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The large-scale impact of climate change to Mississippi flood hazard in New Orleans

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Abstract

The objective of this paper is to describe the impact of climate change on the Mississippi River flood hazard in the New Orleans area. This city has a unique flood risk management challenge, heavily influenced by climate change, since it faces flood hazards from multiple geographical locations (e.g. Lake Pontchartrain and Mississippi River) and multiple sources (hurricane, river, rainfall). Also the low elevation and significant subsidence rate of the Greater New Orleans area poses a high risk and challenges the water management of this urban area. Its vulnerability to flooding became dramatically apparent during Hurricane Katrina in 2005 with huge economic losses and a large number of casualties.

A SOBEK Rural 1DFLOW model was set up to simulate the general hydrodynamics. This improved model includes two important spillways that are operated during high flow conditions. Subsequently, a weighted multi-criteria calibration procedure was performed to calibrate the model for high flows. Validation for floods in 2011 indicates a very reasonable performance for high flows and clearly demonstrates the necessity of the spillways.

32 different scenarios are defined which includes the relatively large sea level rise and the changing discharge regime that is expected due to climate change. The impact of these scenarios is analysed by the hydrodynamic model. Results show that during high flows New Orleans will not be affected by varying discharge regimes, since the presence of the spillways ensures a constant discharge through the city. In contrary, sea level rise is expected to push water levels upwards. The effect of sea level rise will be noticeable even more than 470 km upstream. Climate change impacts necessitate a more frequent use of the spillways and opening strategies that are based on stages. Potential alternatives on how to cope with the flood hazard of this river in the long term, such as river widening and large-scale redistribution of the flow through diversions, are proposed.

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1 Introduction

The Mississippi River has the third largest river basin of the world and drains, in all its greatness, 41 % of the United States. The flood risk of the Mississippi River imposed on urban areas, like Baton Rouge and New Orleans, became apparent during the great flood in 1927 which was the most destructive river flood in the history of the United States (Barry, 1998). The river, discharging more than $85\,000\text{ m}^3\text{ s}^{-1}$, caused levee failures at numerous places, displaced over 600 000 people and flooded almost 70 000 km^2 causing damage for \$ 400 million.

The devastating impact of hurricane Katrina in 2005 made the flood hazard and its social impact in deltaic urban areas even more apparent. The hurricane killed over 1800 people, caused ca. 245 000 inhabitants of New Orleans to migrate to other regions (Krupa, 2011) and had a total property damage estimate of \$ 108 billion (Knabb et al., 2011).

Looking ahead, climate change is expected to affect the river discharge due to alterations in the water cycle. Ericson et al. (2006) found that the relative vulnerability of the Mississippi delta, compared to 39 other deltas, is extreme and is demonstrated by the population potentially being displaced by current sea level trends to 2050. US-GCRP (2000) shows significant increases in the heaviest precipitation events and notes that changes in streamflow follow these changes in precipitation, but are amplified by about a factor three. Additionally, climate change induced sea level rise in combination with the local subsidence of the Mississippi River Delta causes the projected local relative sea level rise in 50 yr to range between +0.5 m and +0.9 m for different rates of sea level rise (USACE, 2009; NOAA, 2011). The uncertainty in these projections is large, since the local subsidence rates vary strongly throughout the delta. Altogether, relative sea level rise is expected to affect river stages further upstream in the future. In combination with the alterations in streamflow the future flood water levels in the Mississippi River are subject to change.

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In view of future changes there are various management challenges in the Mississippi River Delta to be dealt with in order to sustain the economic benefits for society, reduce the flood risk of urban areas, such as New Orleans, and to preserve the environmental value of the wetlands. Many of these issues are interrelated which each other. As an example, the high river levees prevent the river overflowing into the historic flood plains and therefore withhold fertile river sediment being deposited in the floodplains. This sediment starvation induces coastal marsh deterioration. Since the 1930s some 4900 km² of coastal wetlands have already disappeared in the Gulf of Mexico and this process continues at a rate of 65 km² per year (Bourne Jr., 2004). This process is enhanced by the strong subsidence in the area and increases the potential for inundation (Nicholls, et al., 2007). Another water management challenge is more closely related to flood hazard in City of New Orleans. The Mississippi River levees downstream of Baton Rouge, LA, do not have large floodplains to overflow when the bankfull discharge is exceeded. This results in a steep discharge-stage relation compared to a river system that has large floodplains available on the riverside of the levees. Near New Orleans a river stage of +5.18 m above the North American Vertical Datum of 1988 epoch 2004.65 (NAVD88) is used as the safe water elevation. In order to prevent exceedance of this river stage near New Orleans two important spillways have been constructed further upstream: the Bonnet Carre Spillway and the Morganza Spillway (see Fig. 1). The latter diverts water to the Atchafalya River basin which is located to the west of the Mississippi River, and was opened for the second time in spring 2011. The question is how this system of levees and spillways can be adapted in view of future changes.

The objective of this article is to address the future changes in the Mississippi River stages in the context of climate change. For this purpose, a hydraulic model and an overview of modelling scenarios is presented in the following section of this paper. Next, the model results are discussed and an overview of possible implications and potential solutions for the Greater New Orleans area are presented at the end of this paper.

2 Methods

2.1 Hydrodynamic model

An improved one-dimensional hydraulic model was set up to describe the general hydrodynamics of the river and to simulate stages for the lower reach of the Mississippi River, which includes the cities Baton Rouge and New Orleans. This includes a model of the last 492 km of the river before it enters the Gulf of Mexico (see Fig. 1). This model was subsequently used to perform a sensitivity analysis on the response of the river stage to climate change.

A HEC-RAS geometry is used that was provided by the Hydraulics and Hydrologic Branch of the US Army Corps of Engineers (USACE) New Orleans District and is based on a survey done in 2002 and 2003. This geometry is imported in the SOBEK Rural Advanced Version 2.11.002c software (Deltares, 2010) and provides 164 cross-sections between the upstream boundary at Tarbert Landing and the downstream boundary at Venice (see Fig. 1). The modelled reach will hardly receive any significant lateral inflow due to precipitation which validates the use of the hydrodynamic 1DFLOW module within SOBEK Rural and the exclusion of a rainfall-runoff module.

Daily discharge at Tarbert Landing is used for setting the upstream boundary condition for unsteady flow computations. A stage-discharge relation is used to compute the daily discharge based on observed daily stages. A fixed water level, representing the yearly averaged stage, is applied at the downstream boundary condition at Venice, since no hourly data was available to incorporate the tidal signal. Although the tidal signal may have a pronounced effect on the stages in the Mississippi River during low discharges, a fixed boundary is justified, since the study focuses on high flows wherein tidal influence on river stages is negligible.

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2.2 Calibration

The model needs to be calibrated which means that the parameters that are known to be uncertain, are systematically varied in order to find the right setting for the specific study area. Calibration of the model is performed by a weighted multi-criteria procedure for the main channel friction (Manning) parameter. Such a detailed calibration procedure is new for the Lower Mississippi river. The model is calibrated with a particular interest for high flow conditions. In order to include a realistic opening of the earlier mentioned Bonnet Carre Spillway stage a discharge time series originating from 1997 is used for the calibration procedure. Ten discharge bins are defined based on the minimum and maximum discharge of that year. Based on the frequency of days that features each bin a certain weighting factor is defined for the daily discharges in each bin, so that each bin has an equal weight (10%) in the calculation of the statistical parameters. These weighting factors are higher for higher discharges, since their occurrence is lower. A multi-criteria procedure is used, since one parameter does not indicate every aspect of a time series. An optimal friction coefficient is expected by compromising between multiple calibration parameters, such as the Nash-Sutcliffe coefficient (Nash and Sutcliffe, 1970), the weighted linear regression coefficient, the weighted absolute error and the weighted root square error. For six different segments along the Mississippi River the Manning friction value in the main channel is calibrated based on the simulated stages.

Figure 2 presents the results of the calibration procedure. The Nash-Sutcliffe coefficient and the mean absolute error are given for each location. The Nash-Sutcliffe coefficient assesses the predictive power of a hydrological model and its optimum value is 1. It is calculated by one minus the residual variance divided by the data variance. The model results show an overestimation of the maximum discharge peak for all six measurement stations that are used. For the calibration period, the performance of the model to simulate water levels at Carrolton (New Orleans) is described with an 10th and 90th percentile of respectively -0.6 m and $+0.3$ m. At Alliance, the model errors

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are relatively large and are partly caused by the tidal signal that is dominant at this location under low flow conditions. The error becomes relatively larger in downstream direction.

2.3 Validation

After the calibration procedure is completed a validation of the model needs to be performed. It means that the model's performance is investigated by using the calibrated model parameters and by running the model for a different time period. Validation of the model is performed using the Mississippi River flood of 2011. In this year there was an exceptionally high discharge of $45\,845\text{ m}^3\text{ s}^{-1}$ measured at Tarbert Landing (US-ACE, 2011) that required the opening of the Bonnet Carre and Morganza Spillway for several days. The validation run simulates stages for the time period 1 January 2011 to 14 June 2011. The validation results are given in Fig. 3 and show a good representation of the flood that occurred in May. Both the Bonnet Carre Spillway and the Morganza Spillway were opened during this flood. The latter flooded an area as large as 7700 km^2 and caused the displacement of ca. 25 000 people.

At Carrollton (New Orleans) the mean absolute error of the model simulation is 0.31 m. The maximum peak stages are simulated exceptionally well. At Red River Landing and Carrollton the difference of maximum stage is less than 0.01 m, while at Baton Rouge the maximum stage is underestimated with 0.09 m. At Alliance the maximum stage is overestimated with 0.25 m. The simulated hydrographs have a shift with respect to the observed hydrographs. This is explained due to the fact that the velocities in the model are underestimated. However, the model errors described above are relatively small considering the stage range of the Carrollton gage. Its average annual lowest and highest stages are respectively NAVD88 -0.01 m and NAVD88 $+4.34\text{ m}$. The model demonstrates to be capable of simulating the hydrodynamics and, therefore, allows a legitimate use of the model for a comparative analysis.

The model was also used to simulate the stages when the spillways would not have been opened (see Fig. 4). The impact on the stage at Carrollton (New Orleans) is

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especially of interest. The peak stage for this situation is projected to be NAVD88 +7.17 m, while the levee heights at Carrollton are ca. NAVD88 +7.30 m. This clearly demonstrates the benefit that the spillways have in reducing flood hazard for the urban area of New Orleans.

2.4 Climate change projections

The climate change impact on the Mississippi river stages is investigated by using different scenarios of sea level rise and upstream discharges. Based on the earlier mentioned projections and the practical application of sea level rise, four situations are used: no sea level rise, +0.45 m, +0.70 m and +1.00 m sea level rise. These scenarios are within the limits of the appropriate USACE directive (USACE, 2009). Four projections of the upstream discharges are formulated by shifting the discharge hydrograph by a factor 0.95, 1.05, 1.10 and 1.15. Both the mean and standard deviation change according to this factor. Three other projections are formulated by multiplying the difference to the mean with a factor 1.1, 1.2 and 1.3. Hereby, the stages above and below the mean are exaggerated. This does not affect the mean, but increases the standard deviation by the used factors. Tweaking the hydrograph in aforementioned way finally results in four sea level rise projections and eight upstream discharge projections when a reference discharge projection is taken into account. Hence, 32 scenarios are used to assess the sensitivity of the Mississippi River stages to climate change.

3 Results

The defined scenarios are used to get an insight in the potential future behaviour of the Lower Mississippi system. By looking at the sea level rise scenarios where no discharge change is expected it can be concluded that the distance to the Gulf of Mexico, the position where the effect of sea level rise is halved, becomes larger with increasing sea level rise. The minimum stage difference with respect to the reference

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scenario occurs during high flow conditions when the stage is predominantly dependent on the discharge. Then, the sea level rise is halved at 130 km, 142 km and 148 km from the downstream boundary for respectively +0.45 m, +0.7 m and +1.0 m sea level rise as can be seen in Fig. 5. The minimum increase of stage at Carrollton becomes +0.21 m, +0.34 m and +0.50 m for all discharge regimes except the “-5%”-scenario. During low flow conditions the sea level has a stronger influence on the river stages. In this case the sea level rise is halved at 442 km, 444 km and 445 km for respectively the same three sea level rise projections. It is found that the stages along the entire modelled reach are affected by sea level rise for the three projections. The maximum stage increase at Carrollton is dependent on the type of discharge regime as well as the strength of sea level rise.

Changes in discharge characteristics do not affect the stages downstream of Bonnet Carre Spillway when it is closed, since a constant discharge is passed through. However, changes in the upstream discharge would affect the frequency and duration for opening of the spillways. Their effect on the water level near Carrollton is demonstrated in Figs. 3 and 4. The increase of stages in the downstream section is predominantly caused by the sea level rise. Currently, the threshold for a spillway opening is defined by the upstream discharge at Tarbert Landing. Sea level rise causes an increase in stage that changes the stage-discharge relationship. Thus in order to not exceed the NAVD88 +5.18 m threshold at Carrollton it is likely that a lower discharge threshold is needed for opening the spillways.

The relative steep stage-discharge relation due to the confined levees causes a strong increase in stages when upstream discharges increase. A solution for this could be the diversion of water from the Mississippi River by a number of spillways or small-scale river diversions to surrounding water bodies, such as the Atchafalaya River. Therefore, the cross-sectional area of the river is enlarged and stages near urban areas are attenuated. During high flows the sediment volumes in particular are known to be high in the Mississippi River. Small-scale diversions at different locations should also focus on optimizing sediment transport, so that the attenuation of stages

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on the Mississippi River is combined with counterbalancing sediment starvation, subsidence and indirectly salt intrusion. Therefore, these diversions could be opened on a yearly basis during the high flow period in spring. This would also keep the awareness of these diversions high among the people. Lowering of the stages near the urban areas can also be reached by increasing the flooded cross-section further downstream (e.g. relocation of levees, river bypasses).

4 Conclusions

The work that is described above addresses the future changes in the Mississippi River stages regarding “climate change”-induced changes of upstream discharge and sea level. The weighted multi-criteria calibration procedure has provided a hydrodynamic model that is capable of simulating high flows in the Mississippi River within an acceptable error margin and can be used legitimately for a comparative analysis.

The presence of the two spillways has proven to be of vital importance to reduce the flood hazard risk of the city New Orleans. In the future their role will be even more important. The challenges of the Mississippi River delta become even more apparent with expected climate change impacts. All of them increase the flood hazard in the Greater New Orleans area, which is already situated in a flood-prone area. This study shows that sea level rise is likely to be dominant on the downstream end of the Bonnet Carre Spillway which has a strong influence on the stages near New Orleans. At the same time the increased upstream discharge increases the frequency and duration of spillway openings.

Small-scale river diversions and enlarging cross-sectional area in downstream sections are proposed solutions for reducing flood hazard in urban areas. The feasibility of these solutions should be studied, because the urban and industrial areas are located tightly to the river levees and possible impacts on navigation and environment should be clearly investigated. An extension of the Mississippi River model with an

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updated bathymetry and a morphological module would be an added value for these investigations.

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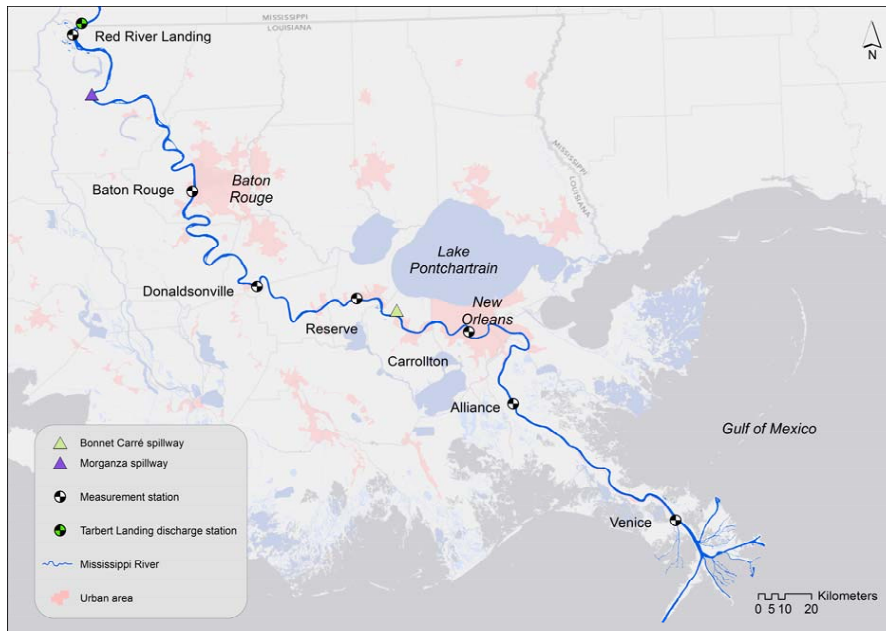


Fig. 1. Map of the study area of the Mississippi River.

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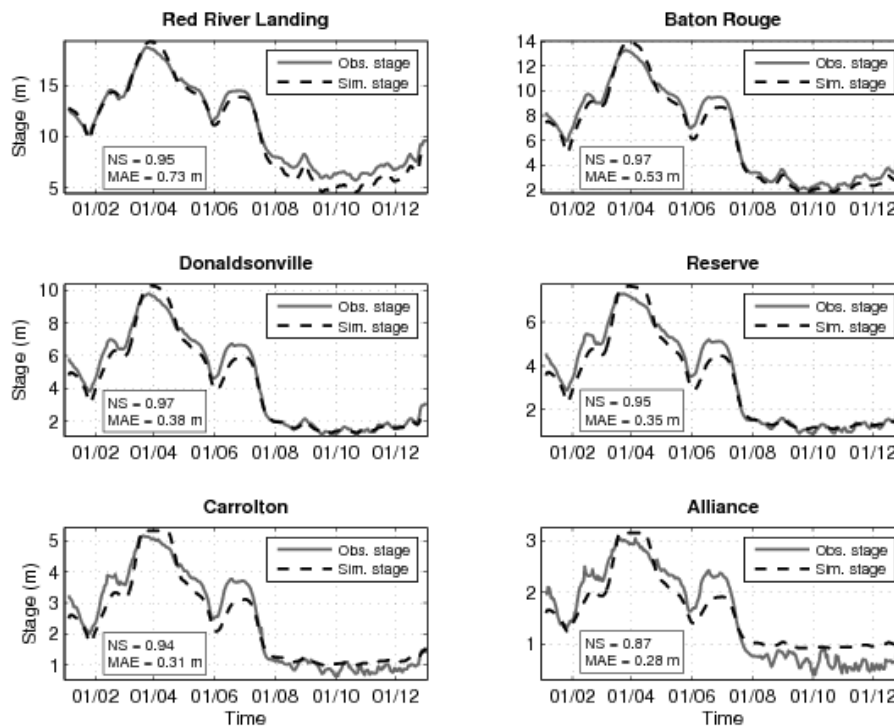


Fig. 2. Hydrographs of calibrated simulation run 1997.

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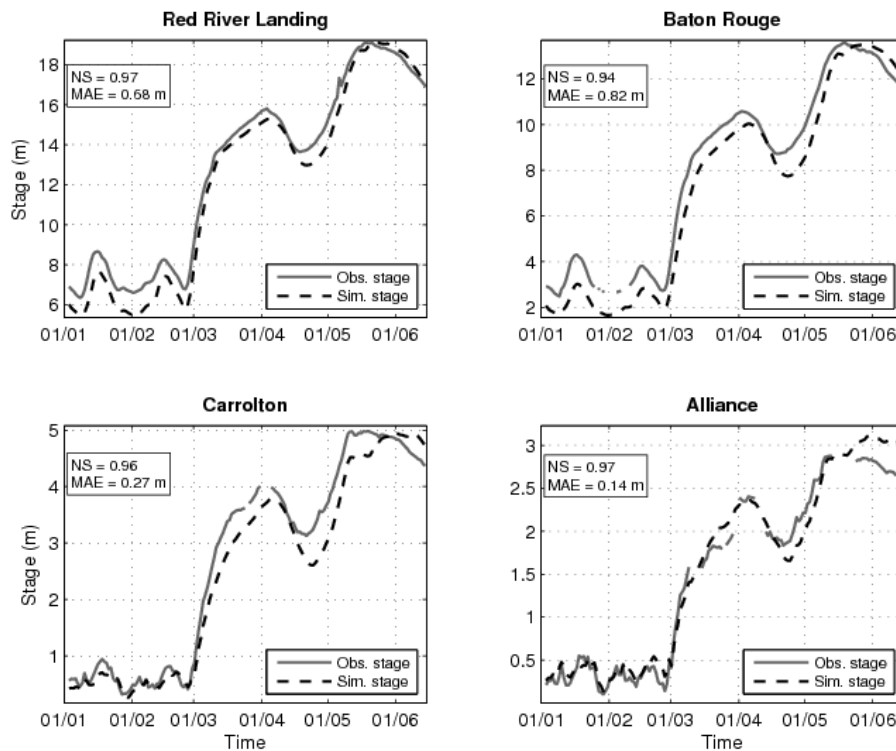


Fig. 3. Validation of the flood in 2011.

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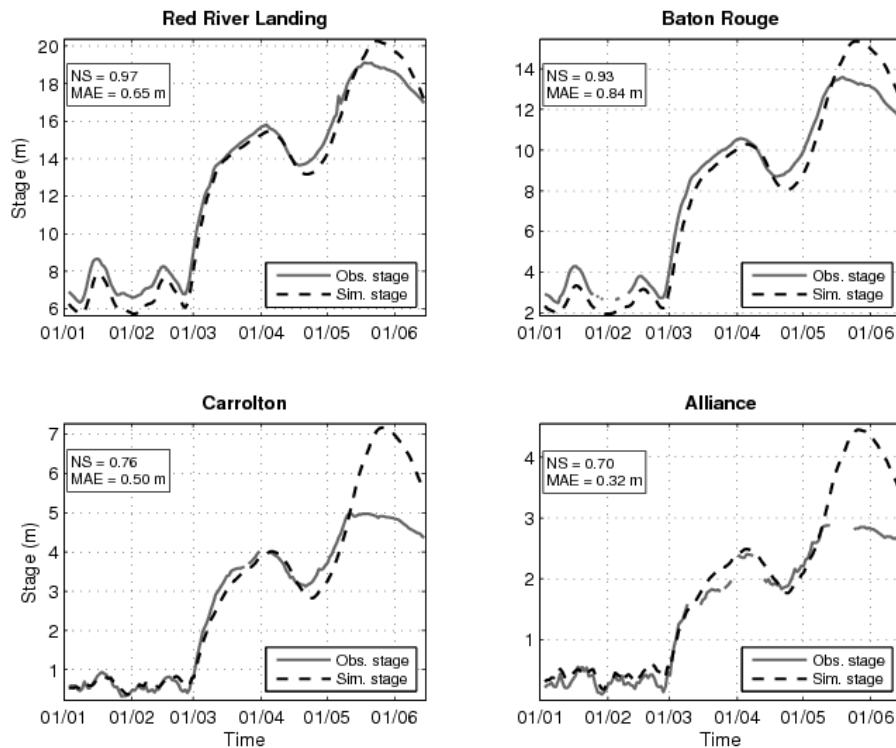


Fig. 4. The validation of the flood in 2011 when no spillways are opened.

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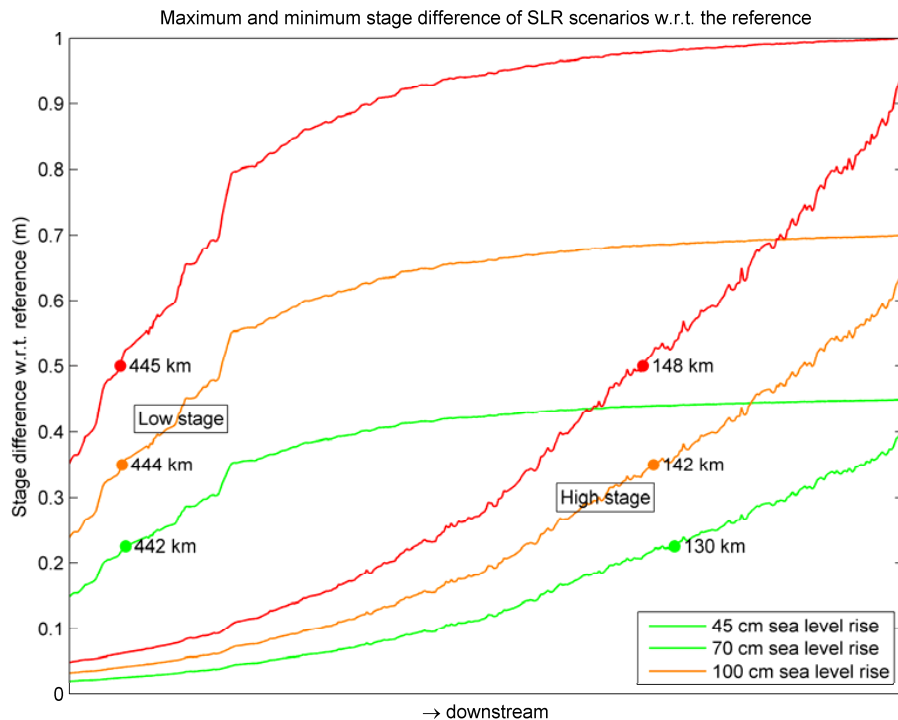


Fig. 5. Minimum and maximum stage differences with respect to the reference for three sea level rise projections.

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