indirect) costs of the blackout caused by *Sandy* can be roughly estimated by comparison with similar past events, which are summarized in Table 13.

For instance, the costs of the 2003 northeast blackout, which has affected 55 million people throughout 8 Northeastern States, were estimated around $6.3 billion. With close estimates of $5.6 billion for one day, Zimmerman et al. (2005) demonstrated the possibility to estimate these costs based on GDP per person and the number of people affected.

Using a similar approach, we can model the power outage changes using customer estimates of the peak outages, 1st November outages and 6th November outages

Using a similar approach, the costs for the power outage following *Sandy* would be approximately $2.6 billion for the first day, and $14.4 billion for ten days of blackout (using a GDP per capita per day of $132.72 and a linear recovery function from 20 million people affected on Monday, October 29 to 2 million on Wednesday, November 7). This linear function correlates well to the number of people reported without power in Table 9, however it overestimates towards the end of the ten day estimate. It should be noted that this value of GDP is a U.S. country average, with the GDP per capita being around 1.3 times greater on the East Coast on average than the U.S. average.

2.5.2 Business interruption

In the affected states, industrial companies are experiencing business interruptions or operating at reduced rates due to power problems. These business interruptions are likely to cause great indirect losses for the U.S. economy.

Business interruptions in industry sectors are probably the main impact of power outages. An analysis of the consequences of the power outage of the 1998 Ice Storm in Canada (Chang et al, 2005) due to infrastructure failure interdependencies has shown that the main impacts in terms of duration, severity, spatial extent and number of people affected concerned the manufacturing industry, with business interruptions contributing to the short-term loss of $1.6 million in Canadian dollars (CAD) to the economic output of the country. Another critical sector was mining and oil, with the closure of two major oil refineries which triggered communication difficulties in emergency services and fuel shortages.

Due to the storm itself, the industry lost two business days affecting on average 27 percent of the U.S. manufacturing sectors. Figure 19 shows the percentages of the most relevant manufacturing sectors located in states affected by *Sandy* with respect to the value added in these sectors.

Table 13: Impact and costs of similar events

Category	**Meteorological event**				**Power blackouts**				
Event	**1998 Ice Storm**	**Hurricane Katrina**	**Hurricane Irene**	***Sandy***	**2002 Port Shutdown**	**1998 GM strike**	**2003 blackout**	**general estimation, Caves et al., 1992**	**voltage disturbance blackouts of 1999**
# people affected by blackout	4.7 million people	6-7 million people	15 million people	Ca. 20-22 million people			55 million people		
States affected				14 north-eastern states			8 northeastern states affected		
Duration of blackout	days or weeks			Days/ weeks	12 ports shutdown		1-to-3 days		
Production shutdown					sporadic shortages / disruption in certain industries		shutdown across multiple states		
Direct losses								$1.50 - 7.50/kWh in the U.S updated to 2005 dollars	over $1 billion
Property damage			$15-20 billion (U.S.)	more than Irene	/	/	/		
cost for government	$1.7 billion				/		$ 0.02-0.1 billion		
indirect costs	$1.6 million CAD **(1.0 mill. U.S.$)** short-term loss manufacturing industry in CAD dollars to the economic output of the country			two lost business days affecting 25 per cent of the U.S. economy			0.693 billion		
lost earnings							$4.2 billion		
loss due to spoilage or waste							between $380 million and $0.94 billion		
total costs assessments	**$3 billion**	**$108 billion**		**$35-45 billion (ABC-news)**	**$1.67 billion**	**$2.7 billion**	**$ 6.373 billion**		

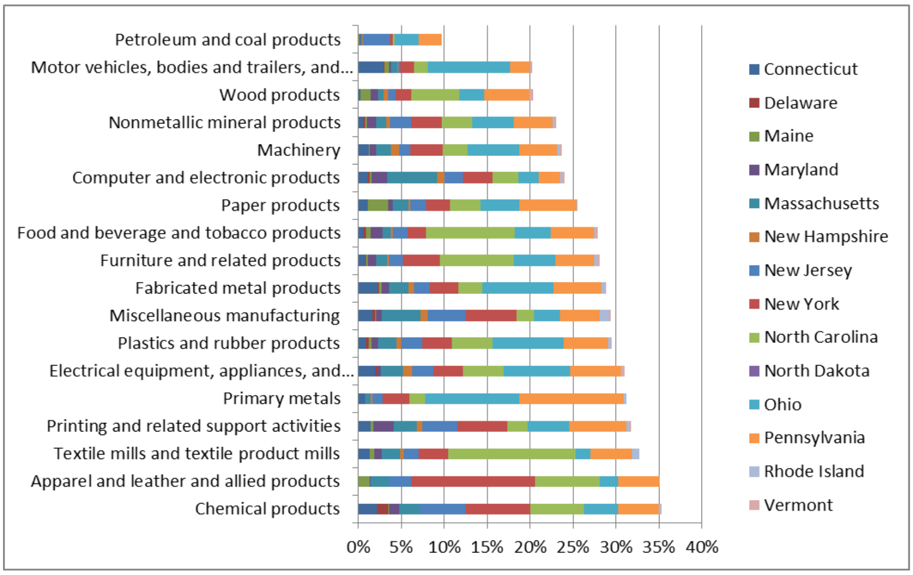

Figure 19: Percent of sectors Value Added in affected States
Image Credit: CEDIM

2.5.3 Disaster vulnerability

The vulnerability of industrial production systems strongly depends on the type of industry, and can be determined with the help of vulnerability indicators (see Figure 20). In general, production downtimes mainly occur due to the damage of production equipment, the obstruction of workers, the interruption of critical infrastructures or the disturbance of supply chain processes (e.g. delivery or distribution processes). Therefore, the industrial vulnerability strongly depends on the degree of dependency on capital, on labor, on infrastructure systems and on supply chain services. In order to operationalize these dependencies by indicators, quantifiable factors describing these dependencies have been identified.

By considering the industrial density of regions of the different sectors (obtained through the value added), it is possible to determine the industrial vulnerability against indirect disaster effects at the regional level (see Figure 20, right).

In this manner, the most vulnerable sectors against disruptions and failure of electricity supply and the transportation were identified. These were the basis for the construction of consequence scenarios, which depend on the

- duration and development of disruption
- vulnerability of the respective industrial sector S_i
- importance of S_i for the economy.

To take into account the interdependencies between critical infrastructures (e.g., power and ICT dependence) multipliers reflecting the degree of the interdependence and the importance of the infrastructures for the respective sectors were used. Figure 21 shows the results for the states affected by *Sandy*.

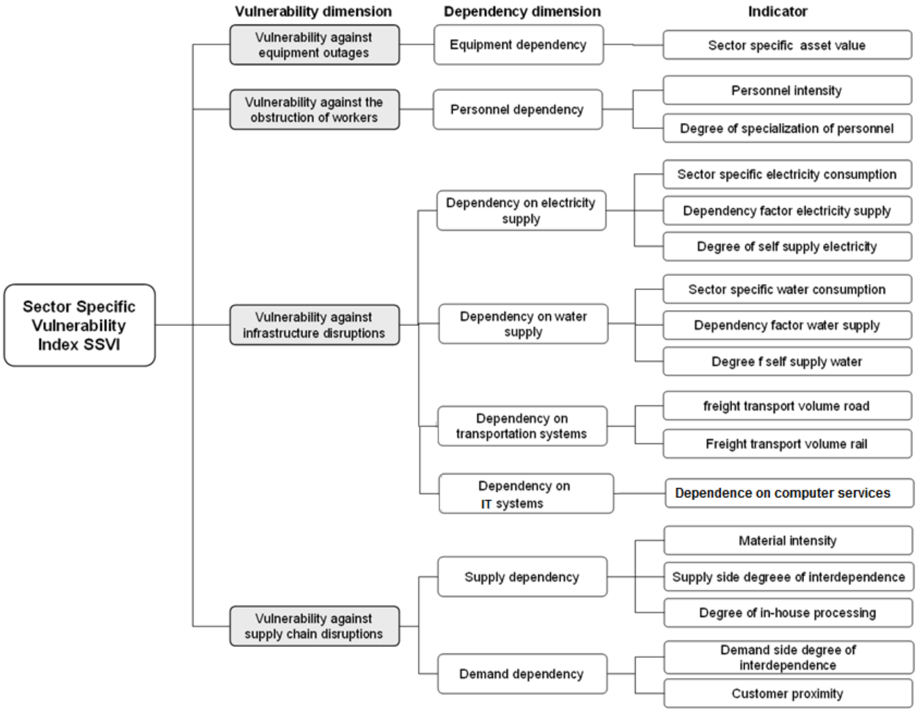

Figure 20: Sector Specific Vulnerability Index
Image Credit: CEDIM

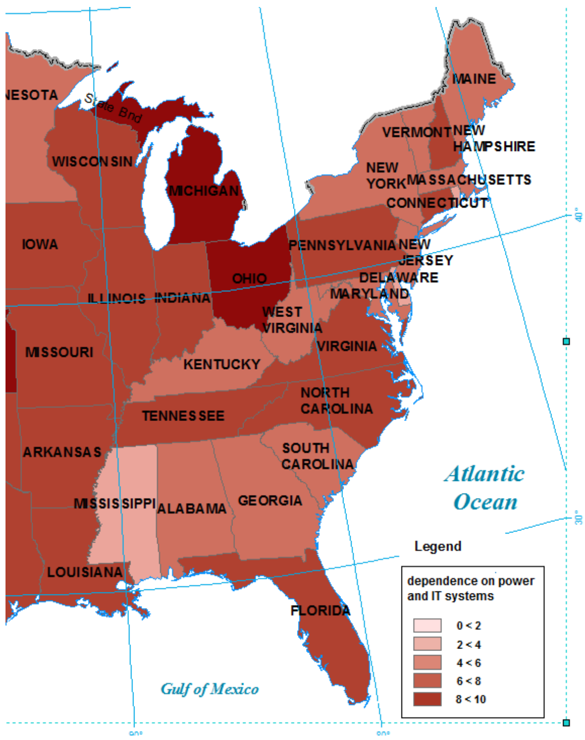

Figure 21: Vulnerability of affected states with respect to power and IT systems
Image Credit: CEDIM

Using input-output multipliers, we estimated the potential impacts of *Sandy* on different business interruption scenarios of the U.S. economy. To consider the indirect costs in a systematic way, the scenarios were split into three parts considering the overall disruption due to the event (across all sectors), the impact of power blackouts and of the closure of stock exchange and the impact of disruptions of the transportation system.

The overall impact depends to a large degree on the assumptions about the disaster recovery. Assuming that the disruptions of the overall manufacturing sector lasted for two days in the 14 states affected by *Sandy*, the costs would approximate $9.4 billion for the two days of the storm. However, the industrial sector has not yet fully recovered, and business interruptions are perpetuating in some industries. The capacity of business to restart their activity during this recovery period highly depends on the vulnerability of the sectors.

Therefore, we calculated different scenarios of recovery, using different possible recovery functions (see Figure 22), where the parameters for the curvature of the exponential recovery function were chosen to be 1, 2, 4 and 6 (following Cimellaro et al. 2010). Depending on the recovery scenario, the indirect costs for the 10 days following the storm might range from $1.4 to $5.6 billion.

Adding to business losses of two days of total shutdown for the manufacture sector with the estimated partial disruptions during the recovery period, total business interruption are estimated between $10.8 and $15.5 billion. Assuming that the closure of the stock exchanges and offices affected 30% of the finance sector U.S.-wide on the two days of the storm, the indirect costs on the economy would approximate $9.8 billion.

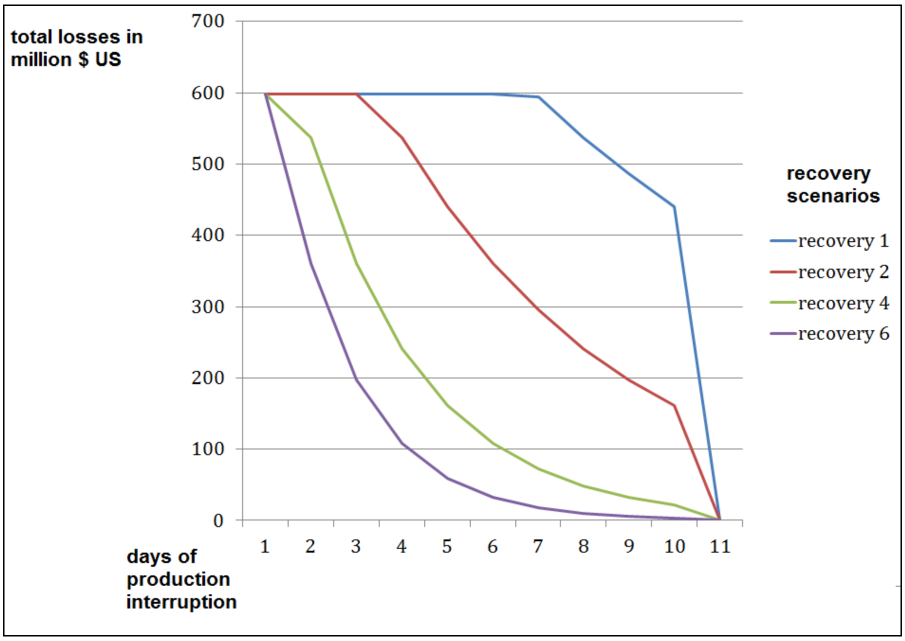

Figure 22: Estimation of losses due to business interruptions during the recovery period
Image Credit: CEDIM

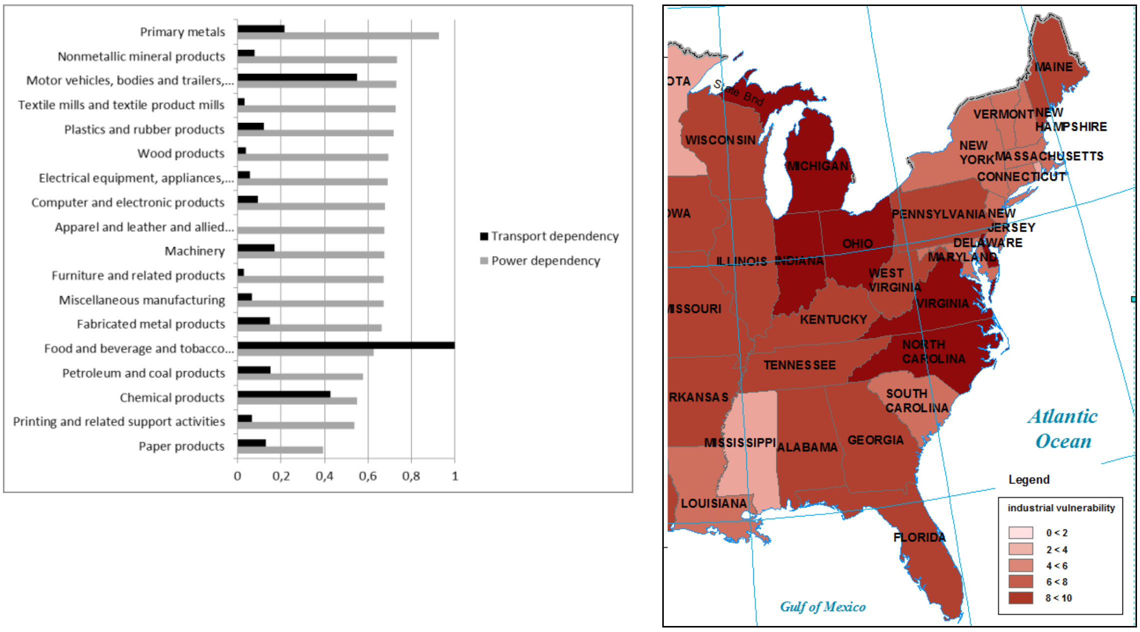

Figure 23: Dependency of manufacture sectors on power and transport (left); Industrial Vulnerability of Eastern U.S. against indirect disaster impacts (right)
Image Credit: CEDIM

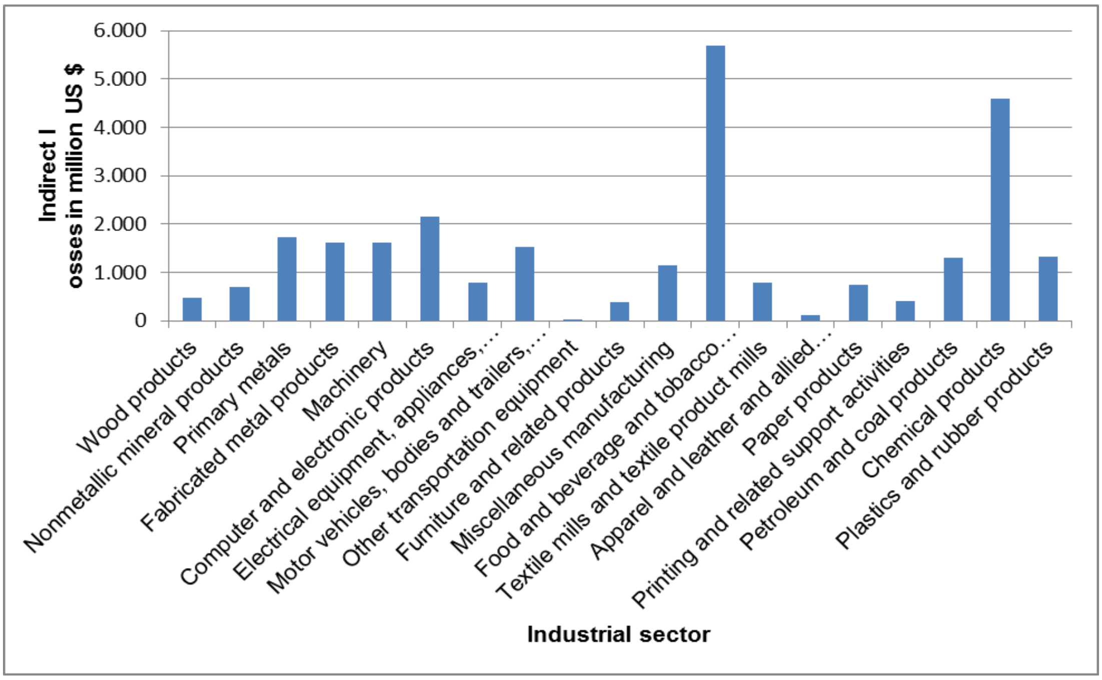

Figure 24: Indirect losses in industrial production
Image Credit: CEDIM

Besides industry, the storm also has affected the retail sector with approx. 2 days business interruption. Here, the recovery is expected to be particularly difficult due to physical damage and personnel shortages. The latter were mainly caused by power blackouts and transport disruptions.

2.5.4 Benefits caused by the storm

The damage caused by the storm also generates economic benefits for some sectors, such as the construction sector which will benefit from a higher demand for reconstruction. According to estimates of the University of Maryland, reconstruction spending might equal 80% of the total economic losses caused by *Sandy*, estimated at up to $50 billlion. The increased demand of the construction sector should have indirect positive repercussions on the economy.

The freight industry is also expected to benefit from the closure of airport and rail networks. With the shortage of products which need to be expedited urgently to market, such as drugs or emergency materials, trucks have been sought as an alternative method of transport by manufacturers. According to some estimates, the sector is likely to gain $2 billion revenue from the storm.

Another sector likely to benefit from rebuilding is the solar system installers with big businesses on the East Coast.

3 Summary and further Research Questions

Hurricane *Sandy* was a storm system with special meteorological characteristics. It caused widespread damage from the Caribbean to the U.S. East Coast. In Haiti, the impact was aggravated by several factors related in part to other prior disaster events. At the U.S. coast, especially in New York, New Jersey and Pennsylvania, *Sandy* resulted in a relatively high death toll compared to historic events. Critical infrastructure failures (electricity, transportation) are expected to lead to a high amount of indirect damages.

The impact of Sandy on the longer term and the indirect losses are difficult to estimate due to the complex interrelations between socio-economic and technical systems. Therefore, further analysis of recovery scenarios will be important. These scenarios should aim at taking into account diverse uncertainties related to the response of the economy (from individual business continuity plans to outsourcing decisions, replacement of suppliers or longer term price developments), the duration of recovery of the critical infrastructure systems and potential policy interventions as well as the behavior of communities and societies.

As it turns out, the recovery period will be distinctly longer than initially expected by the arrival of the new storm Athena. Under this perspective, it would be interesting to study new scenarios on how this new event will affect the current recovery process, by triggering additional ripple effects on the already weakened infrastructure and supply chain networks, and to which extent it will contribute to increase indirect losses.

From the hazard perspective, it is shown that the impact of Sandy was driven by the superposition of different extremes (high wind speeds, storm surge, heavy precipitation) and by cascading effects. Research on how the impacts are amplified by multi-hazards rather than by single extremes may help to better assess potential losses of events such as *Sandy*. A further important question is on the role of climate change on such events due to both the rise of water level (Tollefson, 2012) and possibly a shift in the global circulation patterns (e.g., Francis and Vavrus, 2012; Liu et al., 2012).

Lastly, an important field for further research is the communication of uncertainty. These reports are meant as a means to assess risks and losses as to enable prioritisation of risk management. Therefore, it is crucial to document how the situation could potentially evolve and to highlight potentially harmful developments as early as possible. All these scenarios are, however, prone to uncertainty to an extent which is so overwhelming that the use of standard methods to characterize the probability of each scenario cannot be applied. Here, alternative methods to assess and communicate the risks – particularly for the early stages of the disaster – should be further investigated.

4 List of abbreviations

CEDIM FDA	CEDIM Forensic Disaster Analysis
CEDIM	Center for Disaster Management and Risk Reduction Technology
FDA	Forensic Disaster Analysis
FORIN	Forensic Disaster Investigations (IRDR Working Group)
IRDR	Integrated Research on Disaster Risk
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
USGS	U.S. Geological Survey

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