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A DIGITAL HURRICANE SURGE ATLAS FOR NEW ORLEANS

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Abstract: This paper describes the development and application of a digital Hurricane Surge Atlas for New Orleans. This innovative tool is able to assess the surge threat of hurricanes in flood-prone delta areas in a few minutes during emergency situation with a high degree of reliability. This tool has been developed in the aftermath of Hurricane Katrina in 2005. A wide variety of storm scenarios from the numerical computations have been chosen as its basis. These results have been stored in a large GIS database and a visualization tool has been built to quickly extract storms from the database which resemble the forecasted storm. It turns out that the Hurricane Surge Atlas provides equal or even better results than the standard forecasting tool for surge levels provided that the hurricane has a reasonable match with the available scenarios in the Atlas. An important advantage of the Hurricane Atlas is that it enables the end-user a tool to quickly assess changes in weather forecasts (e.g. strengthening of the storm, or changes in storm track). It is recommended to further explore the performance of the Atlas for non-typical hurricanes and also integrate the information with levee characteristics to obtain direct insight into the performance of the flood risk reduction system.
Keywords: Hurricanes, storm surge, New Orleans, hazard forecasting.

INTRODUCTION

Large-scale coastal flooding disasters in low-lying deltas around the world have succeeded each other rapidly in recent years. Hurricane Katrina in New Orleans (2005) and Cyclone Nargis in Myanmar (2008) are two well-known examples of flood events with extreme damage and loss of life. When Hurricane Katrina hit the city of New Orleans in 2005, the levees failed due to a complex combination of technical and political factors, causing flooding for three weeks. Over 800 people lost their lives during this hurricane in New Orleans itself (Jonkman et al., 2009) and the direct and indirect damage was very significant. Myanmar was hit very hard in 2008 when Cyclone Nargis made landfall in the Irriwaddy Delta early May 2008. This cyclone was the deadliest tropical cyclone in the area since 1970 and it affected more than 1.5 million people. Although the exact numbers are still unknown, the number of casualties is probably more than 100,000.

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In the aftermath and evaluation of flood disasters, it has become apparent in recent decades that state-of-art numerical tools can further reduce flood risk in flood-prone areas around the world. Real-time flood forecasting has often been proposed and also successful implemented for low-lying areas along rivers and near coasts. A real-time system focuses on predicting the potential hazard based on actual weather predictions during the event itself. It is obvious that the setup and use of real-time systems can be challenging. For instance, real-time forecast systems require a reliable ICT infrastructure which operates during extreme events. Also, the flood forecasting models have to be quick in terms of processing time. This can hamper the necessary details to predict the floods accurately. Third, the process of real-time forecasting often does not provide sufficient time/flexibility to do scenario (what-if) analysis.

Hurricane Katrina (2005) initiated a large program in New Orleans to reduce flood risk. Apart from structural measures such as levees and barriers, also non-structural measures were critically evaluated. Up till then, a real-time forecasting system was in use only during hurricane situations. Based on a successful pilot during Hurricane Gustav (2008), a Digital Hurricane Surge Atlas has been developed for use parallel to the real-time forecasting systems. The digital atlas concept is based on the idea that a wide variety of possible scenarios are defined and processed in advance of any emergency situation. During an extreme event, specific scenarios can be retrieved quickly from a large database of scenarios and displayed for analysis, interpretation and decision-making. Also, scenario analysis can be carried out efficiently. An important question is how accurate the estimates from the digital atlas are compared to the real-time forecasting and – even more important – the real situation. Since this digital atlas has been applied in various hurricanes and tropical storms after Hurricane Katrina, this aspect can also be addressed.

This paper discusses the development and application of the Digital Hurricane Surge Atlas in New Orleans. First, some background information is provided about New Orleans and the flood risk reduction program after Katrina. Next, the setup of the Hurricane Surge Atlas is described. The tool has been tested during various hurricanes and tropical storms which are discussed thereafter. It also includes a discussion about the potential use for other areas around the world. This paper ends with conclusions and recommendations for future work.

HURRICANE RISK REDUCTION IN NEW ORLEANS

New Orleans and Hurricane Katrina

New Orleans is protected against storm surge by 560 kilometers of levees and floodwalls (Figure 1), the so-called Hurricane Storm and Risk Reduction System (HSDRRS). Additionally there are numerous structures embedded in the line of the defense: outlet canals and drainage pumping stations, which drain rainwater from the city. The scheme of levee and floodwall works around New Orleans was implemented after the "Hurricane with NO NAME" of 1947 and was continued after Hurricane Betsy in 1965. Three congressionally authorized projects were initiated in the decades after hurricane: Lake Pontchartrain and Vicinity, New Orleans to Venice, and West Bank and Vicinity. These projects cover the entire New Orleans region including the areas along the Mississippi downstream of New Orleans. Main portions of this system, however, were not complete and below their authorized elevations in 2005 (IPET, 2007).

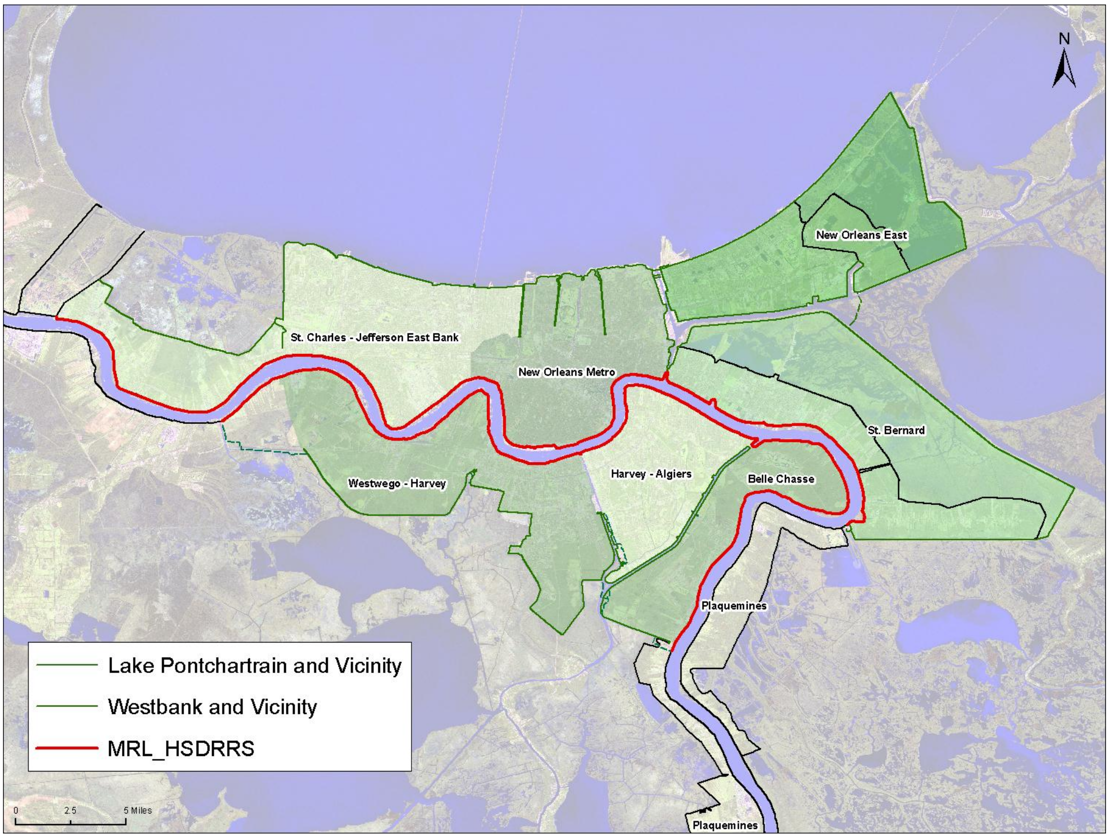

Fig. 1. Hurricane Storm Damage and Risk Reduction System (HSDRRS) around New Orleans.

In 2005 Hurricane Katrina showed the New Orleans' extreme vulnerability to coastal flooding. After the first landfall in Florida, Hurricane Katrina intensified to a Category 5 hurricane in the Gulf of Mexico. The second landfall took place near Buras in Louisiana. It generated storm surge levels at the coast with a maximum water level of 9m above mean sea level (9m+MSL) near Biloxi (Mississippi). Over 50 breaches in the levee system around New Orleans resulted in a major flooding of the city. With a total property damage estimated at $81 billion (2005), it was the costliest natural disaster in US history, and 1836 people lost their lives in this tragedy with over 800 in New Orleans itself (see e.g. Jonkman, 2007).

Importance of detailed surge modeling

The coastal flooding during Katrina has initiated various federal and state programs to reduce flood risk in this area. The US Army Corps of Engineers has been responsible for executing a program to improve the levee system around New Orleans to the 100-yr design standard. This 6-year program was focusing on flood risk reduction in the short term and has resulted in a $ 14 billion investment program in levees, pumping stations and storm surge barriers to provide the necessary level of protection. The Louisiana Coastal Protection and Restoration Project (LACPR) from the US Army Corps of Engineers and Louisiana's Comprehensive Master Plan for a Sustainable Coast from the State of Louisiana have been focusing on the long-term flood risk reduction. In essence, the proposed plans follow the conceptual framework of the multiple lines of defense strategy from Lopez (2009). These multiple lines include structural measures such as the further raising of levees and barriers but also a range of non-structural measures such as wetland restoration, evacuation and changing building codes to further reduce flood risk.

A key element in the federal and state programs described above has been the joint effort to establish water levels and waves for different return frequencies in Southern Louisiana. This so-called Joint Coastal Surge Study was a joint effort of public (USACE, NOAA, FEMA) and private partners has resulted in a new process for estimating hurricane surge for extreme events. The basis of this work is a joint probability method for optimal sampling. The reader is referred to Resio et al. (2008) for further details. The basic information applied in the hurricane surge atlas described in the next section originates for a large part from this effort.

THE DIGITAL HURRICANE SURGE ATLAS

Current real-time methods

Currently, there are two modeling frameworks for real-time storm surge forecasting during hurricane conditions in the United States. The National Hurricane Center (NHC) forecasts storm surge using a SLOSH model (NHC, 2008). SLOSH inputs include the central pressure of a tropical cyclone, storm size, the cyclone's forward speed, the storm track, and the expected maximum winds. Local topography, bathymetry, astronomical tides, as well as other physical processes are taken into account and calculated on a relatively coarse grid. The advantage of this forecast method is that it is able to produce (and ad-just) a forecast very rapidly. The downside is that the forecast is only 20 percent accurate and the results very coarse, making the application of the forecast in most cases only relevant on a regional scale rather than a local scale.

The ADCIRC model is also applied for estimating hurricane surge (see e.g. Westerink et al, 2008). ADCIRC is very detailed numerical depth-averaged hydrodynamic model that computes water levels based on predicted wind speeds, air pressure, bathymetry and surface roughness. The advantage of such a high detailed model is that physical and hydraulic processes are more accurately modeled and forecasts of water level are made at a very high resolution. The disadvantage is that such a model run is time consuming and that the processing of the model can take up to a few hours. Knowing that complicated weather systems like a tropical cyclone can change track and intensity in a matter of hours, the forecast that took a few hours to produce may already be outdated. Moreover, there is always the possibility of the model crashing, or the computer systems going down during a storm event.

Hurricane Atlas Concept

The pros and cons of the above real-time methods show that a compromise needs be made between a timely forecast and the level of detail and accuracy of the forecast. Also, the reliability of real-time computations is not 100%. A Digital Hurricane Surge Atlas can provide an alternative in tackling the limitations of real-time methods (see also Kluskens et al, 2012). The atlas holds a dataset of high resolution modeling results for a wide array of pre-defined and pre-calculated storm scenarios. Looking up the storm that most resembles the forecasted storm provides instant insight in the maximum water levels without the need to perform time consuming computations and data processing. Additionally various scenarios can be rapidly evaluated (in minutes rather than several hours): what if the forecasted storm changes track or intensifies?

Looking up a more extreme storm with a different track will provide instant insight in changing water levels. At the same time a storm atlas can provide a high resolution water level forecast very quickly. The atlas can be prepared before the storm season starts and the successful application of it depends on the number of available storm scenarios. The concept of a storm surge atlas can be implemented in a GIS environment and makes the results available through an interactive map for quick visualization and decision-making.

Implementation for New Orleans

The starting point for New Orleans has been the suite of storms developed during the Joint Coastal Surge study (USACE, 2008). A set of 152 storms were evaluated for both the eastern and western part of the Southern Louisiana (with one river discharge level in the Mississippi River). This storm suite consists of storms with differences in track, intensity, size, forward speed, angle of incidence. Figure 3 shows the different tracks available for the eastern part of Southern Louisiana. On each track, various storm scenarios are available with differences in storm characteristics. These variations have been chosen to cover the entire probability space of possible hurricanes in this region. The central pressure ranges from low to high-intensity storms, and the same holds for the size and the central speed of the storms.

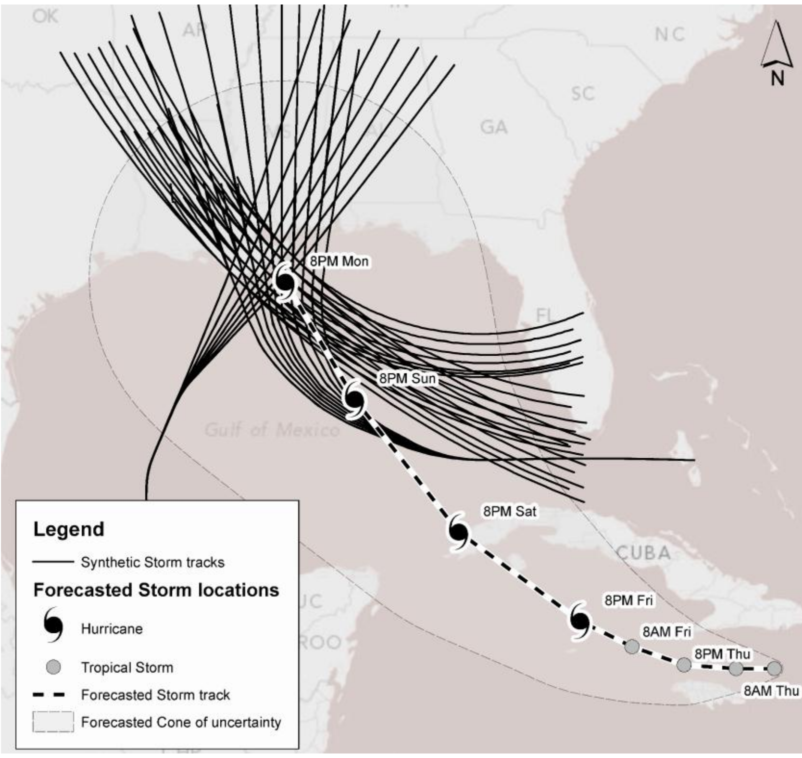

Fig. 2. Digital Hurricane Atlas Interactive Map with tracks for Southeastern Louisiana.

The storm surge at the Mississippi River is an important aspect for the New Orleans region. The levees in the downstream portion of the Mississippi River are not only protecting the low-lying areas against river flooding but also against the protruding high surges into the river during hurricanes. Figure 3 shows a storm surge of more than 4 meters during Hurricane Katrina near downtown New Orleans which is more than 150 kilometers upstream from the river mouth. It is obvious that this effect changes when the river discharge is different. Hence, insight in the storm surge along the river for different river discharge levels is necessary in the Digital Hurricane Surge Atlas to assess the situation during these extreme events accurately. Therefore, the river discharge has been added later on as an additional variable in the Digital Hurricane Surge Atlas.

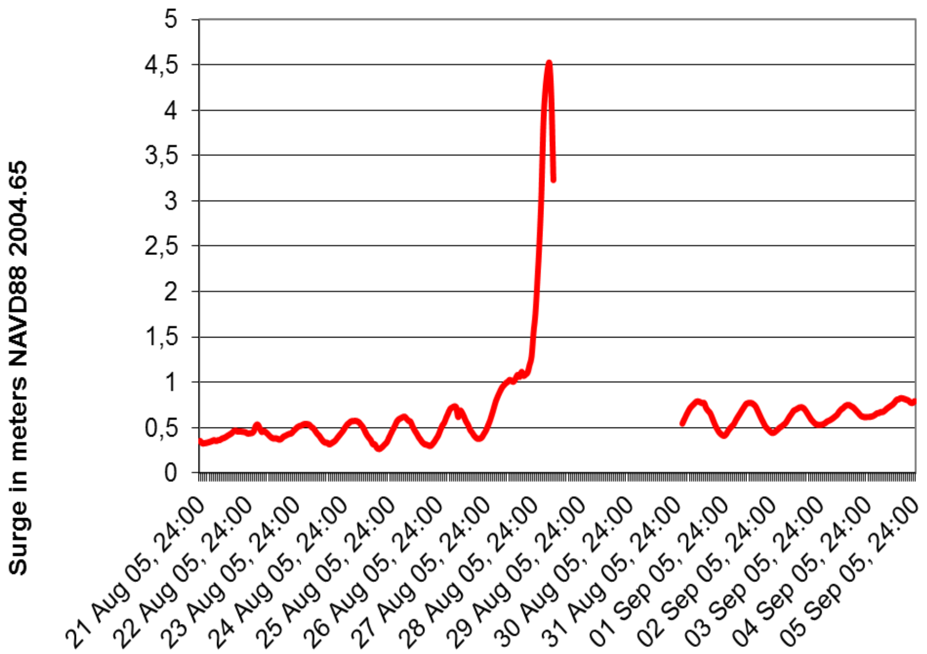

Fig. 3. Hurricane Surge near downtown New Orleans during Hurricane Katrina. Note: there is a gap after the peak surge due to lack of data.

In the current version, more than 500 storms have been incorporated in the Digital Hurricane Surge Atlas for Louisiana. For each of the storm scenarios in the Digital Hurricane Atlas, the following information is available:

- Storm development in terms of wind speeds, forward speed, minimum central pressure and time to landfall for different Mississippi river discharges.
- Maximum Still Water Levels
- Maximum Wave height and Peak Wave Period

Once a storm scenario is manually selected that closest resembles the forecasted storm in terms of track and storm parameters, it is also possible to combine this information with the flood protection geometry to calculate possible overtopping and overflow conditions.

APPLICATION OF THE ATLAS

The Digital Hurricane Surge Atlas has been applied during various hurricanes and tropical storms. Here, we describe the application during Hurricane Gustav (2008) and Hurricane Isaac (2012). These were selected since these were the first and the last application up till now with this tool. For both events, the experiences with this Digital Atlas next to the real-time forecasting tools are described.

Hurricane Gustav (2008)

This hurricane originally was a severe hurricane in the central portions of the Gulf of Mexico. It reached Category 4 strength on the Saffir-Simpson Hurricane scale. Based on its predicted characteristics and landfall location near New Orleans, a mandatory evacuation was ordered of the residents of New Orleans at August 31, 2008. Hurricane Gustav remained on its forecasted track but reduced substantially in strength traveling across the Gulf of Mexico. It made landfall as a Category 1 hurricane at September 1, 2008.

The Digital Hurricane Surge Atlas was used during the entire storm next to information of the real-time forecasting systems SLOSH and ADCIRC. During traveling across the Gulf of Mexico, the Digital Hurricane Atlas was applied for “what-if” analyses and variations in track, size and intensity were quickly evaluated. Close to landfall, it appeared that one of the storms from the Digital Hurricane Surge Atlas (Storm 50) was very similar to the characteristics of Hurricane Gustav in terms of central pressure, size and track/landfall location. The predicted peak water levels from this specific storm from the Atlas and also the predicted peak water levels from the real-time systems at five characteristic locations in the system around New Orleans have been listed in Table 1. This prediction has been made about 1 day prior to landfall (Aug 31, 2008). These numbers have been compared with the actual measured peak water level at September 1, 2008.

Table 1. Peak water levels in m+NAVD88 at five characteristics locations around New Orleans during Hurricane Gustav (2008). Highlighted in green are the predictions within +/- 0.25 m from the measured peak water level.

Location	Measurement	ADCIRC advisory 32 from USACE	SLOSH Advisory 32 from NHC	Storm 50 from Digital Hurricane Atlas
Gulf Intra Coastal Waterway	3.5	3 – 3.2	2.0 – 2.1	3.4
Caernarvon Outfall Canal	3 – 3.3	3 – 3.3	1.8 – 2.0	3.7
Lake Pontchartrain	1.4	1.2 – 1.5	0.6 – 0.8	1.6
Golden Meadow	2.0	3.2 – 3.5	2.3 – 2.4	1.9
Harvey Canal	0.9	1.4 – 1.5	0.8 – 1.1	1.2

It can be concluded from Table 1 that the Digital Hurricane Surge Atlas proved to be very accurate compared to SLOSH for all locations except for Harvey Canal. Also, it turned out to be much closer to reality in at least one location (Harvey Canal) than the ADCIRC advisory 32. One explanation is that the real-time forecasts are carried out on a (much) coarser grid than the Digital Hurricane Surge Atlas in order to meet time constraints for real-time forecasting. Southern Louisiana has a very complicated geometry with the shallow wetlands and the deep, narrow creeks and canals in between. These subtleties are not captured in the very coarse bathymetry of SLOSH. Although the real-time version of the ADCIRC model has a much more detailed bathymetry, it also hampers lack of detail at locations far away from the relatively undisturbed coastline.

Hurricane Isaac (2012)

Hurricane Isaac made landfall at the US Gulf Coast in Louisiana at August 29, 2012. This low-intensity hurricane was non-typical in terms of its large size (40 – 45 nautical miles). Also, it was slow moving and drifted along the coast towards the west just before landfall resulting in a "kink" in its track. The hurricane produced 45 hours of tropical force winds from the south and south east on a track west of New Orleans, Louisiana. The combination of long duration and the unfavorable track caused significant surge levels resulting in inundation in several communities outside the greater New Orleans Hurricane and Storm Damage Risk Reduction System. The Braithwaite polder just east from the Caernarvon Outfall Canal was severely hit with more than an inundation of about 3-4 meters. Also, communities bordering the northern and southwestern edges of Lake Pontchartrain were inundated.

Because of Isaac's non-typical hurricane characteristics, it appeared to be difficult to find a similar storm scenario within the Digital Hurricane Surge Atlas. Both Storm 51 and 124 were selected from the Digital Hurricane Surge Atlas based on expert judgment. These storms, however, were too strong in terms of their intensity but also too small compared to Hurricane Isaac's characteristics. These two aspects have opposite effects in terms of surge and therefore still result in a reasonable estimate as can be observed in Figure 4. The overall trend for all peak water levels is reasonable ($R^2 = 0.7$), but some significant differences are observed at specific locations with differences of about 0.5 – 1 meter. The non-typical hurricane characteristics are the main factor explaining these differences.

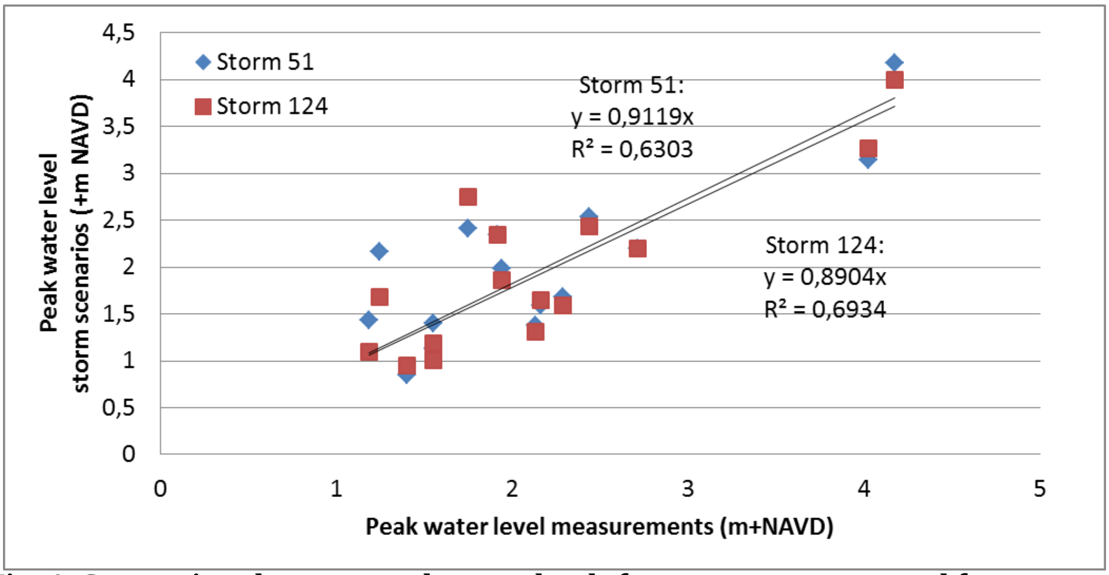

Fig. 4. Comparison between peak water levels from measurements and from storm scenarios at 15 characteristics points in the New Orleans region based on Digital Hurricane Atlas during Hurricane Isaac (2012).

Lessons learned and outlook

From the applications with the Digital Hurricane Atlas, the following can be concluded. First, the results from the Atlas can have similar accuracy compared to real-time models. In some cases, the results can be even more accurate as has been shown in the Hurricane Gustav case. In contrast, the application of the Atlas can be challenging if the hurricane characteristics are non-typical in terms of track, size and/or intensity (e.g. Hurricane Isaac, 2012). Feedback from end-users indicates that the Digital Hurricane Surge Atlas adds value next to the real-time models. The big advantage of the Atlas is that the quick assessment can be carried out including many what-if scenarios. These what-if scenarios (worst case, best case etc.) are critical to inform decision makers in the days prior to landfall.

An interesting step forward is to explore improvements of the Atlas performance for non-typical hurricanes. This may be done through intelligent interpolation between different storms in the atlas. Smith et al. (2012) call this surrogate modeling and present an example for Hawaii. A second recommendation is to investigate whether this Atlas concept also would work for non-hurricane conditions (e.g. extra-tropical storms) and other regions in the world (e.g. cyclones in Asia). Finally, it is recommended to further explore the possibility of integrating the information from hurricane surge with the performance of critical infrastructure (e.g. levees, barriers). A pilot version has been presented in Kluskens et al. (2012) in which the information of the Digital Hurricane Atlas is coupled with levee strength information. The resulting levee performance for a pilot area in the New Orleans region is presented in a web-based dashboard providing managers and operators of a flood defense system with a recommended action/mitigation plan.

CONCLUSIONS

This paper presents the development and application of the Hurricane Surge Atlas for New Orleans. This Atlas is based on a wide range of pre-defined hurricane scenarios. During a hurricane, a storm scenario from the Atlas can be selected which agrees well with the forecasted hurricane characteristics based on expert judgment. This enables the end-user to have a very quick insight in the potential hurricane surge. Two applications have been presented in this paper: Hurricane Gustav (2008) and Hurricane Isaac (2012). The applications show that the Digital Hurricane Surge Atlas provides a similar accuracy of the hurricane surge compared to detailed real-time models. The latter requires hours of computational time, whereas the Digital Atlas provides the results within minutes. For specific cases, the prediction based on the Atlas can be even better than real-time models due to more details included in the modeling approach. An important restriction is that there is a good match between the forecasted hurricane and the available hurricane scenarios in the Atlas. It is recommended to explore whether the performance of the Atlas can be improved for hurricanes with non-typical characteristics.

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