pearl
Preparing for Extreme And Rare events in coastaL regions

D6.2 Report

Summary report on EU and international case studies

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Dissemination level (select one):
PU = Public
PP = Restricted to other programme participants (including the Commission Services)

Document Information

Project Number	***603663***	Acronym	**PEARL**
Full Title	Preparing for Extreme and Rare events in coastaL regions		
Project URL	http://www.pearl-fp7.eu/		
Document URL			
EU Project Officer			

Deliverable	Number	D 6.2	Title	Summary report on EU and international case studies
Work Package	Number	WP6	Title	Case studies areas

Date of Delivery	Contractual 31.12.2016	Actual	31.03.2017
Status	version 1.0	final □	
Nature	prototype □ report x dissemination □		
Dissemination level	public □ consortium □		

Abstract (for dissemination, 100 words)	The present report "D6.2: Summary report on EU and international case studies" represents a status report on the research activities in the European and international case studies (due date 31.12.2016). The report encompasses a description of the case study area and the types of hazards and risks. Furthermore, research activities and available results in the relevant work packages are summarized. Special emphasis lies on the description of governance strategies deployed, leading to the lessons learned in regards to improvement of the risk governance and further recommendations.
Keywords	Case study areas, flood risk assessment, flood management

Version Log				
Issue Date	Rev. No.	Author	Change	Approved by

Disclaimer

The research leading to these results has received funding from the European Union Seventh Framework Programme (FP7/2007-2013) under Grant agreement n° 603663 for the research project PEARL (Preparing for Extreme And Rare events in coastaL regions).

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Summary

The present report “Summary report on EU and international case studies” (D6.2) has been produced as a deliverable of the Work Package 6 on Case Study Areas. This work package aims at enabling efficient managment anf conduction of the flood risk assessment and management tasks (given in WP1-WP5) to be performed in the case study areas. It will further evaluate the potential and uptake of the PEARL methodology for holistic risk management and governance in coastal regions based on the performed case study work (D6.3, M40).

The report summarises the research activities in the European case studies as well as in the international case studies (Task 6.2, Task 6.3, Task 6.4) until the due date of the report (M36-31st, December 2016).

The report encompasses a description of the case study areas and the types of hazards and risks. Research activities and available results in the relevant work packages have been summarised. The presented case studies have analysed the potential strategies to mitigate flood risk including the nature based solutions (NBS) which by M48 (end of project) will lead to the lessons learned in regards to improvement of the risk governance and further recommendations.

Although the presented case study exhibit a high variety of the challenges and the key issues of concerns, a variety in the deployed methodologies and tools, their common ground is a step forward the holistic view on the flood risk and its consideration for the development of the flood risk mitigaiton strategies in the selected areas.

Contents

1 Introduction

The presented report "D6.2: Summary report on EU and international case studies" represents a status report on the research activities (WP1-5) in the European and international case studies (due date 31.12.2016) under the WP6.

The case study areas with their main characteristics have been summarised in Table 1 and their geographic spread is given in Figure 1.

Table 1 Overview of the PEARL Case study areas

Case study area		
1.	Greve	Denmark
2.	The Elbe Estuary	Germany
3.	Les Boucholeurs	France
4.	Genova	Italy
5.	Marbella	Spain
6.	Rethymno	Greece
7.	Tainan	Taiwan
8.	St. Lucia	The Caribbean
9.	St. Maarten	The Caribbean
10.	Ayutthaya	Thailand

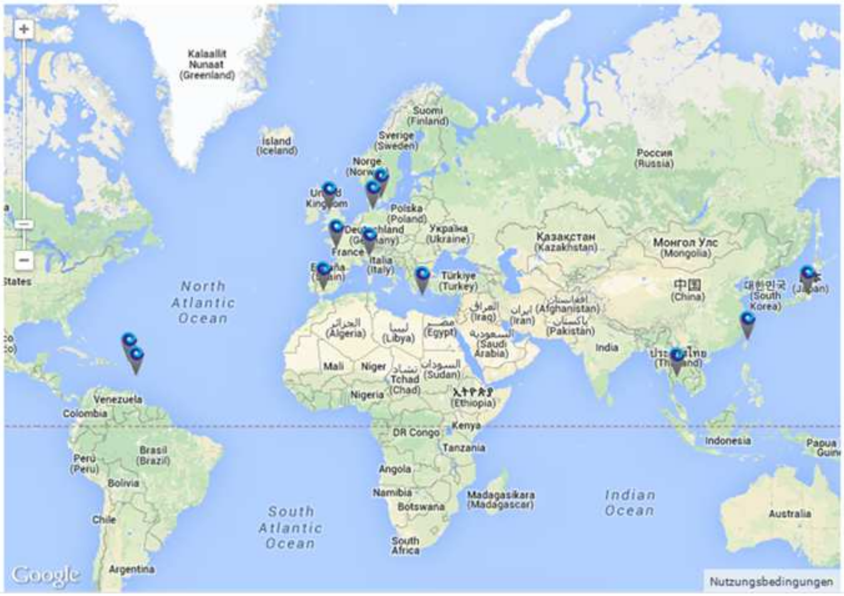


Figure 1 Geographic spread of the PEARL case study areas

The report encompasses a description of the case study area and the types of hazards and risks. Furthermore, research activities and the available results related to the formation of vulnerabilities (WP1), formation of multiple hazards (WP2), holistic risk assessment (WP3), early warning systems (WP4) as well as the decision support and the policy development (WP5) are briefly presented. For each study area, the key research activities as well as the additional activities i.e. the ones that are either included in the research portfolio during the project lifetime (e.g. FORIN Desk study of WP1 of the German case study) or the ones that are were not substantially addressed as of the month 36. A more detailed description of the research work performed in the individual work packages is given in the corresponding reports (deliverables).

2 Case Study – Greve, Denmark

2.1 Introduction to the case study area

2.1.1 General description of the case study area

Greve is a municipality in eastern Denmark. It is a sub-urban area located around 20 km southwest of the Danish capital Copenhagen (Figure **Error! Reference source not found.**). The Municipality has a total area of around 60 km2, with 9 km of coast to the southeast bordering the Baltic Sea at Køge Bay. The coastal boundaries stretch from Hundige Beach Park in the north to the sandy coast of Kalstrup Beach Park in the southwest. The beaches in this area are mainly sandy and very flat-bottomed. The coastal area is the most densely built-up part of Greve, and is characterized by relatively flat terrain with elevations between 2 and 6 m (above MSL).

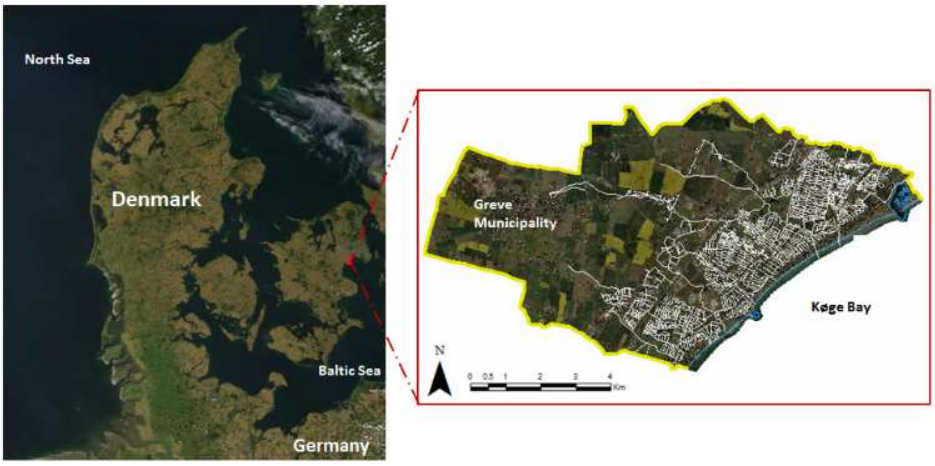


Figure 2: Location of the Greve case study area in eastern Denmark.

The sandy beaches, as well as the natural ecosystems of marshes and shallow lagoons in the area, attract local and tourist populations, which has led to the development of numerous holiday and detached houses near the coast. In addition, Greve is in part of a highly industrialized area in the south of Copenhagen, where four municipal wastewater treatment plants and several industries are located. The municipalities in the northern part of Køge Bay, which includes Greve, have some of the largest population densities in Denmark (Økonomi- og Indenrigsministeriet, 2013), and residential settlements are densely built up along the coast.

Case Study Objectives

Coastal flood risk assessment in Greve was performed as a case study in the PEARL Project. It was conducted as part of a Master Thesis project by Berbel Roman (2014).

Traditionally, flood risk assessments are performed considering isolated extreme events, but several studies have demonstrated that this is not realistic (Lian et al., 2013; Zheng et al., 2013; Zhang et al., 2014). Given the identified vulnerabilities of Greve to both pluvial and coastal

flooding, flood risk assessment based on concurrent occurrence of extreme rainfall and storm surge events was performed. A joint flood risk analysis methodology was developed and applied to quantify flood damages for single as well as combined events in present and future (climate change) extreme event scenarios.

2.1.2 Hazard and risk situation in the case study area

The main climate change threats to Denmark are increased rainfall and cloud bursts (EC, 2009). The sewer systems are unable to cope with large amounts of water as was demonstrated in Greve during the storms of 2002 and 2007. In August 2002, a rain event of 1000 years return period caused damages in the city centre, inundating important facilities such as the city hall and the local high school (Sto. Domingo et al., 2010). In July 2007, a series of rain events with a joint probability of occurrence of 500 years caused severe flooding in Greve, necessitating evacuation of citizens due to widespread flooding in the area (Greve Kommune, 2007). The serious flooding in Greve in 2002 prompted formation of a Technical Committee to evaluate the performance of the storm- and wastewater systems in the Municipality and implement adaptation measures. However, the flood of 2007 showed further actions were needed (Greve Kommune, 2007).

Greve is considered one of the most flood-prone areas in Denmark (EC, 2009). It is located along the Baltic Sea, and has been deemed vulnerable to coastal flooding. In addition to extreme rainfall and cloudbursts, the region is at risk from coastal flooding due to storm surges and general water level increase because of its location in Køge Bay (Vestergaard, 2011).

There have been 28 documented high sea level events in Køge Bay with magnitudes greater than 1.52 m—the highest water level observed in the area for the period 1955-2002. However, the extreme coastal flood in Køge Bay ever recorded was in 13 October 1760 with an estimated maximum water level of 3.7 m. In addition, extreme storm surge flooding happened the night between the 12 and 13 November 1872, where water levels reached 2.8 m (Madsen, 2008; Colding, 1881). This flood event was described in detail by Colding (1881) in the report "*Nogle Undersøgelser over Stormen over Nord- og Mellem-Europa af 12te-14de november 1872 og over den derved fremkaldte vandflod i Østersøen* (Some studies of storms over northern and central Europe on 12th -14th November 1872 and flood consequences around the Baltic Sea)". Estimates of these historical extreme coastal flood events using simple Terrain (GIS) Analysis are shown in Figure 3 below.

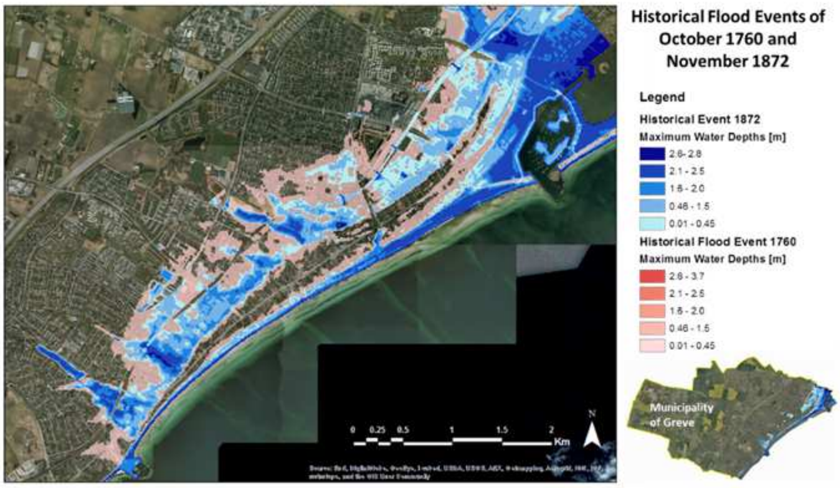


Figure 3: Plots of historical flood events in Greve in October of 1760 with an estimated maximum water level of 3.7 m and November of 1872 with an estimated water level of 2.8 m estimated using Terrain Analysis (Berbel Roman, 2014).

2.1.3 Current institutional and governance practice

The administrative and legal framework in Greve follows the national Danish Guidelines, where only flood risk plans must be prepared for pluvial flood risks. This is a top down planning system and no stakeholder analysis have been carried out. The current flood protection and risk mitigation strategies are for the moment being prepared by Greve Municipality. They are expected to be finished during summer 2017.

2.1.4 Available data used for research activities

Data for relevant coastal flood forcing event(s) in formats that may be used as boundary conditions to subsequent flood modelling were derived for the study (see also chapter 2.2.1). In addition, joint probability analysis was performed in the derivation of event data to consider the occurrence of concurrent events.

Extreme Sea Level Data

In Køge Bay, an 8-cm increase in mean sea level has been observed in the period 1891 to 1990 (Kystdirektoratet, 2002). This rate of increase is expected to continue in the future (Madsen, 2008), and GEUS and DMI (2012) estimated that mean sea level rise around Denmark will be 0.8 ± 0.6 m, up to 1.5 m by 2100 (Figure 4). In Køge Bay, estimated mean sea level rise values range from 0.75m to ± 0.6m.

Figure 4: Estimates of mean water level increase in year 2100 compared to today. The location of Køge Bay, near Greve, is shown. (Source: GEUS and DMI, 2012)

Synthetic extreme sea level event time series near Greve were derived from earlier climate change studies (Madsen, 2008; DHI, 2012). In "*Vandstandsstatistik i Køge Bugt under klimaændringer*" (Water level statistics in Køge Bay under climate change), Madsen (2008) analysed sea level statistics in Køge Bay to derive future projections for extreme sea levels in the area under climate change conditions. Regional climate and hydrodynamic modelling were employed to derive extreme sea level statistics. Wind and pressure data from regional climate modelling (RCM) were used in a 3D hydrodynamic model of the seas around Denmark to obtain long-term sea level values around Køge Bay (RiskChange, 2015). Statistical analysis of these sea level results, and comparison against observed statistics, were performed to determine appropriate change factors for scaling actual extreme sea level statistics into future scenario estimates. In the study, 100-year extreme sea levels were projected to increase by 69 cm in the future (from 153 cm to 222 cm) under the A1B climate scenario. DHI (2012) updated this study based on additional observed data, and revised estimates from an ensemble of Regional Climate Models (RCMs) for modelling future sea levels, obtaining new estimates of changes to extreme sea level statistics in Køge Bay (Table 2).

Table 2: Changes in storm signal [m] in Køge Bay in 2100 based on the three RCM/GCM projections for different return periods (DHI, 2012).

Return Period [yrs]	**HIRHAM_ARPEGE**	**HIRHAM_ECHAM5**	**HIRHAM_BCM**	**Average**
10	-0.14	0.14	-0.06	-0.02
50	-0.17	0.19	-0.07	-0.02
100	-0.18	0.21	-0.08	-0.02

This information was then combined with updated estimates for mean sea level rise in Denmark by GEUS and DMI (2012) (Figure 4), giving total storm signal change estimates for the most extreme future scenario projections as shown in Table 3 below. For the extreme future scenario, a 100-year extreme sea level event is projected to increase by 1.56 m considering the highest storm signal change estimate.

Table 3 Calculation of most extreme (Upper) estimates for sea levels in Køge Bay considering changes in storm signal and mean sea level rise for different return periods T

T [yrs]	Current Extreme Statistics [m]	Year 2100 Upper Estimates [m]	2100 Upper Change [m]
10	1.35	2.84	1.49 *(0.14 + 1.35)*
50	1.47	3.01	1.54 *(0.19 + 1.35)*
100	1.52	3.08	1.56 *(0.21 + 1.35)*

Extreme Rainfall Data

Synthetic rainfall hyetographs derived based on a regional statistical model for extreme precipitation (Madsen et al., 2002) using the Chicago Design Storm (CDS) method were used in the case study (see Figure 4). According to the Intergovernmental Panel on Climate Change (IPCC), more intense and frequent extreme rainfall is expected in Denmark in the future, especially during summer periods (IPCC, 2007). Therefore, extreme design rainfall used in the case study should include climate change impacts. Climate factors were thus applied to the CDS rain time series to account for increased precipitation due to climate change. A guideline document has been published in Denmark recommending climate factors to scale extreme rainfall data for climate change impact assessments (Gregersen et al., 2014), and a summary of the recommendations are shown in Table 4 below.

Table 4: Recommended climate change factors for extreme rainfall events in 2100 in Denmark (Gregersen et al., 2014)

Return Period (years)	2	10	100
Mean Climate Factor	1.2	1.3	1.4
High Climate Factor	1.45	1.7	2.0

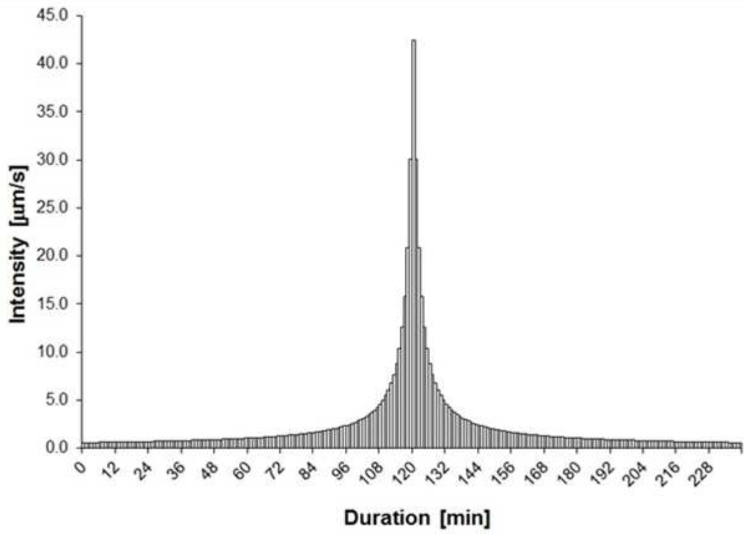


Figure 4: Future CDS design rainfall time series derived for a 10-yr return period event considering a climate factor of 1.3.

Joint Probability Analysis

Joint probability analysis was performed for extreme rainfall and storm surge, in order to assess the correlation between the relevant flood-driving events in the case area—i.e. rainfall and sea levels, and investigate the threshold conditions for flooding under their combined impacts. It involved frequency analysis with long term observed data for derivation of corresponding marginal probability distributions of extremes (e.g. extreme rainfall and extreme water levels), and the estimation of probabilities for different concurrent conditions of the extreme events. Information about the concurrence probabilities of combinations of events was used to select the event time series data for flood modelling.

2.2 Key research activities and results

2.2.1 *WP2- Understanding formation of hazards under extreme events*

T2.2 and T2.5

Evolution of sea level rise

Eastern Denmark is influenced by land uplift due to the glacial isostatic adjustment. In the city of Copenhagen, the land uplift is about 1.2 mm yr-1 (Hallegatte et al. 2008). However, the increment of the global sea level by the thermal expansion, water mass addition due to negative mass balance of the cryosphere and regional changes of the oceanic and atmospheric circulation associated with anthropogenic climate change more than compensates the negative trend of the glacier isostatic adjustment at the Greve location, thus leading to positive values of RSL change. A positive trend of 0.4 mm yr-1 of the total relative sea lev el (RSL) is calculated for the decades 1960-1990 in the model. This trend agrees well with the 0.44 mm yr-1 from observations that have been reported for the city of Copenhagen (Hallegatte et al. 2008).

Extreme high stands of sea level of 154 cm (in 1902) and 157 cm (1921) above normal sea level have been recorded for the city of Copenhagen. Hallegatte et al., 2008 obtained a 150 cm 100y return level (RL100y) value using a Peak Over Threshold approach based on a long time series 1890-2007 of gauge data for the Copenhagen harbour. For the simulated historical period, the RL100y calculated is 122 cm near the location of Greve (Table 5), nearly 30 cm lower than the value calculated by Hallegatte et al., 2008. This difference is not unexpected given the limited number of years available in the historical period (1960-1990) and because the model did not simulate such observed extreme high water levels from the early 20th century.

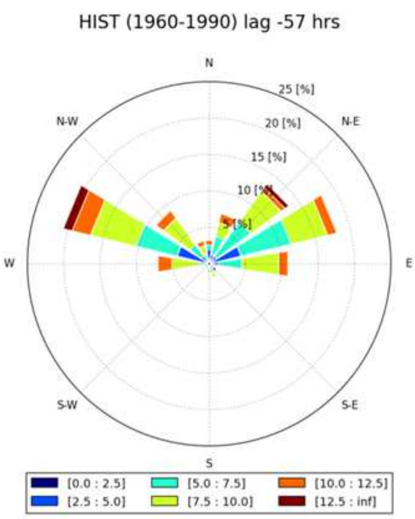
Table 5: Mean, standard deviation, 99th percentile, and100 years return level with 95.45% confidence intervals for the total relative sea level and statistic of the 5 highest sea level events per year (in cm)

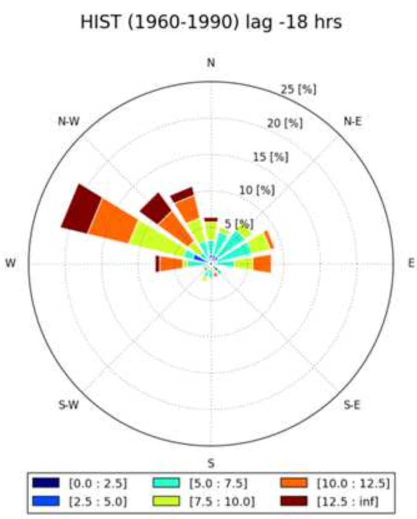
	Total relative sea level					**5 highest sea level events per year**			
	mean	**std**	**p99%**	**RL100y**	**95.45% CI**	**mean**	**std**	**p99%**	**Max**
HIST (1960-1990)	0.0	22	52	122	[106 - 145]	64	9	97	105
RCP45 (2070-2100)	57	23	111	191	[169 - 224]	122	9	161	176
RCP85 (2070-2100)	74	24	135	273	[214 - 378]	143	12	187	214

The models shows at the end of the 21st Century (2070-2100) for both climate change simulations an increase of the total RSL with respect the reference period 1960-1990. In the high-end RCP 8.5 scenario, the rate of projected RSL rise is 8.9 mm yr-1, while it is 3.7 mm yr-1 in the moderate RCP 4.5 scenario. The resulting sea level rise averaged for the period 2070-2100 (relative to the reference period) is 0.74 m and 0.57 m for the scenarios RCP 8.5 and RCP 4.5, respectively (Table 5). Notice that the temporal evolution of the sea level rise is not linear. The faster rise rate for RCP 8.5 is caused mainly by an increase of thermal expansion and contributions from water mass additions. The contribution of the ocean and atmosphere dynamics in this period is 0.23 m and 0.15 m for the RCP 8.5 and RCP 4.5 scenarios, respectively.

Storm surges

The atmospheric mechanisms leading to the formation of surges in the area of interest are linked to low pressure systems travelling eastwards into the Scandinavian region. The associated southward Ekman transports lead to high sea level stands in the south of the Baltic Sea and Kattegat (Hallegatte et al., 2008). In combination with the decrease in atmospheric pressure load, this can cause extremely high water levels in the region. Particularly in south of the Baltic Sea, a low pressure core displacement can also combine consecutive north-westerly and north-easterly winds that produces high water events (Feister et al,. 2003) by the excitation of seiches in the Baltic.





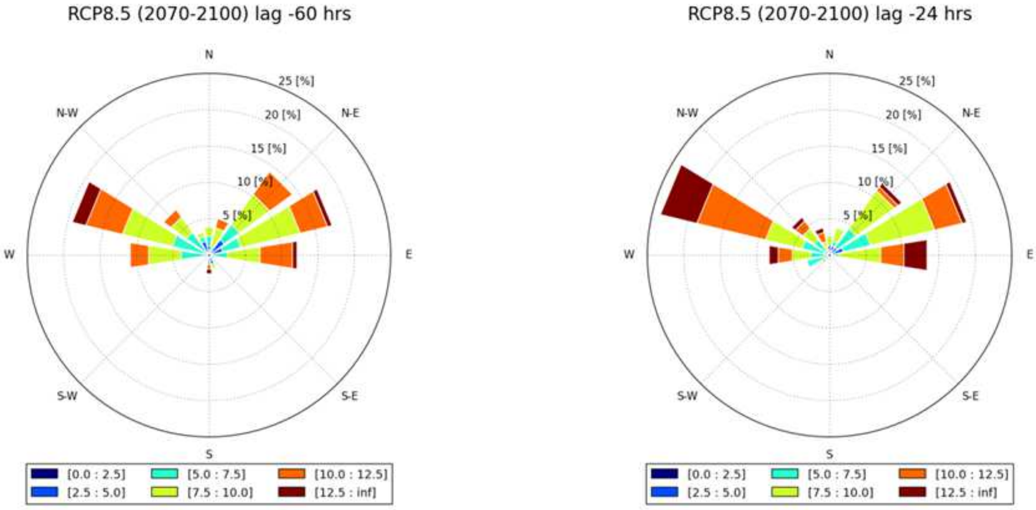


Figure 5 Frequency of occurance of the wind direction (%) and wind speed (m s^{-1}) corresponding to lagged wind conditions to surge events at Greve averaged over the periods 1960-1990 for the historical climate and 2070-2100 for the RCP8.5 scenario. The negative time values correspond to two time-lag correlation maxima between surges and wind speed time series.

To investigate the effects of changes in ocean circulation, the ocean thermal expansion and atmospheric-induced processes on surges (extreme high water levels) at Greve, a time series for storm surges is created by selecting the five maximum values per year from the DSL simulated by the model. The surges time series is time lag correlated with the three hourly averaged wind speed time series at Greve's location. This lagged correlation shows two maximum correlated times. The wind direction averaged in a 9 hours window centred at the maximum time-lagged correlation for each of the episodes is depicted in figure 5. In the historical simulation, the first local maximum correlation occurs in average 57 hours before the extreme sea level event. The predominant wind directions are from the northwest and northeast with similar frequency of occurrence. The second correlation maximum occurs in average 18 hours prior to the surge event with stronger westerly or north-westerly wind direction up to 25% more frequent wind speeds over 10 m s-1 than the easterly winds. These results agree well with the wind driven high water mechanisms described by Feister et al. 2003 and Hallegatte et al., 2008.

The simulations of the projected future climate scenarios do not show changes in the wind direction associated with the occurrence of surges, but in the intensity of the wind. The frequency of winds associated with extreme high water levels with speeds above 10 m s-1 and 12 m s-1 in the high emissions scenario (RCP 8.5) increases by 10% and 6%, respectively (but not statistically significant). In in our future climate simulation the storm activity slightly increases for northern Europe, increasing not only the intensity but also the frequency of storms. As a result, the mean of the five strongest storm surges per year increases by 58 cm and 79 cm (table 5.1) at the Greve site for the last decades (2070-2100) of the 21th Century for the RCP 4.5 and RCP 8.5 scenarios, respectively.

Loew et al. (2005) found that taking into account the total RSL, the 50 yr. return period storm surge event (RL50y) becomes 40 – 60 cm higher than today around the western coast of

Denmark by the end of the Century for the A2 SRES emission scenario (from the medium-high emission scenarios family). In our case the changes of the RL50y values calculated from the total RSL are lower than Loew's values, 67 cm and 133 cm higher than the historical period for the RCP4.5 (medium-low emissions) and RCP 8.5 (high emissions) scenarios, respectively. The changes of the 100 yr. return period are 69 cm and 151 cm for RCP4.5 and RCP8.5, respectively.

T2.6

Urban coastal flood hazards

In coastal cities, flooding may be from runoff generated by extreme rainfall, elevated sea levels, or a combination of both occurring simultaneously or in close succession (Zheng et al., 2013). However, most flood risk analyses have been performed considering only extreme rainfall or high sea levels individually. For some areas, the combined effect of both events and the joint probability of extremes should be considered for better flood risk assessment (Lian et al., 2013).

A 1D-2D hydrodynamic model was used for flood hazard analysis in the coastal area of Greve. It was built using MIKE Flood FM, a modelling system integrating one-dimensional and two-dimensional models into one dynamically coupled model (DHI, 2014). It comprises of a 1D model of the drainage system representing storm water sewers and streams, coupled to a 2D surface flow mesh model of the inland and sea areas along the coast. The drainage network is included in the flood model to ensure simulation of pluvial and fluvial flooding, as well as consider the influence of the drainage network in conveying flooding from the sea further inland.

The 1D network model is relatively comprehensive and detailed, covering most of Greve Municipality and consisting of around 7 000 nodes, 6 500 links and 9 outlets to the sea. MIKE 21 FM, a 2D modelling system based on a flexible mesh approach, was used to build the 2D model in Greve. The model covers 53 km2 of the area made up of sea and inland regions along Greve's coast. It uses a flexible computational mesh to represent the terrain surface.

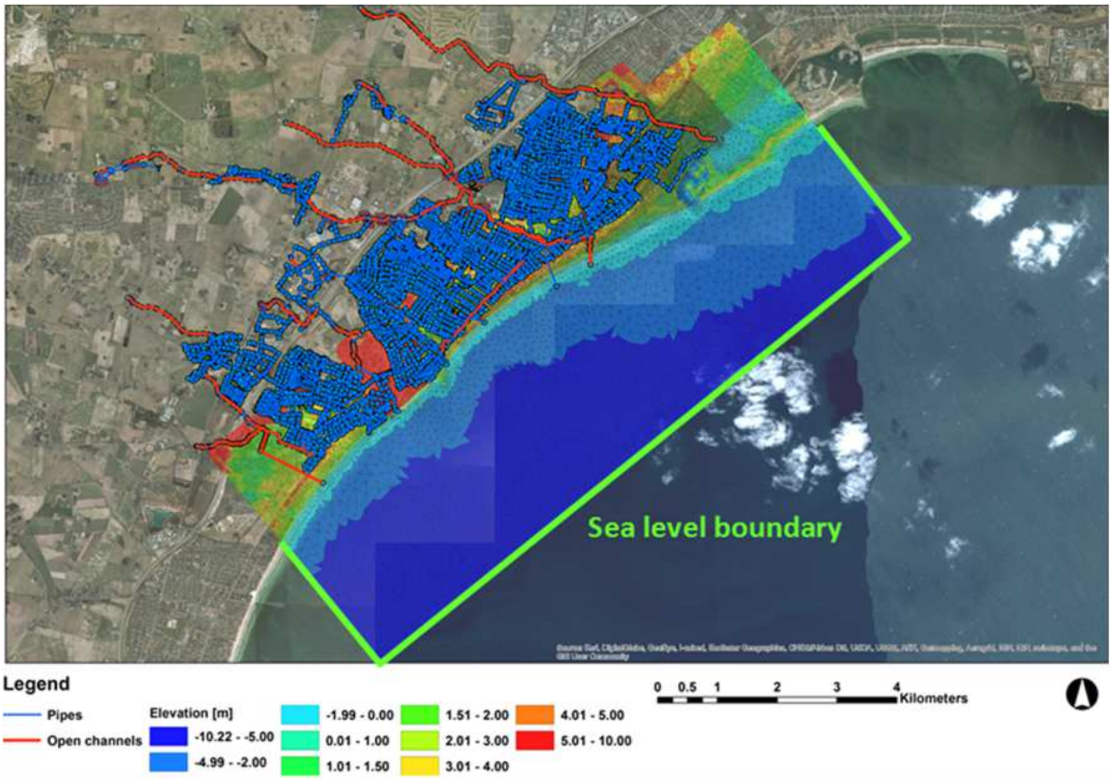


Figure 6: A map showing the 1D-2D coastal flood model for Greve. A 1D model of the drainage system comprising of streams (red lines) and stormwater sewers (blue lines and points) is linked to a 2D mesh model of the coast (coloured areas). The triangular elements of the terrain mesh and open boundaries of the 2D model are also shown.

Coupled 1D-2D hydrodynamic models are the state-of-the-art in analysing flooding from the sea in urban coastal areas (Henonin et al., 2013). 1D-2D models are able to simulate flows in the pipe network, flows over the land surface, as well as the interactions and flow exchanges between the two systems. In this approach, the urban coast and topography are represented in the 2D model, which simulates water levels and flows over surfaces based on computations solving the 2-dimensional shallow water equations. The underground drainage system is represented by a 1D pipe model, which simulates flows through the network using equations of flow in one dimension (i.e. along sewers).

Modelling either individual or concurrent events using 1D-2D models is done through specification of appropriate boundary conditions in the respective model systems. Rainfall, or sea water levels, or both, can be applied as driving or boundary conditions to both systems in the coupled model. Rainfall may be specified as input to the conceptual runoff model component of the 1D model to simulate runoff over the urban area. Rainfall may also be applied as a 'source' to the 2D model. Sea water level and flux time series boundaries may also be applied along open boundaries of the 2D model. In addition, water level boundaries may be specified at outlets of the 1D network model to the receiving body of water (i.e. the sea).

Summaries of the different individual and concurrent flood events analysed in the case study are shown in Table 6 and Table 7 below.

Table 6: Summary of individual flood forcing events analysed in the case study.

	Return Period [years]		
	100	**10**	**2**
Sea level	x		
Rainfall	x		
		x	
			x

Table 7: Summary of concurrent flood forcing events analysed in the case study.

		Sea level
	Return Period [years]	100
Rainfall	100	x
	10	x
	2	x

Figure 5 shows a plot of one of the flood events analysed in the case study. It shows the maximum calculated flooding for an individual future extreme sea level event (upper estimate) with 100 years return period (Event 2).

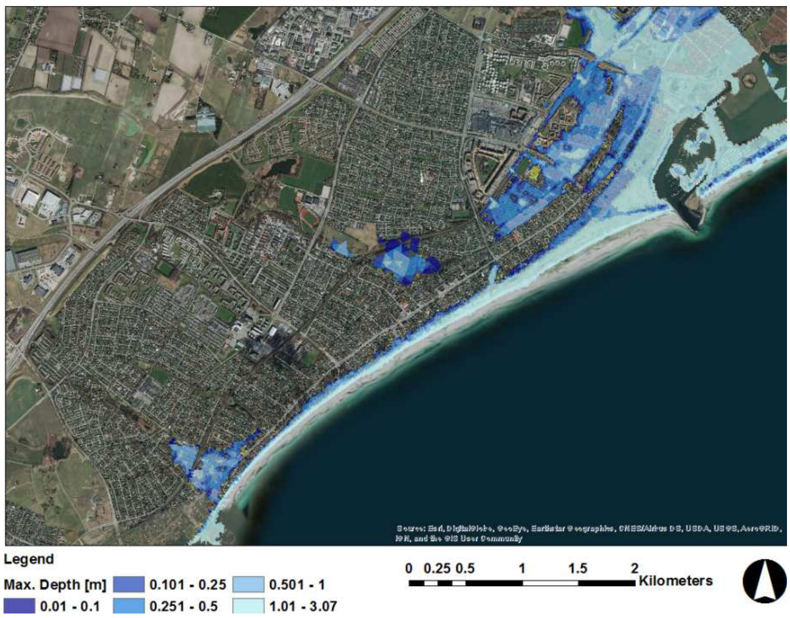


Figure 5: Calculated maximum flooding in Greve for future 100-year extreme sea level event scenario. (Source: Berbel Roman, 2014)

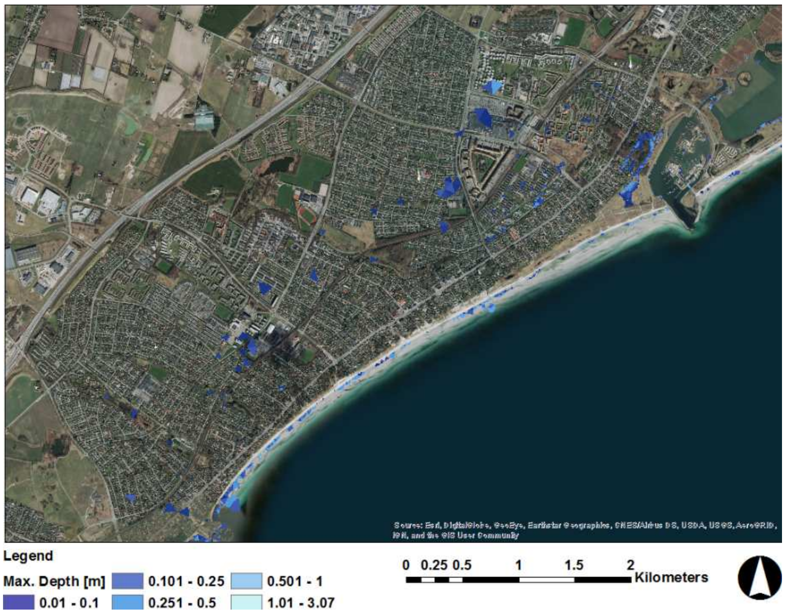


Figure 6: Calculated maximum flooding in Greve for future 100-year rainfall event scenario. (Source: Berbel Roman, 2014)

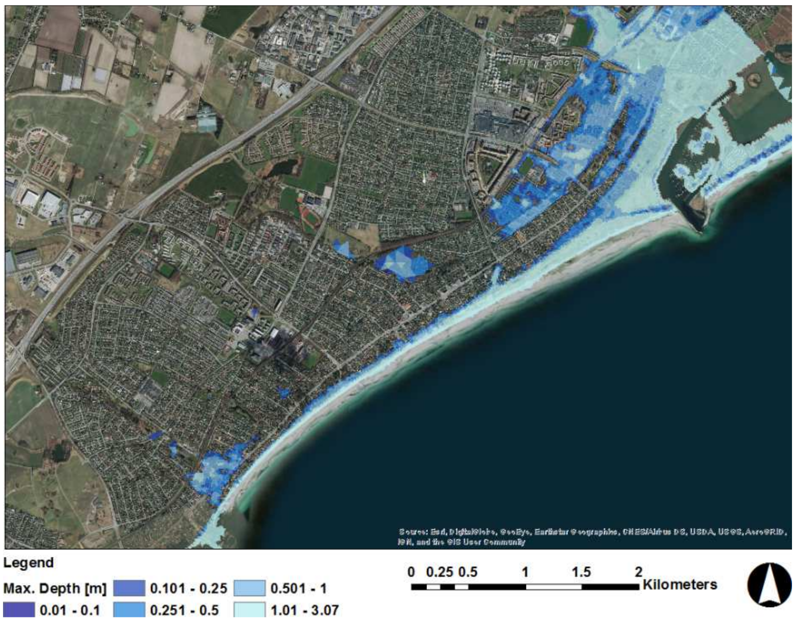


Figure 7: Calculated maximum flooding in Greve for future concurrent 100-year extreme sea level and 2-year rainfall events scenario. (Source: Berbel Roman, 2014)

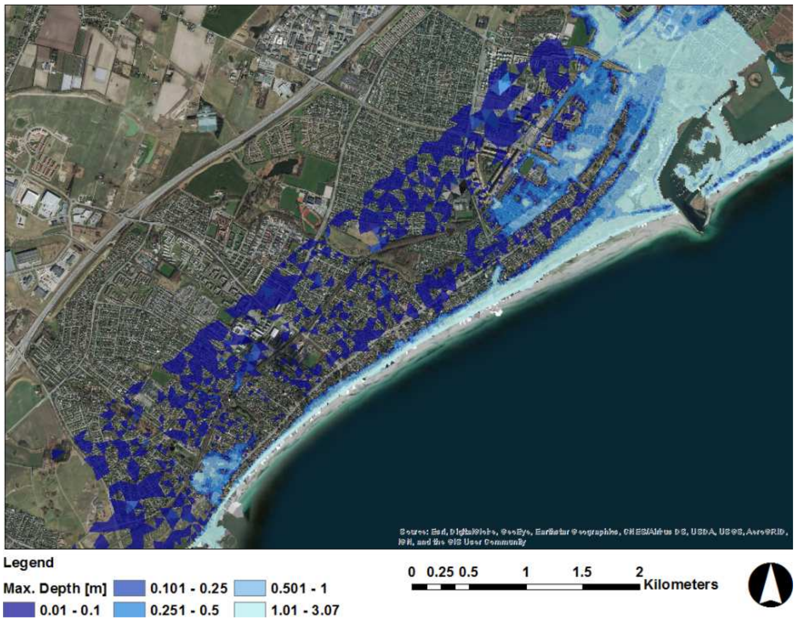


Figure 8: Calculated maximum flooding in Greve for future concurrent 100-year extreme sea level and 100-year rainfall events scenario. (Source: Berbel Roman, 2014)

2.2.2 WP3- Holistic and Multiple Risk Assessment

Flood damages and risks

Two different approaches were used to estimate flood damages in the case area. The first one used a value mapping technique where flood damage was estimated based on aggregated gridded values of properties in the case area (i.e. value maps or værdikort). The value maps are grid data containing information on the total aggregated value of properties (land and buildings), and property area sizes, within each grid cell. The other method used a flood depth-damage curve, which defined damage costs for different flood depths. Both methods required flood maps of maximum water depths, flood durations, and spatial data on valued properties in the study area. Geo-spatial data on buildings/properties and value maps were obtained from the Danish Data Agency, while flood depth-damage data were obtained from the Municipality of Greve. Details about the computation of the methodologies developed to compute flood damages are given in deliverable 3.2 (D 3.2).

The event probabilities were estimated based on joint probability analysis results of extreme rainfall and extreme storm surges. The probability of a flood event being exceeded in one year was computed to estimate the risk associated to each event. For example, a flood event with 100 years return period has an expected occurrence of 1% within a year. Flood risks were quantified using the following:

$$\text{Risk} = \text{Damage [DKK]} \times \text{Probability}$$

2.2.3 WP4- Flood forecasting and early warning systems for coastal regions

T4.1

In July 2007, a series of rain events with an estimated return period of 500 years caused severe flooding in Greve (Greve Kommune, 2007). In addition to extreme rainfall, Greve is also vulnerable to flooding from extreme sea levels along its coast. Greve is at risk from coastal flooding due to storm surges and general water level increase because of its location in Køge Bay (Vestergaard, 2011), which has been identified as 1 of 10 most at-risk areas in Denmark from coastal flooding (NIRAS, 2014).

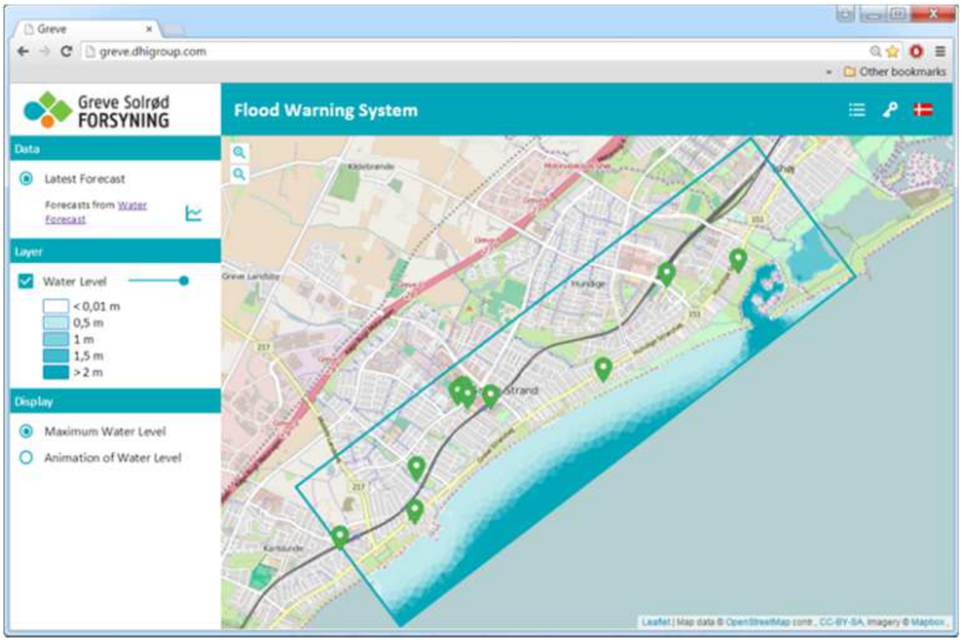


Figure 12: Homepage for the online coastal flood warning system in Greve, Denmark (www.greve.dhigroup.com). A map of the most recently calculated maximum water depths is displayed by default. Pre-determined critical points (see place markers) are colour-coded from green to red depending on the magnitude of forecasted flooding.

Thus, a coastal flood warning system has been developed for the municipality of Greve Figure12). It employs a 1D-2D hydrodynamic flood model for flood forecasting, which makes use of NWP rainfall forecasts and 3D hydrodynamic model water level forecasts as boundary conditions. Details on the different components and functionalities of the warning system are presented in the following sections.

Framework and methodology

The Greve coastal flood warning system employs a hydrodynamic flood model that calculates potential flooding using forecasted rainfall and sea water levels. The main components of the system are illustrated in Figure 913. Data collection and processing of flood forecasts are done through a desktop client, and a website is used to show flood forecast information as well as system data (see Figure).

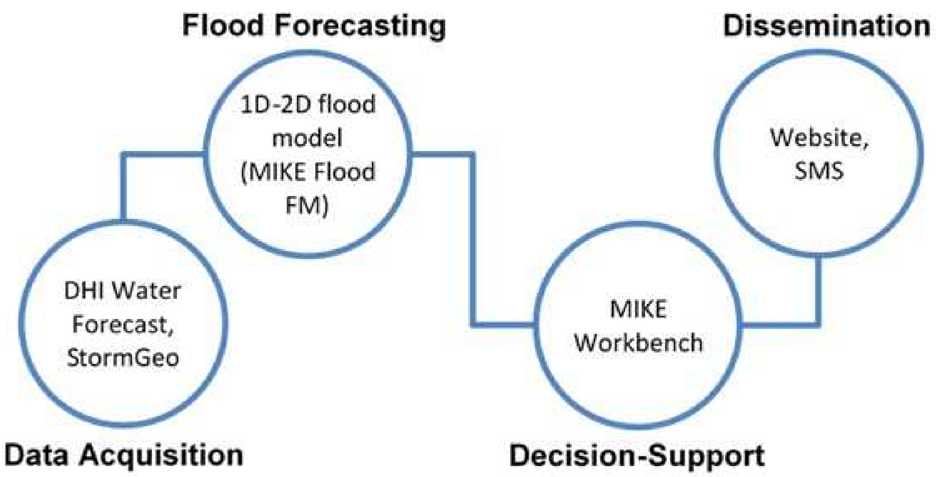


Figure 9: Diagram showing the main components of the Greve Flood Warning System

Data Acquisition from DHI Water Forecast and StormGeo

Forecasted sea water level and rainfall data are obtained and used as boundary conditions for the coastal flood model. In the acquisition process, data are routinely collected from two sources: Water Forecast by DHI (DHI, n.d.) and StormGeo (StormGeo, n.d.). DHI's Water Forecast provides 6-day sea level forecasts in Køge Bay every 12 hours, using results from a 3D hydrodynamic and wave model covering the Inner Danish Waters and the Baltic Sea (DHI, 2011). The data is accessed from an internal MySQL database located at DHI. The rainfall forecast for the next 24 hours over the area of Greve is also acquired from the Water Forecast database, which retrieves and stores NWP rainfall forecasts from StormGeo. The collected data are stored through MIKE Workbench, a desktop client for interactive data analysis and processing, and are processed to ensure that they cover the flood model simulation period. The processed data are converted to *.dfs0-format files and used as boundary conditions for the flood model. The files are updated for every forecast, and the simulation period for the flood model is adjusted accordingly. Information on the rainfall and water level forecast data are published on the website as time series plots (Figure 10).

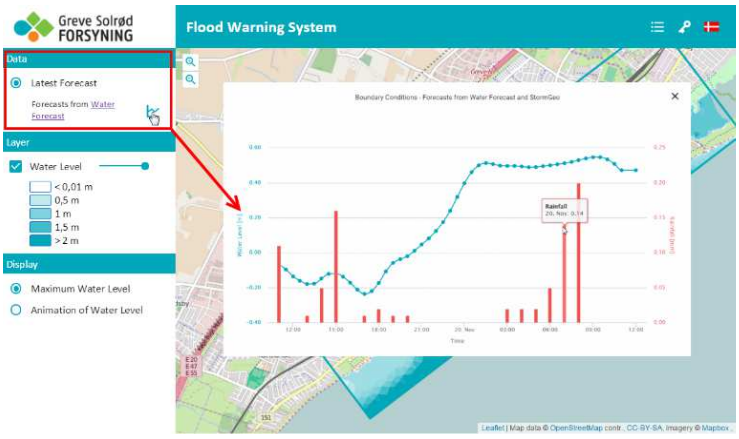


Figure 10: Forecasted sea water level (blue lines) and rainfall (red bars) data used to drive the coastal flood model in the Greve Flood Warning System. Plots of the most recent data may be viewed on the website (http://greve.dhigroup.com/).

Flood Forecasting with MIKE Flood FM

A 1D-2D hydrodynamic model is used for calculating potential flooding in the coastal area of Greve. It was built using MIKE Flood FM, a modelling system integrating one-dimensional and the two-dimensional models into one dynamically coupled model (DHI, 2013d). It comprises of a 1D model of the drainage system comprising of stormwater sewers and streams, coupled to a 2D surface flow mesh model of the inland and sea areas along the coast (see Figure15). The drainage network is included in the flood model to ensure simulation of pluvial and fluvial flooding, and consider the influence of the drainage network in conveying flooding from the sea further inland.

The 1D network model is relatively comprehensive and detailed, covering most of Greve Municipality and consisting of around 7 000 nodes, 6 500 links and 9 outlets to the sea. The model employs a conceptual (Time-Area) runoff model to calculate rainfall runoff from the 6 000 sub-catchments of the area, and a 1D fully hydrodynamic pipe flow model simulating water levels and flows through the underground pipes and open channels comprising the drainage system. Forecasted rainfall data obtained from StormGeo is used to calculate runoff, which is then applied as an input to the network model.

MIKE 21 FM, a 2D modelling system based on a flexible mesh approach, was used to build the 2D model in Greve. The model covers 53 km2 of the area made up of sea and inland regions along Greve's coast (see Figure15). It uses a flexible computational mesh to represent the terrain surface. The mesh elements, which could be triangular or quadrangular in shape, vary in size depending on the required/specified computational resolution at an area. The Greve 2D model computational mesh is comprised of 49 000 elements that vary in size from 9 m2 to 20 000 m2. Small mesh elements were used for built-up areas, roadways and flood plains, and bigger elements were used for rural areas and the sea. The element mesh representing the terrain is an important component of the 2D model, and must include and appropriately represent surface features, such as dikes, waterways and overland flow paths, as these are important factors influencing overland flows and flood propagation. Small-sized elements may be used to achieve appropriate computational resolutions at these critical flow areas. In Greve, Terrain Analysis using the estimated maximum sea level ever recorded in Køge Bay (i.e. 3.7 m above MSL on 13 October 1760) was employed to identify these critical areas, and small mesh elements were specified in regions with terrain elevations below 3.7 m. In flood modelling, sea water level forecasts are applied as boundary conditions to the 2D model at its open boundaries to the sea (see Figure15).

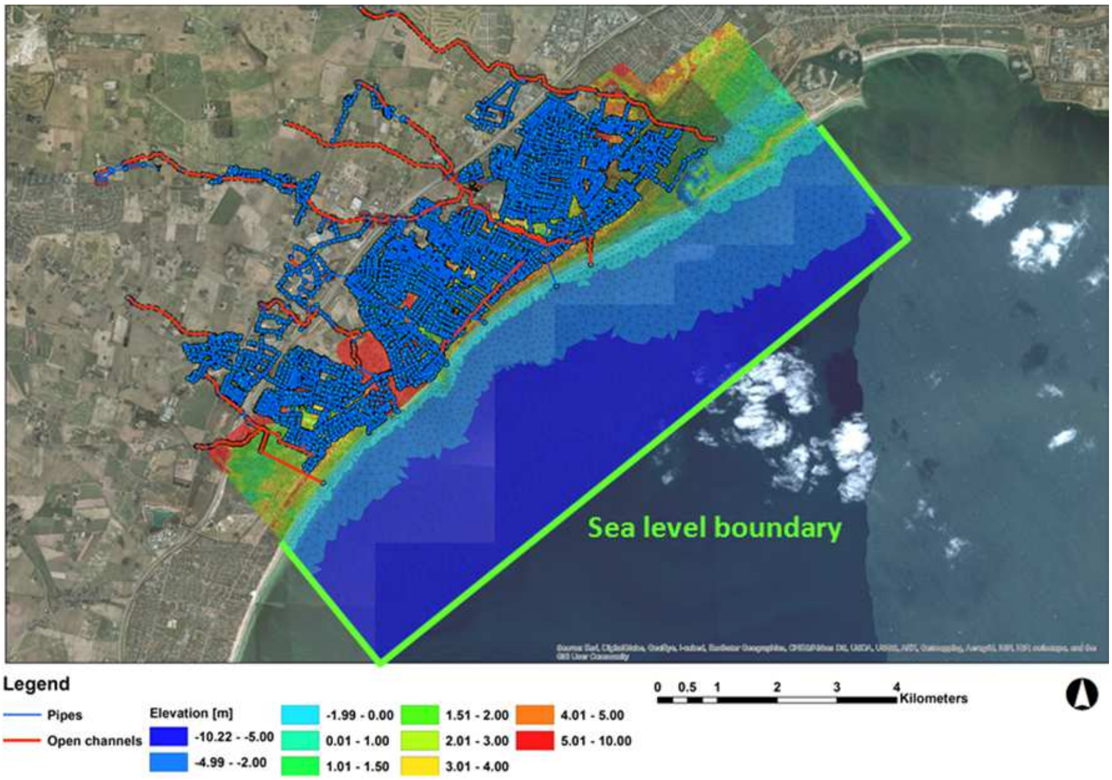


Figure 15: A map showing the 1D-2D coastal flood forecast model for Greve. A 1D model of the drainage system comprising of streams (red lines) and stormwater sewers (blue lines and points) is linked to a 2D mesh model of the coast (coloured areas). The triangular elements of the terrain mesh and open boundaries of the 2D model are also shown.

The 2D surface flow model and1D network model were linked at points where the exchange between the two systems could occur, such as at drainage outlets, stormwater inlets, unsealed manholes, and open channels. The computational links were modelled using the weir equation, which calculates flows based on head differences at linked network nodes and terrain elements (Mark and Djordjevic, 2006). Flows between the two systems can occur in both directions. Drainage network outlets to the sea are explicitly linked to the 2D model at coinciding mesh elements, such that calculated water levels at the linked element are used as water level boundary conditions for the corresponding linked drainage outlet.

Flood forecasts for the next 24 hours are made every 4 hours at 00:00, 04:00, 08:00, 12:00, 16:00, 20:00 CET. The Greve flood forecast model takes around 2 hours computation time to simulate a period of 24 hours. Computation results are shown on the website, wherein static maximum water depths and time-varying water depth animations are plotted on a map.

Decision-Support with MIKE Workbench

Flood model results are stored and processed using the MIKE Workbench desktop client. The results are analysed at pre-identified important points in the model domain, which are plotted as colour-coded place markers on the flood map (Figure16). Warning information is disseminated according to exceedance of set water depth thresholds (0 cm, 20 cm and 40 cm) by forecasted flood depths at these pre-defined important locations.

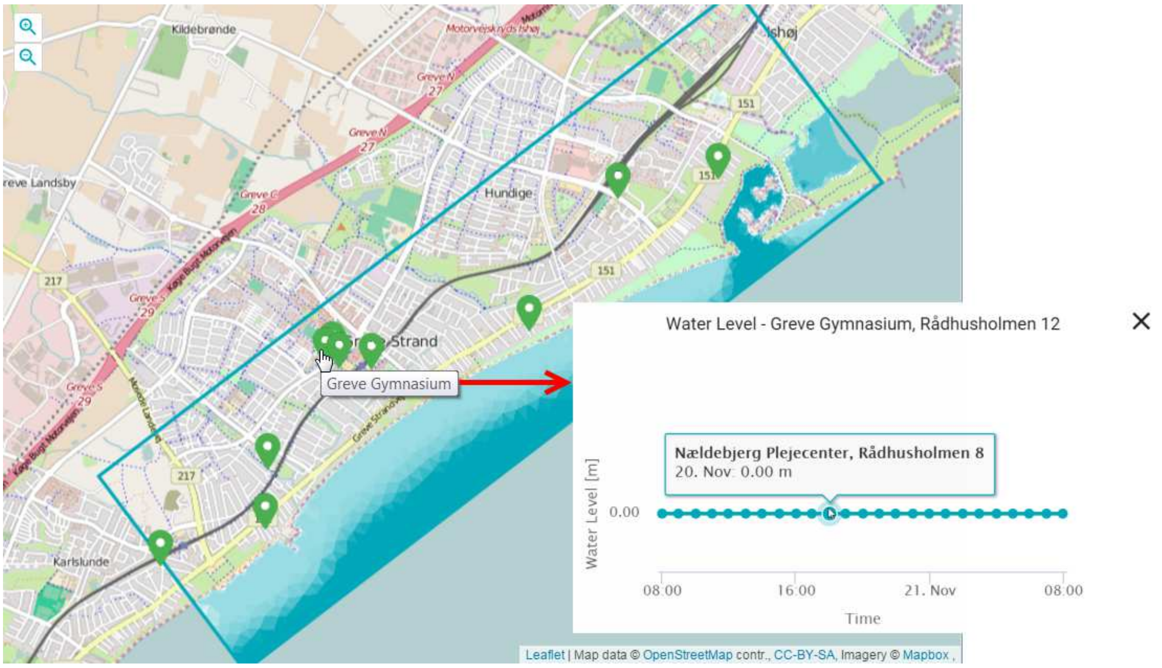


Figure 16: The flood map on the website shows place markers for pre-identified important places in the coastal area of Greve. The markers are colour-coded according to computed flood depths from green (0-20 cm) to yellow (20-40 cm), and to red (above 40 cm).

Information on important locations, such as coordinates, name and location type, as well as the computed flood time series, are stored in a spreadsheet in MIKE Workbench. The time series are extracted for the locations from the flood model result files and stored in MIKE Workbench. The time series are then analysed to identify the maximum value, which is then written back into the spreadsheet for the location. The result files are additionally made available for the website. The data that is available for the website to display are:

- GIS data layer with the model extent
- Spreadsheet with a list of locations and their maximum depth values for the next 24 hours
- Result files for 2D animation of water depth as well as display of maximum water depth
- Time series for water depth at important locations
- Time series for boundary conditions

Dissemination through 'http://greve.dhigroup.com/'

The website was built using Polymer (Polymer, 2015) linking to the DHI Web API (Application Programming Interface), which supports data access in MIKE Workbench. The website allows viewing most recent forecasts, as well as results from extreme event scenarios (see Figure 11). The extreme event scenario results are, however, only available through login for confidentiality reasons. By default, the maximum water depth is displayed on the page, but the user can switch over and display an animation that shows the propagation of flooding.

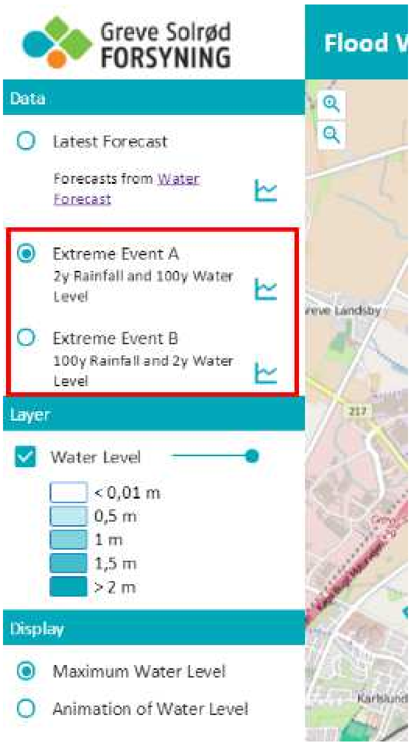


Figure 11: Besides real-time flood forecast, results from other flood modelling scenarios are also shown on the website, although accessible only with login information

Results and evaluation

The online Greve Flood Warning System was launched in September 2015, and there have been 2 down periods to date - in early September 2015 for 6 days (29 forecasts), and early November 2015 for 4 hours (1 forecast), which indicates that the system has been 'reliable' 94% (492/522) of the time.

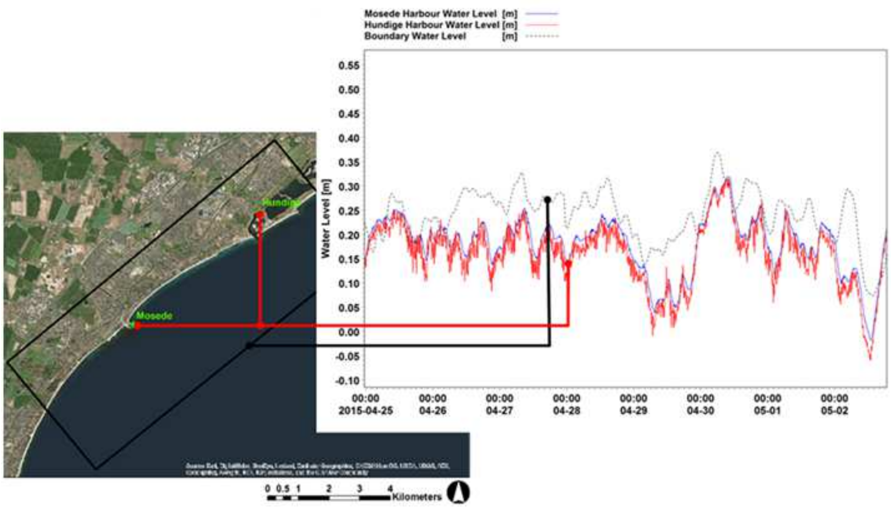


Figure 12: The map shows water level measurement stations at Mosede and Hundige harbour in Greve. The coastal flood model domain is indicated in black outline. Plots of water level measurements at Mosede

(blue line) and Hundige (red line) harbour in Greve are shown on the right. The black broken line shows forecasted sea levels at the sea boundary of the flood model.

There have been no coastal flood events in Greve in recent years, and thus, the flood model has, so far, been only verified at periods of 'normal sea level conditions'. Model verification involved the ex post comparison of calculated/forecasted water levels to actual measurements at Hundige and Mosede harbour for the period 25 April to 5 May 2015 (see example comparison in Figure 13). Rainfall and sea level forecasts retrieved from the DHI Water Forecast system were used as boundary conditions to the Greve flood model.

Comparison of observed and simulated water levels at the measurement stations over different forecast periods show maximum errors of up to 20 cm in Mosede and 25 cm in Hundige, with the larger discrepancies occurring mostly after 2 days into the 5-day forecast period (see Figure 14 and Figure 15). Root Mean Squared Error (RMSE) values averaged over different forecast periods, as shown in Table 8, indicate how forecasts degrade over time, with average RMSE values increasing with forecast period duration. More information about the accuracy of the Greve coastal flood forecast model can also be found in Jensen (2015), a thesis study on integrated storm surge modelling in Greve that was conducted under the PEARL project.

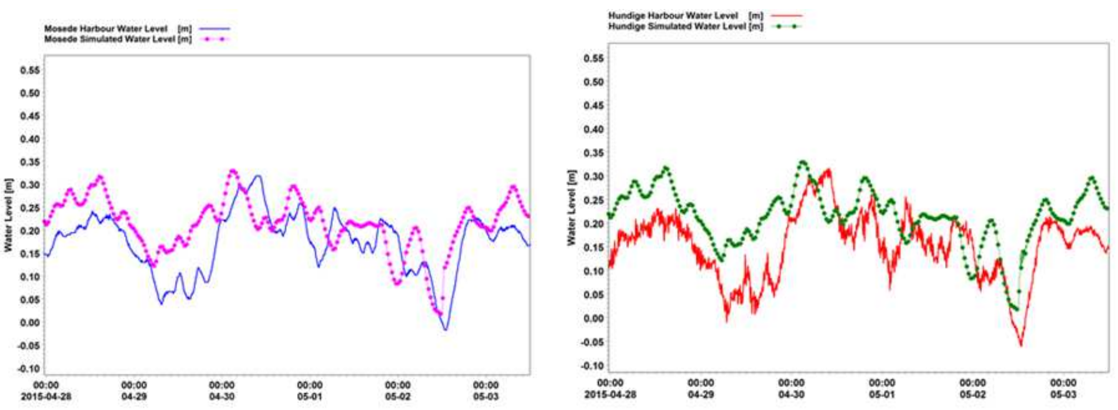


Figure 13: Comparison of observed (thick solid lines) to simulated (dotted lines) water levels in Mosede (left) and Hundige (right) harbour for the forecast period 27/4/2015 23:30 – 3/5/2015 12:00.

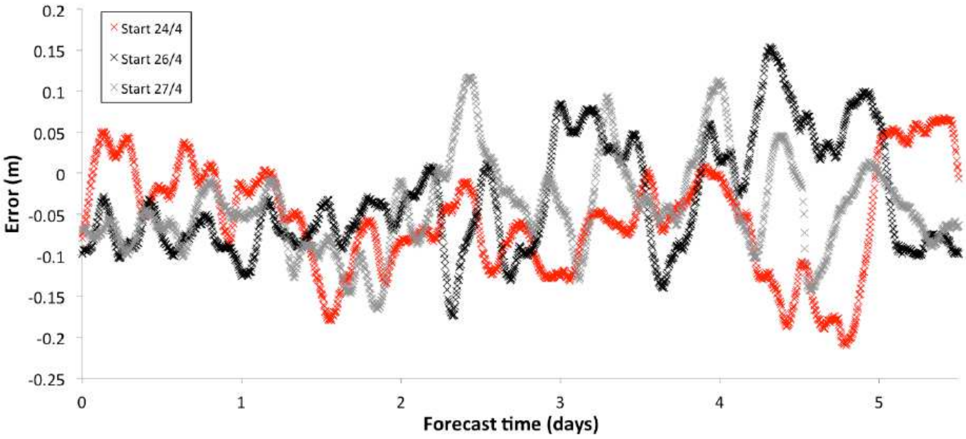


Figure 14: Plot of absolute error from comparison of simulated and observed water levels at Mosede harbour. (Source: Jensen, 2015)

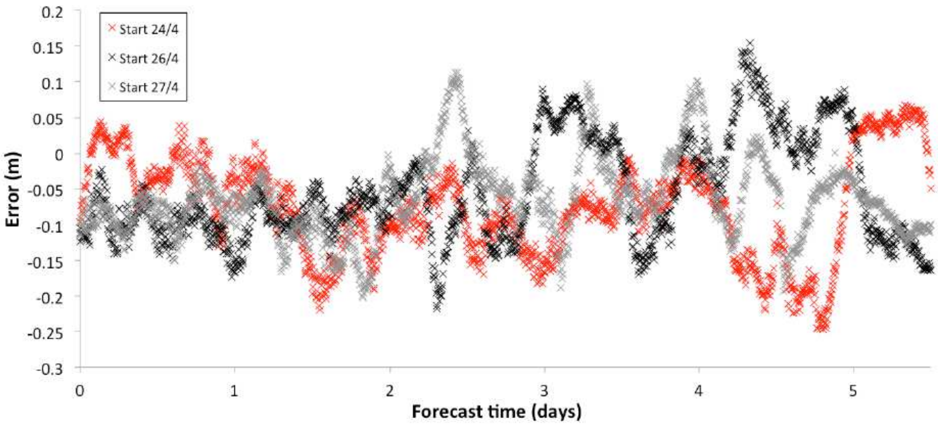


Figure 15: Plot of absolute error from comparison of simulated and observed water levels at Hundige harbour. (Source: Jensen, 2015)

Table 8: Average error statistics over different forecast period durations [h]. (Source: Jensen, 2015)

		Forecast Period Duration [h]										
		12	**24**	**36**	**48**	**60**	**72**	**84**	**96**	**108**	**120**	**132**
Mosede	**ME [m]**	-0.046	-0.048	-0.053	-0.063	-0.057	-0.057	-0.051	-0.048	-0.045	-0.045	-0.043
	RMSE [m]	0.060	0.060	0.064	0.076	0.075	0.075	0.074	0.072	0.075	0.078	0.077
Hundige	**ME [m]**	-0.064	-0.068	-0.073	-0.083	-0.077	-0.078	-0.071	-0.068	-0.065	-0.065	-0.064
	RMSE [m]	0.074	0.077	0.083	0.095	0.093	0.093	0.091	0.089	0.090	0.093	0.093

The water utility company Greve Solrød Forsyning (http://www.gsforsyning.dk/), which is the institution responsible for the drainage system in Greve Municipality, has also been consulted and involved in testing and evaluating the online Greve Flood Warning System. The system will continue to be evaluated and improved within the course of the PEARL Project. Recent consultation with the company has identified several points for improvement for the system, which includes:

- **Refinement of the flood model**. Initialize the flood model with previous forecast results.
- **Adding dissemination media**. Finalizing the implementation of SMS and email service for flood warnings.
- **Adding plots of observed water levels.** Plotting sea water level measurements against sea level forecasts at Mosede port in real time.
- **Adding time series plots in results presentation.** Showing measurements against calculated water levels from the 5 critical locations inland.
- **Adding flood risk information.** Showing outlines of houses that are potentially flooded.

3 Case Study – Elbe Estuary / Hamburg, Germany

3.1 Introduction to the case study area

3.1.1 General description of the case study area

The German case study area is located in the Estuary of the River Elbe with the emphasis on its largest urban area being the City of Hamburg (Figure 16).

Figure 16: Location of the Elbe Estuary and the City of Hamburg

The river Elbe rises in the Czech Republic, traversing much of the Czech Republic and Germany (including the City of Hamburg) before it flows into the North Sea at Cuxhafen. The case study area encompasses the tidal influenced section of the Elbe (tidal Elbe) between the weir in Geesthacht (Elbe km 586) and the navigational mark Kugelbake at Cuxhaven (Elbe km 728) as depicted in Figure 17. This section is called Low Elbe (*Unterelbe*) and has a length of 142 km.

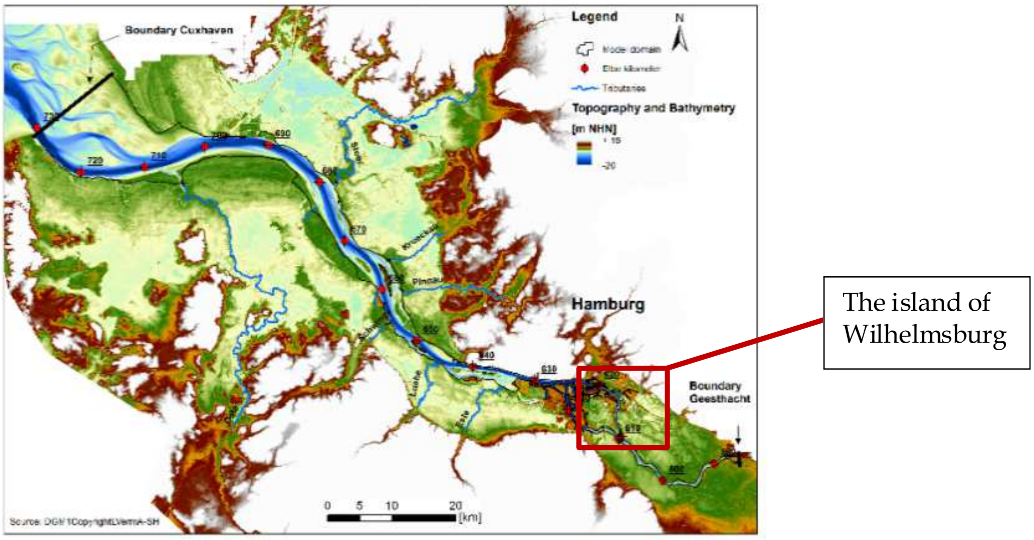


Figure 17: Overview of the Elbe estuary/Hamburg case study area

The Low Elbe is generally divided into three sub-sections, which will be used for further analyses in n the case study area. The first and most upstream sub-section of the tidal Elbe includes the area of the Vier- und Marschlande between Geesthacht and the City of Hamburg. Within the metropolitan area of Hamburg, the Elbe furcates into the Norderelbe and the Süderelbe forming the island of Wilhelmsburg as well as parts of the port of Hamburg – second section. At Elbe km 625, Norder- and Süderelbe re-unify and conflate. This is the beginning of the third sub-section of the Elbe, the Niederelbe, flowing into the North Sea. In this third sub-section, the river morphology is characterized by several small river islands (e.g. Neßsand, Lühesand, Pagensand and Rhinplatte). Additionally, several tributaries (e.g. Krueckau, Pinnau, Este and Schwinge) discharge into the Elbe in this third sub-section.

In the Elbe Estuary, the most significant urban area is the Free and Hanseatic City of Hamburg, located in the North German Plain approx. 100 km upstream of the mouth of the river Elbe in the North Sea (Figure 16). Hamburg counts approx. 1.76 Mio inhabitants (31.12.2014) covering the total urban area of 755.3 km², resulting in the population density of 2,334 inhabitants/km² (31.12.2014).

The Free and Hanseatic City of Hamburg itself and as the centre of the homonymic metropolitan areas has a significant commercial relevance for the region and for entire Germany. The sea port of Hamburg is Germany's biggest seaport and the third largest sea port in Europe (2016)[1].

Due to its low terrain elevations, the City of Hamburg is prone to flooding due to storm surges or even normal high tides. In the island of Wilhelmsburg, which is a densely populated (1532 inhabitants/km²) area located between the Norderelbe and the Süderelbe (indicated in Figure 17), the terrain elevation is below the mean tidal level. Without its ring dikes the island of Wilhelmsburg would be inundated twice a day.

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[1]http://www.manager-magazin.de/fotostrecke/rotterdam-hamburg-und-co-das-sind-europas-groesste-haefen-fotostrecke-134456-5.html

3.1.2 Hazard and risk situation in the case study area

The climatic and meteorological conditions of the metropolitan area of Hamburg and the Elbe estuary are significantly characterized by the proximity of the North Sea and the Baltic Sea with their maritime weather influences. Nevertheless, continental climate conditions get more important with rising distance from the North Sea and in south-easterly direction.

From a climatic, resp. meteorological point of view the case study areas covers both coastal areas and inland areas. In that sense, both the wind conditions over the North Sea in the German Bight and wind condition of the inland area have to be considered for the analysis of the extreme hydro-meteorological events. In general, wind velocities in coastal areas are higher than in inland areas. The annual average wind velocity on the island Helgoland (in the North See) is 8m/s, whereas the annual average wind velocity decreases to 4,5 m/s in Hamburg. Additionally, wind velocities vary with the seasons. In the winter season, wind velocities are 1 m/s - 2 m/s, on the island of Helgoland more than 3 m/s higher than the wind velocities in summer (Rosenhagen and Schatzmann, 2011).

As the wind velocities over the German Bight are high during the winter season, storms are likely to occur. In case of westerly to north-westerly wind directions, strong storm winds can create extreme storm surges moving upstream into the Elbe estuary (Gönnert, 2003). Storm winds creating storm surges in the North Sea evoke from extratropical cyclones, developing along the polar front over the Atlantic Ocean. The strength of the storm winds are depending on the temperature difference of the air masses of the subtropical high pressures belt and the subpolar trough. The higher the temperature differences the stronger the storm winds (Weischet, 2002).

Situation in the past: The storm event in the recent past with the strongest impact on Hamburg and Wilhelmsburg occurred in 1962. A detailed description of this and other extreme storm events can be found in deliverable 5.2. On February 16th, 1962, storm winds up to Beaufort scale 9 from westerly directions were generated. During the day (February 16th, 1962), extreme loads on the dikes along the entire North Sea coast and along the Elbe caused dike failure and inundations. The water levels of 5.7m above NN have been reached at the tidal gauge Hamburg St. Pauli (Figure 18, black solid line). At this time, many dikes have failed in Hamburg and large areas were flooded casing more than 300 casualties and causing the overall damage of 350 Mio € in the whole area of Hamburg. (Hötte, 2012, Roediger, 1962).

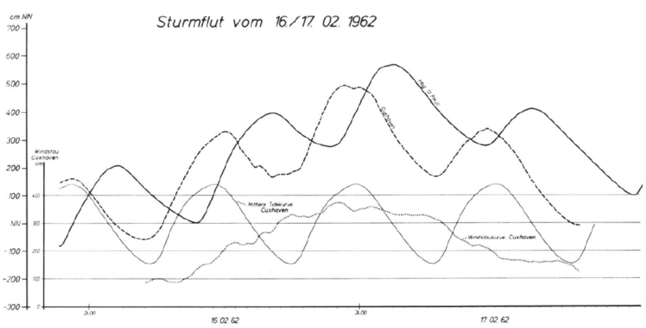


Figure 18: Hydrograph of the storm surge on February 16th / 17th, 1962 (Laucht, 1977)

As a response to this disastrous event, the dikes were reinforced and raised to +7.20m and design of the dike has been improved. The current dike crest elevation varies between +7.70m and +8.35m, well above the design water level, of +7.30m. The design flood level itself is 85cm above the highest recorded stage (Nehlsen et. al. 2007). Even if the design figures are far larger than the maximum water stage, the high uncertainties associated with the climate change figures (IPCC 2007) and the ever-increasing importance of the island, raise questions on how safe the defence structures are.

In the view of the historical development of the flood risk and flood management strategies, this event can be marked as a turning point as it had a decisive influence on the way of thinking and practices and it triggered a set of activities as adaptation, raising and reinforcement of the dikes and the construction of flood barriers. Consequently, storm surges after 1962 did not have comparable effects up to now, even if the storm water levels were higher than in 1962.

Figure 19: Impression of the devastating storm surge in 1962 (Free and Hanseatic city of Hamburg, 1962)

Situation nowadays: Due to the location and the geographical orientation of the estuary storm surges are to be expected in case of very strong westerly winds. Figure 20 gives an impression of the extension of the flood prone areas in the City of Hamburg (blue area). In addition to storm surges, heavy precipitations can lead to high discharges in the estuary casing additional pressure to the *hinterland*. As a consequence, the extreme hydro-meteorological events can occur due to multiple causes (mainly storm surges and heavy precipitation), which may even cause a failure of the flood protection infrastructure.

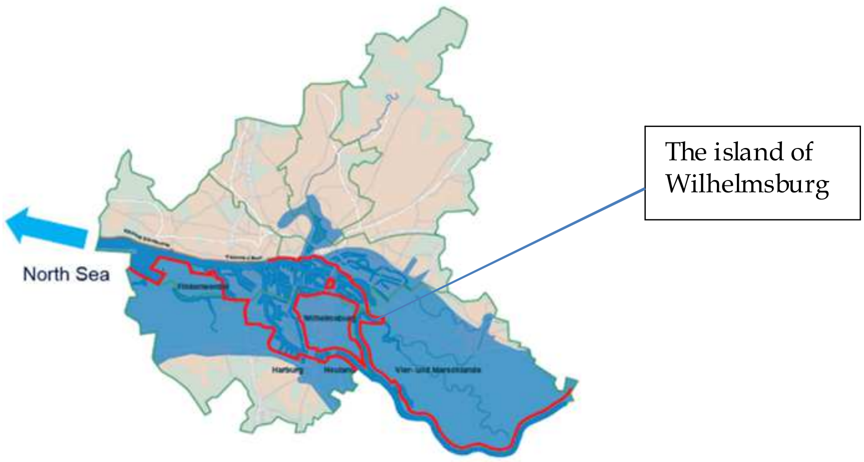


Figure 20: Flood prone areas of Hamburg in case of storm surge without flood protection infrastructures (red line indicates the public flood protection infrastructure as of now (LSBG, 2012)

3.1.3 Current institutional and governance practice

As German system is highly decentralised, the federal states *(Länder),* have the legal and administrative authority for all water related issues, which have to comply with those federal legal frameworks. Each of the 16 federal states releases water laws, regulations and policies, which provide the more detailed legislation and policies to manage water resources at regional or local levels within each state.

The Elbe estuary is governed by three German federal states being Schleswig- Holstein, The State of Hamburg and the Lower Saxony, which adds to the complexity of the flood risk management and requires continuous exchange and coordination between the states.

Within PEARL, a reassessment of the main actors in the Elbe Estuary has been performed. As the Elbe Estuary or its parts have been addressed in a number of national and international projects (e.g. KLIMZUG-Nord and XtremRisk or FP7 Project CORFU), the first step has been to collect the information about the stakeholders and their involvement and reassess its actuality.

Finally, the main stakeholders of the Elbe estuary can be summarised as[2]:

1. The Agency for Roads, Bridges and Waterways- Hamburg (*Landesbetrieb Straßen, Brücken und Gewässer* -LSBG
2. Ministry of Interior Affairs – Hamburg
3. Hamburg Port Authority (HPA)
4. Agency for Coastal Protection, National Resources and Sea Protection, Schleswig Holstein (LKN-SH)
5. Federal Maritime and Hydrographic Agency (BSH)
6. Federal Waterways Engineering and Research Institute (BAW)
7. Waterways and Shipping Office - Hamburg (WSA)
8. German Association for the Protection of Nature (NABU)

[2] For a thorough stakeholder analysis, please refer to the report MS14

9. Friends of the Earth- Germany (BUND)
10. World Wide Fund for Nature (WWF)
11. Dike Associations
12. Public action groups and initiatives
13. Political body represented at the local authorities
14. Private stakeholders

A rainbow diagram of the key stakeholders is given in Figure 21

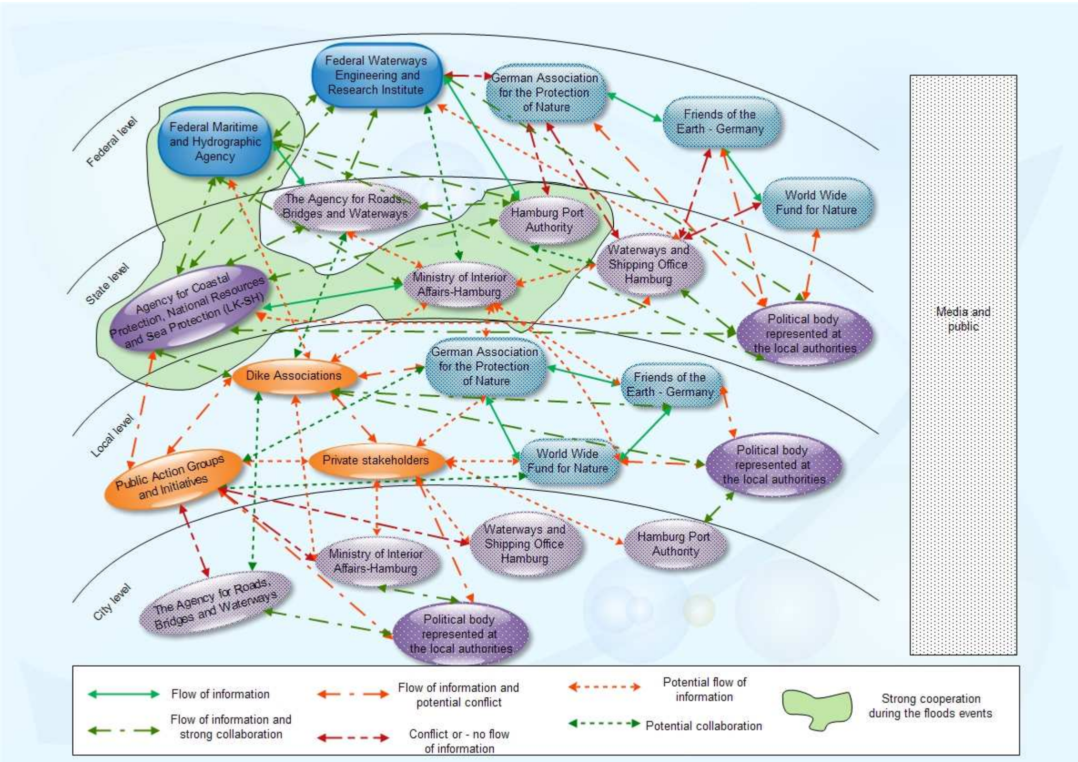


Figure 21: Rainbow diagram of the key stakeholder for the Elbe Estuary/ Hamburg

Out of the assessed key stakeholders, the following ones have been selected based on their influence and relevance for the flood risk management in the Elbe Estuary, existing contacts with the PEARL project team and declarative interest in the methods and tools being developed in PEARL:

Hamburg:

1. The Agency for Roads, Bridges and Waterways (LSBG) together with the Ministry for Energy and Environment (BUE); responsible for flood management in the State of Hamburg (strategic planning, maintenance)
2. Ministry of Interior Affairs – Hamburg; responsible for contingency measures (emergency response and planning) in case of flood
3. Hamburg Port Authority (HPA); its duties are mainly based on the Port Development Plan, flood protection, risk prevention and storm surge warning (with the warning service WADI)
4. Federal Maritime and Hydrographic Agency (BSH)- flood forecasting and warning

Schleswig Holstein- (for analysis and demonstration of the cross-border collaboration in the Elbe Estuary)

5. Agency for Coastal Protection, National Resources and Sea Protection, Schleswig Holstein (LKN-SH) (Planning, maintenance of the coastal protection in Schleswig Holstein)

3.1.4 *Available data used for research activities*

Table 9 give an overview of the data used for the in order to perform the holistic risk assessment and derive the flood risk management strategies for the Elbe Estuary. The application of the data is described in the respective work packages.

Table 9: Overview of the data used for research activities

No.	Data type	Brief description
1.	Bathymetry	Bathymetric data of the Lower Elbe (2006, 2010) Resolution: 1m x 1m Bathymetric of the Elbe from Geesthacht to Neu Darchau (2016) resolution: 1x1m
2.	DEM	DEM of the Metropolitan area of Hamburg, Schleswig-Holstein and Lower Saxony (1 m x 1 m)
3.	Discharge	Time series of discharges for Neu Darchau (Source: Portal Tideelbe)
4.	Water level	Time series of water level for several gauges along the Lower Elbe and the North Sea, time series of BSH water level forecasts and time series of measured storm surge events
5.	Rain fall	Time series of rain fall data for several gauges
6.	Wind data	Wind field data from superior climate models (regional Climate Model Cosmo-CLM forced by Echam 5)
7.	Historic nautical charts	Historic nautical charts including historic bathymetric conditions of the Lower Elbe (1930)
8.	Flood protection infrastructure	Data on recent and historic flood protection infrastructure including the last 2000 years
9.	Census data	Population data
10.	Land use data	Recent land use data and data from previous projects
11.	Cadastral data	Recent cadastral data and data from previous projects
12.	Company data	Data on companies for the city of Hamburg (recent and from previous projects)
13.	Building data	Building data (floor plans, design descriptions, etc.)

14	Evacuation process	Evacuation plans, information of the evacuation process, collecting points and refuges etc.
15.	Direct / indirect damages	Direct / indirect damages for different land use categories and economic sectors (project XtremRisK)
16.	Damage functions	Damage functions for residential buildings, infrastructure and commercial objects
17.	Flood maps	Existing flood maps for comparative purposes
18.	Historic Documents	Available historic documents, books, maps relevant for the Desk FORIN methodology
19.	Interviews with the key stakeholders	The expert knowledge and experience obtained in a direct communication with the key stakeholders within the LAAs and beyond

3.2 Key research activities and results

3.2.1 WP2- Understanding formation of hazards under extreme events

T2.5

The city of Hamburg, located in the North German Plane along the Elbe estuary is threatened by hydro-meteorological events (see 3.1.1, 3.1.2). Based on the events from the past, the storm surges represent a considerable threat to the Elbe estuary and people living in this area (see 3.1.1, 3.1.2, D 5.2).

In order to characterize the extreme hydro-meteorological events such as storm surges, statistical analyses have been performed. A storm surge can be described by a combination of different parameters, which might be interdependent and therefore not representable by univariate statistical models (Salecker et.al. 2012). Rather, multivariate statistical approaches need to be applied. In tidal influenced coastal areas and estuaries, storm surges can be regarded as a superposition of the regular astronomical tide and an increased wind set-up (Figure 22).

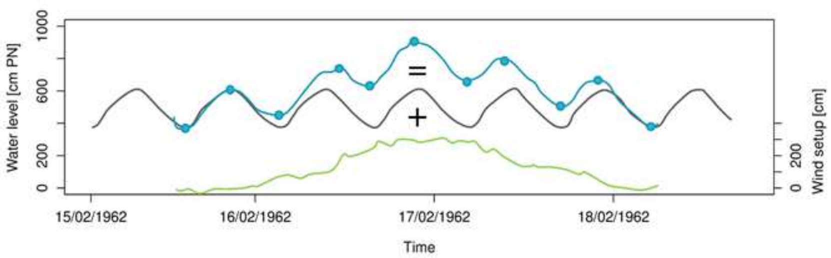


Figure 22: Storm surge hydrograph (blue line) as a superposition of the mean tide (grey line) and a storm induced wind set-up (green line)

The approach of the multivariate statistical analyses of the wind set-up applied to the Elbe Estuary is briefly described in the text below. A detailed description of the approach can be found in Salecker et.al. 2012, Fröhle et.al. 2014 and D 2.2.

The distribution function of a bivariate sample can be derived by means of the marginal distribution of the univariate samples and a copula function describing the dependence structure of the both random variables. The marginal distribution of the univariate samples can be derived using methods of the extreme value statistics. The aim of the bivariate statistical analysis is the identification of the copula function describing the bivariate sample best. There are different copula functions available describing the correlation of the random variables (see Table 10), which can be tested in order to identify the best fitting copula function. Each available copula function has its own generator function, for which the following mathematical correlation exists (Salecker et.al., 2012, Genest and Favre, 2006):

$$\tau = 1 + 4\int_0^1 \frac{\varphi(t)}{\varphi'(t)}dt \qquad \text{Eq. 1}$$

This expression correlates a rank correlation coefficient τ, the copula generator function and its first derivative. The rank correlation coefficient itself describes the degree of the correlation of the random variables (Genest and Favre, 2006).

Table 10: Distribution functions C(u,v) and generator functions φ(t) of different copula functions (Nelson 2006)

Copula	C(*u*,*v*)	φ(*t*)
Clayton	$(u^{-\Theta} + v^{-\Theta} - 1)^{-\frac{1}{\Theta}}$	$\frac{t^{-\Theta} - 1}{\Theta}$
Gumbel	$e^{\left[-\left((-\log u)^{\Theta} + (-\log v)^{\Theta}\right)^{\frac{1}{\Theta}}\right]}$	$\lvert \log t \rvert^{\Theta}$
Frank	$-\frac{1}{\Theta}\log\left[1 + \frac{(e^{-\Theta u} - 1)(e^{-\Theta v} - 1)}{e^{-\Theta} - 1}\right]$	$-\log\frac{e^{-\Theta t} - 1}{e^{-\Theta} - 1}$
Joe	$1 - \left[(1-u)^{\Theta} + (1-v)^{\Theta} - (1-u)^{\Theta}(1-v)^{\Theta}\right]^{\frac{1}{\Theta}}$	$-\log\left[-1(1-t)^{\Theta}\right]$

Probability of occurrence can be assigned to an arbitrary number of combinations of random variables (u,v) in the interval (0,1) (Genest and Favre 2007, Salecker et.al. 2012,Fröhle et.al. 2014).

The goodness of fit is assessed by comparing combinations of measured parameters (e.g. water level and sea state, water level and fullness) and simulated combinations. Thereto, an arbitrary number of equally distributed random variables in the interval (0,1) is created. Inserting the equally distributed random variables in the reverse function of the derivation of the copula function lead to interdependent random variables (u,v).

These random variable (u,v) are inserted into the reverse function of the univeriate marginal distribution functions and the simulated pairs of data are converted into real units (Genest and Favre 2007; Salecker et.al. 2012, Fröhle et.al. 2014).

By the means of this methodology an arbitrary number of combinations of water level and fullness with a conjoint identic probability of occurrence can be derived (Figure 23), which can further be used to derive storm surge hydrographs.

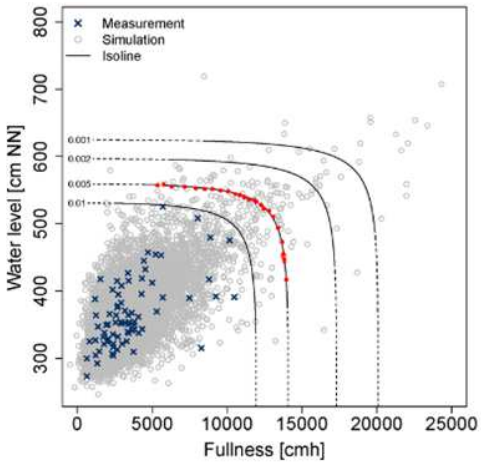


Figure 23: Example for a set of events with identic return period

Basis for the creation of new storm surge hydrographs are standardized courses of the wind set-up of measured storm surge hydrographs. The standardized hydrograph can be divided into an ascending (left part) and descending part (right part). The course of the left and right of the peak water level is simulated separately (Salecker et.al. 2012, Fröhle et.al. 2014) and both simulated and standardized courses of the wind set-up are scaled using the previous derived water level and fullness (Figure 24, Salecker et.al. 2012, Fröhle et.al 2014).

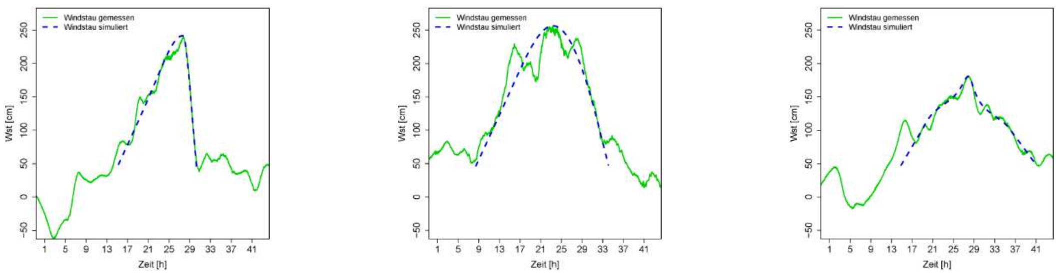


Figure 24: Scaling of the simulated courses of wind set-up with the maximum water level and fullness

By adding the mean tide to the scaled wind set-up new storm surge hydrographs are created.

The described approach is implemented into a storm surge generator. Using the storm surge generator a large number of storm surge hydrographs can be generated automatically. There are two options for generating storm surge hydrographs. The user can define the return period and the desired number of storm surges for a specific gauge location. The second option is to define a specific period of time for which the storm surge hydrographs are generated (Fröhle et.al. 2014).

Beside storm surges, extreme precipitation events can occur in the case study area. In order to derive scenarios representing concurrent occurring extreme events storm surge (represented by the water level) and precipitation events are statistically analysed. The statistical analyses are focussed on the two gauges Cuxhaven and Hamburg St. Pauli. For the both gauges high tide measurements and daily precipitation values are available. A correlation analyses examines the statistically correlation of the both parameters. Figure 25 shows the scatter plots for the considered gauges. It can be seen that there is no correlation between the water level and the precipitation. Therefore, both parameter are statistically independent, which simplifies the following investigations to univariate statistically analyses.

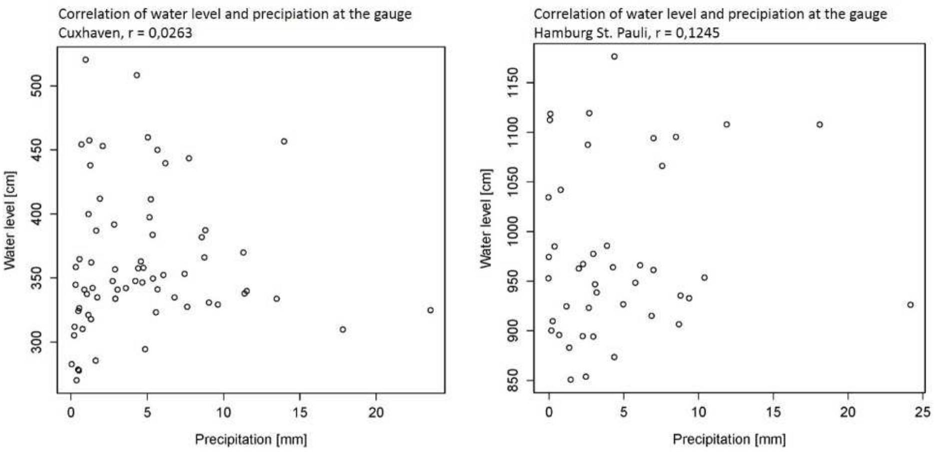


Figure 25: Scatter Plot of water levels and precipitation for the gauges Cuxhaven (left) and Hamburg St. Pauli (right)

Different univariate distribution functions have been fitted to the water level and precipitation measurements. The best fitting univariate distribution functions are as follows:

	Cuxhaven	Hamburg St. Pauli
Water Levels	Log Normal	Gumbel
Precipitation	Weibull	GEV

Using the best fitting univariate distribution function, different water level and precipitation events have been derived (Table 11)

Table 11: Water levels and precipitation events for different return periods at the considered gauges

Return period [a]	**Cuxhaven**		**Hamburg St. Pauli**	
	Water Level [cm]	Precipitation [mm]	Water Level [cm]	Precipitation [mm]
10	433,34	10,66	1074,54	10,12
25	463,65	15,03	1134,61	15,07

50	484,36	18,55	1179,18	19,56
100	503,74	21,69	1223,41	24,86
200	522,18	25,04	1267,49	31,13
500	454,43	29,48	1325,64	41,23

Since, both parameters (water level and precipitation) are statistically independent the concurrent probability of occurrence can be obtained by multiplying the probability of occurrence of the individual parameters.

T2.6

Extreme events are used as boundary conditions in hydrodynamic numerical models to simulate the impacts on the area under investigation.

The hydrodynamic model of the Elbe estuary is implemented using the open source modelling system Kalypso (https://sourceforge.net/projects/kalypso/), which is jointly developed by Hamburg University of Technology and the company Björnsen Consulting Engineers (BCE). Along with providing standard functions for hydrological and hydrodynamic simulations, Kalypso is distinguished by its modular design and operator-friendly user interface, containing a multitude of efficient tools, which provide means for generating models (pre-processing), running models (processing) and analyse of the model results (post-processing).

The numerical model of the Elbe estuary is set-up using the module Kalypso Hydrodynamic. Amongst others, Telemac-2D is implemented as calculation core. A detailed documentation of the model suite can be found on the website of open Telemac – Mascaret.

The Elbe estuary model includes the Elbe and its hinterland areas from the weir in Geesthacht to Cuxhaven at the mouth of the river Elbe at the North Sea (Figure 17). The unstructured triangular 2D model domain consists of approx. 100.000 elements with a mesh resolution of 3 m² up to 400.00 m² (Shaikh et.al. 2016). For simulation of (coastal) estuaries with a 2D or 3D numerical model approach, two different boundary conditions have to be applied at the model boundaries. At the upstream boundary at the weir in Geesthacht (see Figure 17), a discharge boundary is applied. For the 2D-HDN model the discharges are based on daily data of the discharge gauge Neu Darchau (Figure 26, black line). At the downstream boundary a water level boundary condition is applied based on the water level data of the gauge Cuxhaven-Steubenhöft (see Figure 26, blue line).

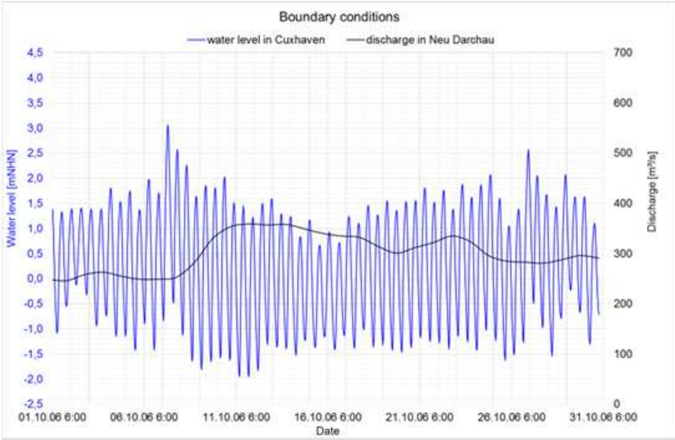


Figure 26: Hydrodynamic boundary conditions of the 2D-HDN model (water level - blue, discharge – black)

The 2D-HDN model has been calibrated with a focus on the hydrodynamical characteristics water level and flow velocities (Shaikh et. al. 2016) based on a typical spring-neap cycle (see Figure 26). Figure 27 shows the results of the calibration process for the considered hydrodynamic characteristics.

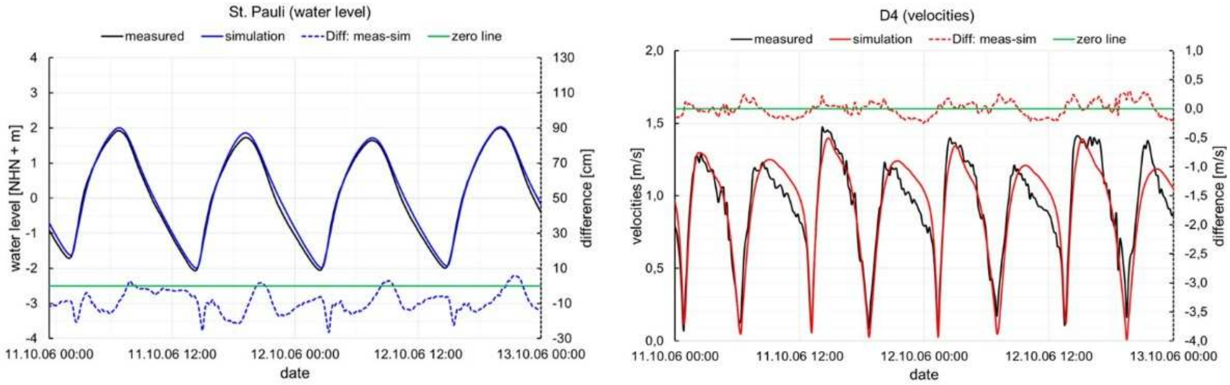


Figure 27: Measured and simulated water levels (left) and flow velocities (right) (Shaikh et.al., 2016)

The application of the set-up 2D-HDN model of the Elbe estuary is described in the respective chapters of the present report (see 3.2.2 and 3.2.3)

3.2.2 WP3- Holistic and Multiple Risk Assessment

T3.7

The impact and risk assessment is focussed on the flood prone area of the largest urban area in the Elbe Estuary being the city of Hamburg (Figure 1, marked in blue) and encompass the following activities:

- damages to the built environment focusing on a densely populated Hamburg district of Wilhelmsburg, which is undergoing an intensive urbanisation process in the recent years (IBA, 2012). Here, PEARL is building upon the research outcomes from the EU project CORFU and the project XtremeRisK funded by the German Ministry for Education and Research, in which the impact assessment has been performed as of the year 2010. This is

taken as a baseline for the investigations described in this report. Due to the development of the urban area of Wilhelmsburg, which mainly took place after 2010 (see chapter 1.5.2) it is the objective of this study to assess the temporal development of the impacts and flood risk in the area, mainly triggered by an intensive urban development process. This development will be further considered for the holistic risk assessment and the FORIN method (in further text***: the District of Wilhelmsburg***)

- direct and indirect damages for critical infrastructure, for the port of Hamburg and the public and private transportation sector (are still an ongoing research, where the activities so far the intermediate results are thoroughly documented in Gkliati (2015), Blaj (2016), Zhamo (2016). (In further text: ***Critical Infrastructure***)

A overview of the impact assessemnt activities for the City of Hamburg is given in Figure 28.

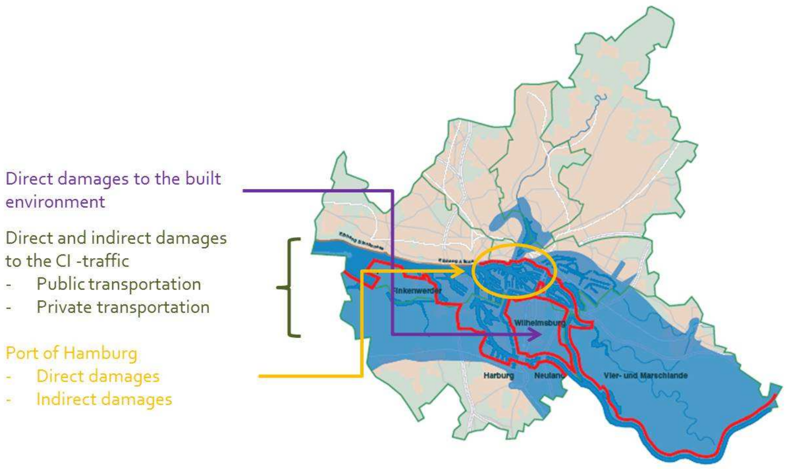


Figure 28: Actual overview of the research activities for the Elbe estuary/Hamburg case study (red line indicates the public flood protection infrastructure)

The district of Wilhelmsburg: For the risk assessment in the area of Wilhelmsburg, the flood hazard assessment and the considered scenarios are based on the results of the projects Corfu and XtremRisK, being described in the following text.

Past state (2010): In a first step, the storm surge scenarios have been derived on the basis of recorded storm surge hydrographs from the recent past. These storm surge hydrographs have been superimposed by phenomena like bores and extreme spring tide set-up. The methodology for the derivation of the storm surge scenarios can be found in Gönnert et.al. (2012) and Rudolph (2011, in: Oumeraci, 2012). In total, three storm surge scenarios have been derived based on recorded storm surge hydrographs from the recent past (see Figure 29). A detailed description can be found in Oumeraci et.al. 2012 and Rudolph 2011 (in: Oumeraci, 2012).

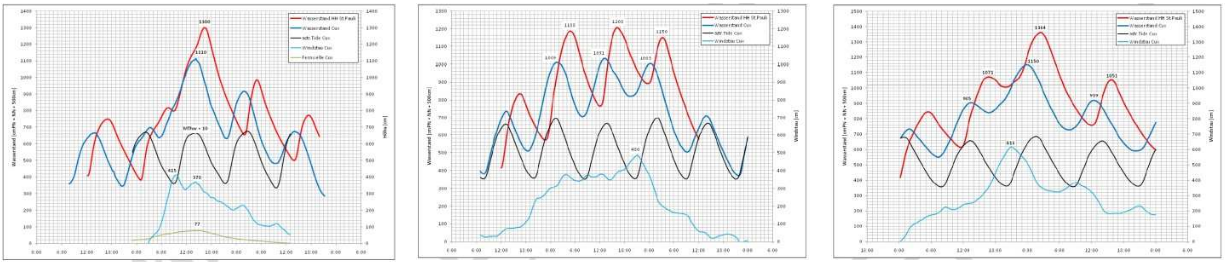


Figure 29: Storm surge scenarios derived for the tide gauge Cuxhaven

All three scenarios have been statistically analysed using multivariate models in order to assign a probability of occurrence to each of them (Oumeraci, 2012). The following table gives an overview of the scenarios.

Table 12: Characteristics of the considered storm surge scenarios (Oumeraci, 2012, modified)

Scenario	**HH_XR2010A**	**HH_XR2010B**	**HH_XR2010C**
Peak water level [cmNN]	610	531	650
Fullness [-]	537	770	767
P_e [1/a] (bivariate)	$3{,}17 \cdot 10^{-4}$	$7{,}20 \cdot 10^{-3}$	$4{,}27 \cdot 10^{-4}$
Fresh water discharge [m³/s]	3600	3600	3600
$P_{e,\ Oberwasser}$ [1/a]	$2{,}50 \cdot 10^{-2}$	$2{,}5 \cdot 10^{-2}$	$2{,}5 \cdot 10^{-2}$
P_e, Hamburg [1/a] (trivariate)	$7{,}72 \cdot 10^{-6}$	$8{,}09 \cdot 10^{-8}$	$5{,}3 \cdot 10^{-8}$

The described scenarios are the basis for a hydrodynamic model, leading to the hydraulic input parameters for the damage assessment assuming a functional failure (overtopping of the dike line). The results from the inundation model are analysed to derive the maximum water depth, as this is the decisive input parameter for the assessment of the direct tangible damages and the calculation of the flood risk (Figure 30).

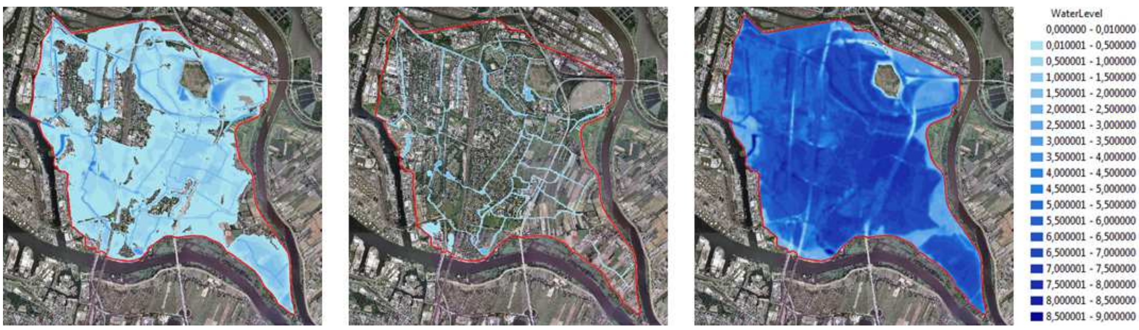


Figure 30: Results of the inundation modelling for the considered scenarios HH_XR2010A (left), HH_XR2010B (middle) and HH_XR2010C (right) (Ujeyl, 2012)

The landuse in Wilhelmsburg is predominantly residential, commercial followed by the infrastructural elements. The elements at risk (residential buildings, commercial objects, infrastructure areas) have been divided into categories of equal characteristics, based on the gathered data. For the representation of the residential objects representative building types have been defined, based on a multi-criteria analysis considering i) the type of the building, ii) the occupancy of the ground floor and iii) the wall construction.

After the residential have been classified, the evaluation of the asset values and the derivation of the depth-damage curves is carried out. Concerning the residential objects, the vulnerability has been assessed with regard to the following potential damages considering the respective costs (Ujeyl, 2012):

- Damages to structural elements:
- Costs for cleaning-up:
- Damages to the inventory:

Damage curves for each representative building type have been calculated for both the building itself and the inventory (Figure 31).

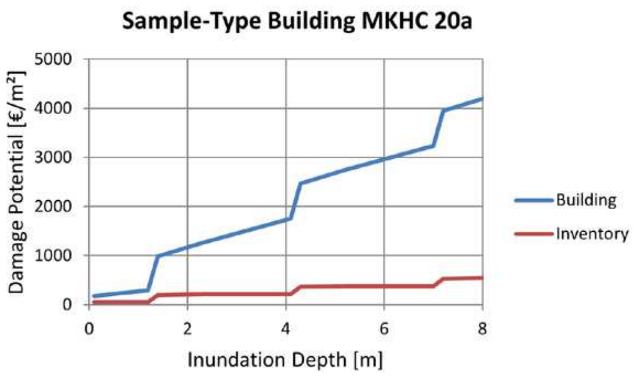


Figure 31: Damage curves for building and inventory for a representative building type (Ujeyl, 2012)

A cell based risk assessment approach is used to calculate the direct tangible damages using a developed ArcGIS toolbox and subsequently the flood risk (see D3.4). The water levels are intersected with the objects at risk resulting from the vulnerability analysis. Thereby, the affected objects are localized by means of determination of the affected grid cells. Water level relevant for the calculation of the damages is calculated depending on the results of the inundations modelling, the representative building type and the number of storeys. With the help of the derived water levels, the resulting damage potential can be calculated from the damage curves. By multiplying the damage potential with the area of the affected cells, the resulting damage due to the flooding is gathered. Table 13 gives an overview of the damages and the corresponding flood risk caused by the considered storm surge scenarios (Ujeyl, 2012).

Table 13: Calculated damages and flood risk based on the considered scenarios (Ujeyl, 2012, modified)

Scenarios	Damages in Mio. €			$P_{e, Hamburg}$ [1/a]	Risk [€/a]
	Residential	Commercial	Total		

	Buildings	Inventory	Buildings	Equipment			
HH_XR2010A	572,47	67,57	87,15	311,29	1038,48	$7,72*10^{-6}$	7477,06
HH_XR2010B	0,26	0,03	2,12	1	3,14	$8,09*10^{-8}$	0,25
H_XR2010C	2297,04	323,47	824,53	1907,47	5252,51	$5,3*10^{-8}$	278,38

Present state (2016): A number of new and innovative urban development projects have been evolved and realised during the last years in Wilhelmsburg (see D 3.4). Amongst others, residential districts have been rebuilt or have been newly built using innovative construction methods as happened in the district Wilhelmsburg Central within the Development Program of the Hamburg Senate "Leap over the Elbe" (BSU, 2007).

In order to derive the magnitude of change of the flood impact and risk the same methodology (and in D3.4) is applied. Both conventional and innovative house construction can be found in the building stock. Existing damage curves, developed during the XtremRisK project, are assigned to buildings of conventional construction technique. Due to the innovative construction technique of the residential houses in Wilhelmsburg Central (see Figure 32) new damage curves have been developed, based on the respective building specifications and available floor plans. Figure 33 shows exemplarily the damage curves of the "Smart Material House BIQ" for both the building and the inventory. Similar damage curves will be developed for the other IBA projects. It is expected that the overall vulnerability will significantly increase, due to the new created asset values.

Figure 32: Overview of the IBA projects in Wilhelmsburg Central

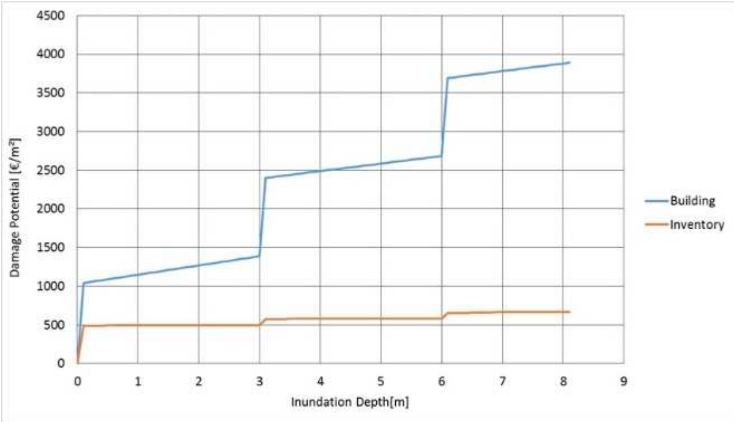


Figure 33: Damage curve of the "Smart Material House BIQ"

As reported in D3.4, this activity is work in progress and will be finalised by End of 2017. The impact assessment will go in line with the updates of the flood hazard maps for the District of Wilhelmsburg in WP2. This report will be updated accordingly.

Based on the preliminary results, it is expected that the calculated damages will have significant magnitudes. Whereas, the damages to the buildings are expected to be higher than the damages to the inventory, which is due to the specialized building services located on the ground floor of each building and the specialized construction technique (e.g. WoodCube: mere wooden construction).

Critical Infrastructure: The impact assessment on the Critical Infrastructure in the City of Hamburg encompasses the following elements:

- the seaport of Hamburg as part of the supra-regional transportation system and important element of the regional and supra-regional economy (for Hamburg being the third largest seaport in Europe).
- direct and indirect damages on the transportation sector

The Port of Hamburg: The preliminary study of the direct and indirect impacts of a flood event has been carried out for the Eurogate Container Terminal of the seaport of Hamburg. In a first step, a general analysis of the process chains in a seaport was carried out and all buildings, facilities and equipment relevant for a proper port operation have been compiled in order to get an overview of the port operations and the operations in the container terminal. Depth-damage curves have been developed for all relevant buildings, facilities and equipment based on free available data. Where no data was available reasonable assumption have been made (Figure 34).

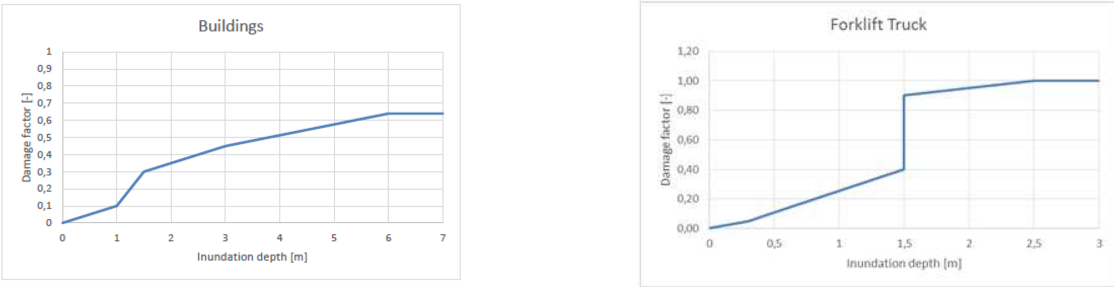


Figure 34: Examples of derived fepth-damage curves (Gkliati, 2015)

At the same time, notional inundation scenarios have been developed based on recorded storm surge events of the recent past. These scenarios cover a wide range of possible and extreme storm surge water levels. The storm surges water levels amounts to: 6,00 mNN, 6,70 mNN, 7,70 mNN and 8,70 mNN, resulting in inundation depths of 0,3 m, 1,00 m, 2,00 m and 3,00 (Gkliati, 2015).

The direct impacts of the notional storm surge scenarios has been calculated on the basis of the derived depth-damage curves and the inundation depths corresponding to the storm surge scenarios. Figure 35 shows exemplarily the direct damages to the general facilities (left) and handling equipment (right).

Figure 35: Initial rough estimation of the direct damages to general facilities (left) and handling equipment (right) of the Eurogate Container Terminal (Gkliati, 2015)

In the initial investigation the indirect damages have been obtained using the approach of Hallegate (2014), which connects the indirect damages (ΔY) and the direct damages (ΔK) (Eq. 2)

$$\Delta Y = (1+\alpha)\frac{3}{2}r\Delta KN \qquad \textit{Eq. 2}$$

Figure 36 shows the indirect damages resulting from the respective scenarios.

Figure 36: Indirect damages for different scenarios based on the approach of Hallegate (2014) (Gkliati, 2015)

<u>Public Transportation:</u> Flood impacts to the public transportation sector has been carried out in the collaboration and exchange with the Columbia University, New York, USA and making use of the post-Sandy (2012) assessments and lessons learned. Two different approaches, which have been used to assess the flood damage to the transportation system of New York City as a result of the hurricane Sandy, have been applied to assess direct and indirect impacts on the public transportation (*U-Bahn*) of the City of Hamburg. The first approach, by Jacob et.al. (2011) connects costs from the direct physical damages and costs for restoration of the transportation system depending on the time which is needed to reach 90% of its capacity before the event to calculate the total losses (Figure 37).

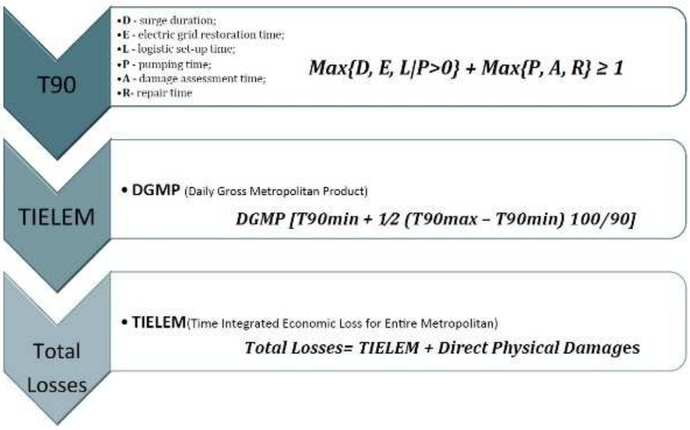


Figure 37: Approach of Jacob et.al. 2011 for the assessment of direct tangible flood damages (Zhamo, 2016)

The second approach, by Compton et.al. (2009), calculates direct tangible flood damages assuming a direct relationship between the length of track flooded and the resulting direct damages (Figure 38).

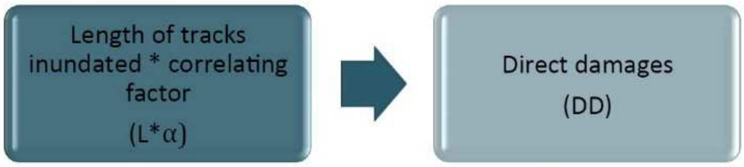


Figure 38: Approach of Compton et.al. 2009 for the assessment of direct tangible flood damages (Zhamo, 2016)

The correlating factor αis derived from the statistical analysis of recorded subway/railway flood incidents.

The approach to estimate indirect tangible damages is based on the statistics of people travelling through the floodplain area and derives the compensations in case of delay/cancellation of service (FHRC, 2008) (Figure 39).

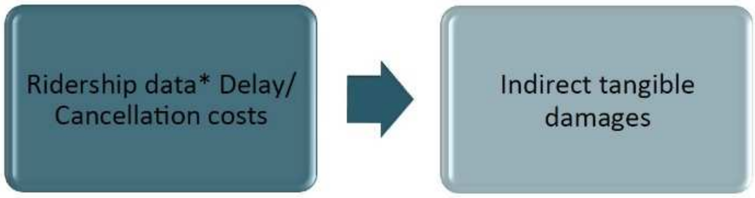


Figure 39: Approach to estimate indirect tangible damages due to service interruption in case of flood event

Figure 40 summarizes the results of the investigations and gives a summarizing overview of the applied approaches.

	DIRECT TANGIBLE DAMAGES (Jacob et al., 2011)	DIRECT TANGIBLE DAMAGES (Compton et al., 2009)	INDIRECT TANGIBLE DAMAGES (FHRC, 2008)
The main factor to consider	Damage to physical infrastructure added to the time needed for the economy to restore to 90% of its functionality.	Damage is directly related to the length of tracks inundated.	Cancellation/delay of service
Clear boundary between direct/indirect damages	No	Yes	
Accuracy of data	High	Medium	High
Transferability	Yes	Yes	Yes
Knowledge gaps	"Worst case" scenario leads to overestimation of results. No defined relationship between each type of asset and damage caused by flooding.	Oversimplified approximation leads to uncertainties in the results. Lack of recorded flood damage assessments leads to errors in the correlating factor	Estimations and surveys conducted in the UK where governance of railway systems is private rather than public. Latest available surveys were conducted in 2009.
Considerations for improvement	Estimations based on more realistic scenarios Infrastructure-damage relationship for each different type of asset	Inclusion of existing flood protection measures in the estimations Creation of a digital database Increasing the number of case studies included in the regression analysis	Conduct surveys and post-damage assessment based on the ridership data and subway fare of the urban area to be studied
New York results (US$)	56 billion	587.3 million	343 million
Hamburg results (€)	908 million	209-269 million	39 million

Figure 40: Summary of the gained results and the applied approaches (Zhamo, 2016)

3.2.3 WP4- Flood forecasting and early warning systems for coastal regions

T4.1

A water level forecast systems based on real-time simulations has been developed on the basis of th

the multi-regression gauge based forecast system developed and implemented by BSH, the German Federal Maritime and Hydrographic Agency (BSH). The so-called MOS-forecast (MOS – **M**odel **O**utput **S**tatistics) system provides pointwise water level forecasts for up to 6 days for several locations (gauge stations) along the Elbe River (Müller-Navarra, 2012). Since it is a pointwise forecasting system, no information about the spatial distribution and the spatial development of the water level along the river exists. This information together with flow velocities and wave information is necessary to assess the safety of the constructions and is generated within the TUHH forecast approach in order to derive the spatial distribution of the water level.

The early warning system for the Elbe estuary is based on the 2D-HNM of the Elbe Estuary, which is described in chapter 3.2.1. This early warning system calculates the current status and a forecast over up to 3 days of the temporal and spatial development of the water level and respective currents along the Elbe estuary and to detect potentially endangered sections of the flood protection infrastructure.

Figure 41 shows the operational sequence and the data flow of the developed early warning system.

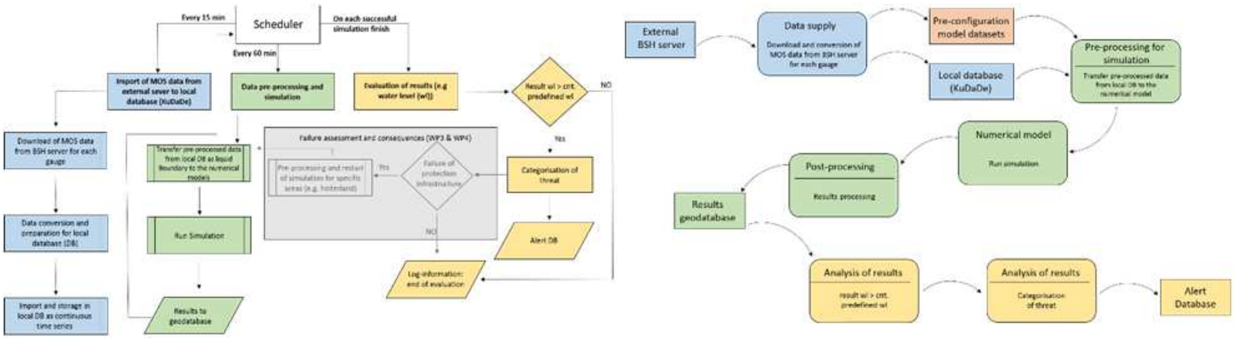


Figure 41: Flow chart (left) and data flow chart (right) of the early warning system for the Elbe estuary

Basically, the operational sequence of the water level forecast system consists of three threads. Water level data (MOS data) is downloaded from the external server of the BSH to the local database at TUHH (see Figure 41, blue thread) and is provided adequately to the numerical model. The second thread covers the data pre-processing and the simulations (see Figure 41, green thread). For each successful finished simulation (see Figure 41, yellow thread) the resulting water level is evaluated with respect to a critical predefined water level in order to detect endangered sections of the flood protection infrastructure in the forecast area. The

results of the evaluation are stored into an alert database. A scheduler manages the processes described above. A more detailed description can be found in the D4.1

The numerical model of the Elbe estuary has been divided into three sub-models (Figure 42) in order to integrate as many MOS stations as possible. The location of the model boundaries have been chosen on condition that within each sub model at least one MOS station is available for verification purposes.

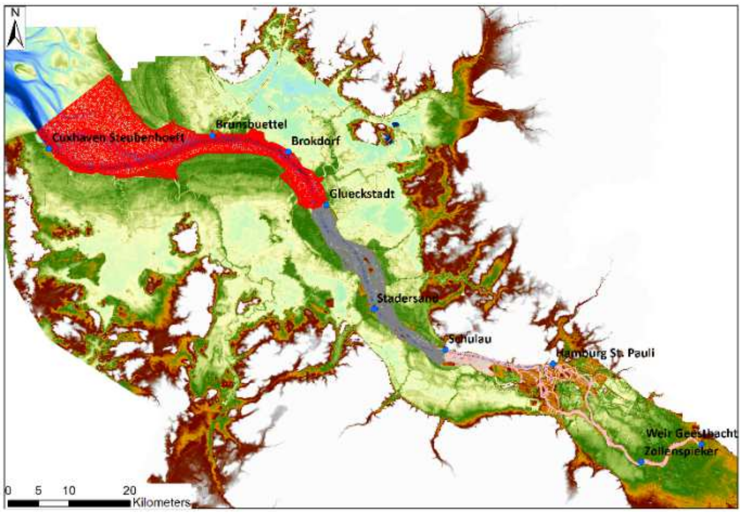


Figure 42: Overview of the sub-models of the numerical model (marked in light red (I), grey (II), red (III))

Each sub-model has two boundaries located at a MOS station to assimilate and integrate the water level prediction provided by the BSH into the sub-model. That is a mandatory requirement to run each sub-model independently in serial for a MOS water level forecast period. Additionally, discharge boundary is applied to each upstream sub-model boundary (Shaikh et.al., 2016).

After finishing the forecast runs of each sub-model, the results of the calculated water levels are analysed in a separated process. The results of all three runs are summarized and transferred to the result database.

The summarized results are stored in a geodatabase and processed for visualization on a web site (see Figure 43). The web site content includes a background map, the entire model domain of the Elbe estuary and the forecasted water level for different time step within the current simulation (forecast) period. Time series of forecasted water level for selected locations are shown on the web site (http://pearl.wb.tu-harburg.de/forecast/).

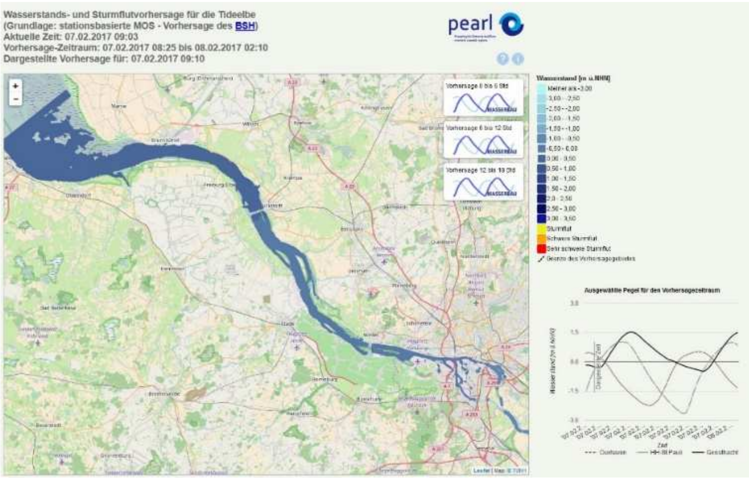


Figure 43: Screen shot of the visualization of the water level forecasts on the web site

For validation purposes the result of the numerical model of the Elbe estuary are compared with the water level forecasts of the BSH and measured water level time series for the available location, within each sub-model (see Figure 42). Figure 44 shows exemplarily the comparison the water levels at the tide gauge Hamburg St. Pauli.

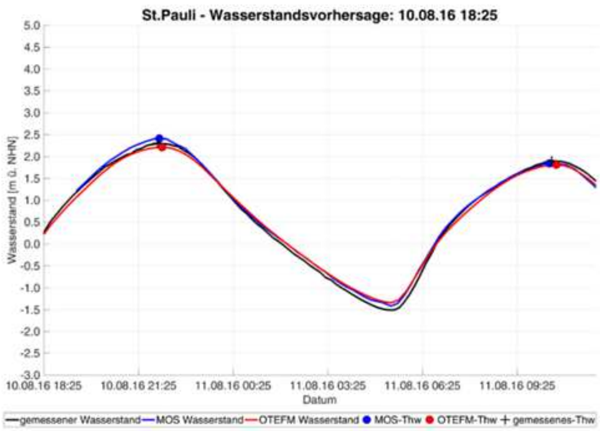
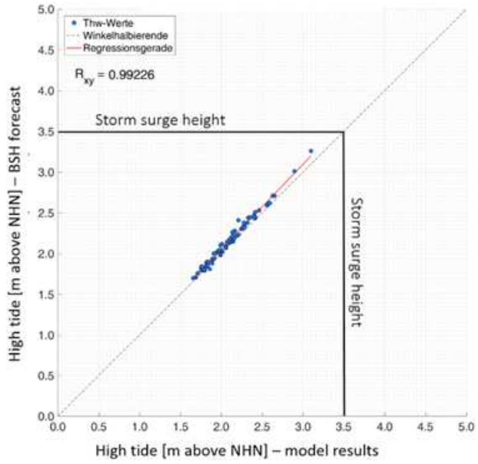


Figure 44: Comparison of the BSH water level forecast (blue line), TUHH simulated water level (red line) and the measured water level (black line) at the tide gauge Hamburg St. Pauli

Furthermore, statistical analyses have been performed in order to verify the model results. Figure 45 shows exemplarily such a statistical analysis. One can see, that the modelled results correspond well with the BSH water level forecast (BSH, Figure 45, left) and the measured water level (Figure 45, right)



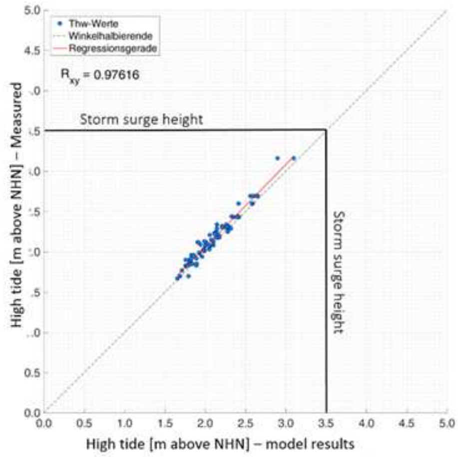


Figure 45: Correlation analysis of the forecasted water levels and the modelled water level (left) and the measured water level and the modelled water level (right)

T4.2

The application of the innovative technology of CPU/GPU computing especially for the realization of an evacuation module within the Kalypso model suite is explored by the TUHH aiming at the development of an evacuation model which can be run on an average NVIDIA®CUDA enabled desktop computer. A prototype for such an evacuation module is developed and applied to the Hamburg district Wilhelmsburg.

The overall evacuation concept encompasses pedestrian evacuation, evacuation by public transport, evacuation by private cars and the vertical evacuation. At present, the evacuation model covers the pedestrian evacuation to collecting points (bus stops) or to safe places (refuges) (Figure 46). The evacuation model will be extended during 2017.

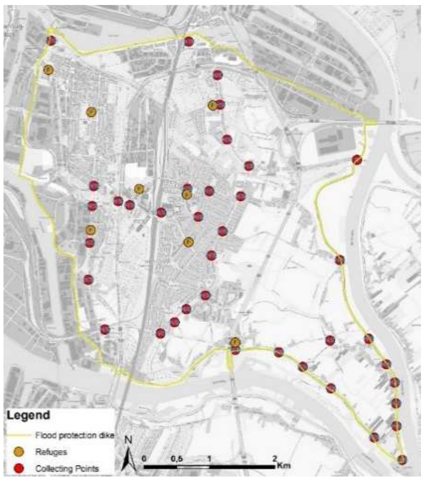


Figure 46: Collecting points and refuges in Wilhelmsburg

The evacuation model for pedestrian evacuation, which simulates the movement of the pedestrians to the collecting points, is carried out based on a hybrid GPU/CPU implementation.

In order to simulate the pedestrian dynamics a spatially continuous force-based model is applied, representing a robust and quantitatively verified model (Chraibi et.al. 2010). This approach couples the pedestrian dynamics with the dynamic topology. Newton's second law of dynamics is the basic principle for the applied force-based model (Chraibi et.al. 2010). According to Newton's second law of dynamics the movement of pedestrians can be described by driving and repulsive forces (Eq. 3):

$$m_i \ddot{\vec{R_i}} = \vec{F_i} = \overrightarrow{F_i^{drv}} + \sum_{j \in N_i} \overrightarrow{F_{ij}^{rep}} + \sum_{w \in W_i} \overrightarrow{F_{iw}^{rep}} \qquad \textit{Eq. 3}$$

Repulsive forces are used to represent the avoidance of possible collisions performed by pedestrians guaranteeing a certain volume exclusion of the pedestrians. Driving forces model the movement of the pedestrians form an initial position to a specified destination with a certain speed (Chraibi et.al. 2010). The applied centrifugal force model takes into account the distance between the pedestrians and their respective relative velocities.

In order to apply this pedestrian dynamics approach, the following key data has been used:

- population data (number of people per age groups)
- the location of the different collecting points and refuges (targets for the pedestrian dynamics simulation)
- the building stock (obstacles for the pedestrians) in the considered area

These data have been processed in order to serve as the input for the pedestrian evacuation model. First, sub-evacuation areas of the collecting points and refuges have been derived based on adapted Thiessen polygons (Figure 47). This divide and conquer approach is used in order to support the efficiency of the selected mathematical-physical model and to increase the simulation efficiency. The borders of the sub-evacuation areas have been adjusted to streets and other constraint points, e.g. highways and rail tracks to create areas as simple as possible.

The building stock of Wilhelmsburg, available in shapefiles from the cadastral maps, are aggregated to bigger building blocks (Figure 47) aiming at the reduction of obstacles for simulation purposes for increasing the simulation efficiency.

People living in Wilhelmsburg are to be distributed to the building blocks. For this purpose, population data, provided by the statistical office for Hamburg and Schleswig-Holstein, are used. These data is available in a shape file for bigger statistical areas containing the number of people per age groups. The distribution of the people to the buildings blocks is made on a percentage basis with respect to the area sizes.

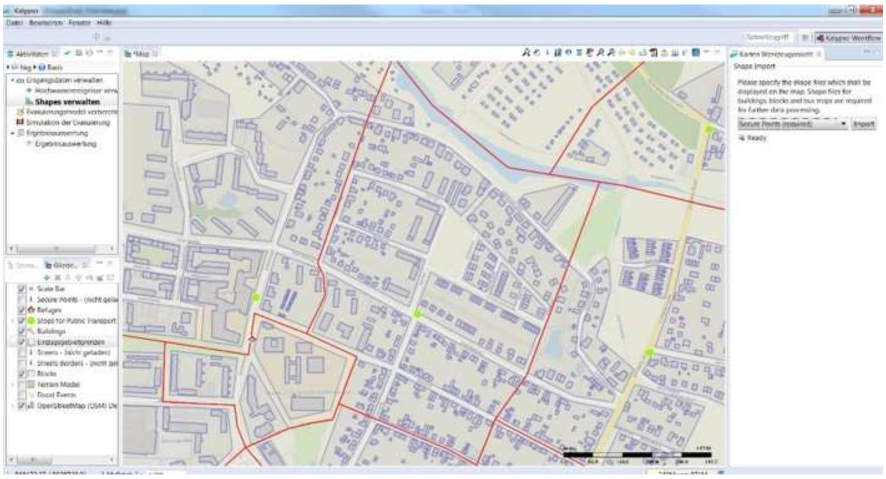


Figure 47: Screen shot from the Kalypso GUI showing "catchment areas" (red polygons), building polygons (small blue polygons) and aggregated building blocks (bigger blue polygons)

The mathematical-physical model, mentioned above, describes the movement of the pedestrians from the initial positions (building blocks) to the targets (collecting points or refuges). The simulation based on this model results in a distribution of the arrival times of the people at the targets, being the input for the simulation of further evacuation processes on CPU level, which will be implemented during 2017.

3.2.4 WP5- Decision support and policy development for strengthening resilience of coastal regions

T5.1

An adapted LAA model has been applied to the Elbe Estuary (described in D5.1) in order to involve the key stakeholders in the development of the holistic flood risk management practices and is composed of the following main phases:

1. Stakeholder analysis- who is (should be) involved? - Reassessment of the key stakeholders, their relations, interdependences… (desk study and interviews, link to WP1 (FORIN Desk study))
2. Tailored approach to the selected stakeholder groups and individuals addressing their specific interest (face to face sessions)
3. Towards the joint planning - 'from the parts to the whole' analysing the interactions of the key stakeholders (mutual and with the PEARL methods and tools) - (the final plenary discussions, final analysis)

The results of phase 1) are given in section 3.1.3. In phase 2) a series of active face to face meetings have been conducted with the objective to continuously identify and if necessary reassess the needs and interests, barriers or potential clustering of the key stakeholders based on their interests and current activities. The PEARL outcomes and findings in general and in particular related to the Elbe Estuary pilot area are regularly made available to the stakeholders either during the meetings or in a digital form, including the internet. The assessment of the

potential for PEARL to contribute to the overcoming of the barriers and meet the interests of the targeted stakeholders groups is regularly assessed in a form of oral feedback sessions.

The interests of the key stakeholders and the way they of their engagement are given in the table below:

Key stakeholder	Assessed Interest in PEARL	Way of engagement
The Agency for Roads, Bridges and Waterways (LSBG)	Hazard& risk assessment, modelling tools developed, EWS	Regular face-to-face meetings on a monthly basis with the key representatives
Ministry of Interior Affairs-Hamburg	Evacuation model	Regular meetings including the assessment of the needs and interests session related to the Evacuation model (D4.2)
Agency for Coastal Protection, National Resources and Sea Protection, Schleswig Holstein (LKN-SH)	Hazard& risk assessment for the Schleswig-Holstein area, modelling tools developed,	Occasional personalised meetings
Hamburg Port Authority (HPA)	Hazard& Risk assessment in the port of Hamburg area, EWS	Regular face-to-face meetings with the key representatives,
Federal Maritime and Hydrographic Agency (BSH)	EWS	Active involvement and exchange of experiences; regular working meetings, joint publications
Ministry of environment and energy- BUE (the highest level administrative body)	Final results, policy briefs	Meetings with the officials PEARL PCM scheduled for January 2017 in the premises of the Ministry

At the end of phase 2) an increasing interest in the PEARL results and in further collaboration within PEARL and beyond could be observed. The process had a snowballing character as we could motivate additional institutions to actively contribute to the development of the PEARL tools such as the Ministry for Interior Affairs that continued actively supporting the PEARL-TUHH team regarding the necessary data for the evacuation tool. The addressed stakeholder groups are very well aware of the flood situation in the Elbe Estuary (and can be considered as the key local knowledge owners but also the key users of the PEARL outcomes), they have been actively involved in the design of the PEARL methods and tools. The common problem and tools ownership has been gradually increasing during this reporting period, which could be observed on the increased communication flux with the representatives.

In the case of BSH, active working sessions and regular feedback sessions have been organised regarding the jointly developed tool Elbe OTEEM (see D4.1), which also resulted in the production of joint publications.

During reporting period M18-M36 (which coincides with the phase 2 of the LAA implementation), the basis have been created for a potential future LAAs that could be brought on a broader platform, which would be the target of the phase 3 (M36-M48).

T5.2

The method for flood resilience assessment, developed by Batica et.al., 2013 and improved in the scope of the PEARL project has been applied to assess the Flood Resilience Index (FRI) for the Elbe Estuary, focusing on the City of Hamburg (D 5.2).

For the calculation of the FRI, weights were assigned independently by the experts from TUHH to each indicator having the following considerations:

- Natural indicators are assigned a weight of 3 and 5.
- Emergency evacuation & warning, and accessibility are given an importance of 4 and 5
- Land use and urban expansion have a weight of 5, as well as protected critical facilities
- Volunteers and solid waste management are assigned a weight of 5 and 3.

Following the method defined by Batica et al., 2013 the three characteristics are taken into account in the evaluation of FRI (i) environment, (ii) estimated risk and (iii) price. The weights are assigned after consultations with researchers at our organisation and stakeholders from case study and literature review related to the analysed event.

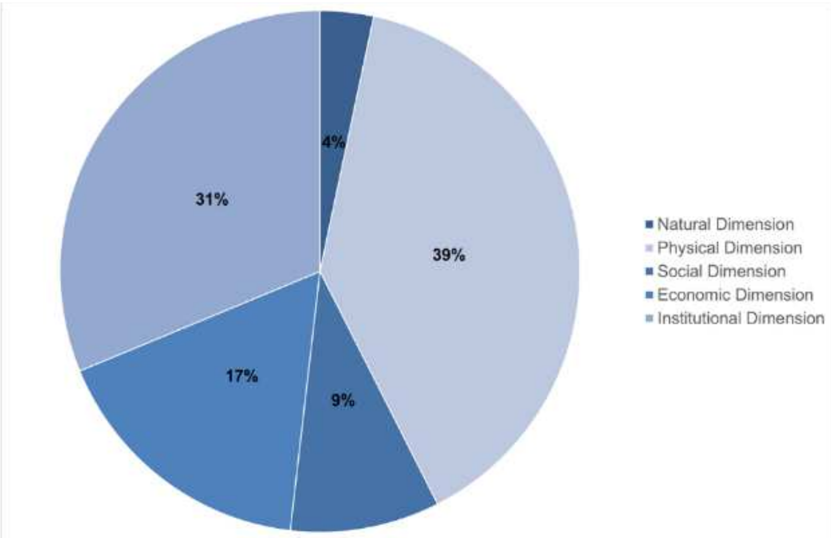


Figure 48: Weight of each dimension on the overall FRI for the Free and Hanseatic City of Hamburg

As presented in Figure 48 the importance of each dimension varies from 4% for natural up to 39% for physical dimension.

The evaluation of overall FRI has been followed by assigning values to each indicator with their corresponding weights. For the given conditions, the FRI for the Free and Hanseatic City of Hamburg is 3.96. The result in the form of table shows separate FRI for each dimension and the overall index.

Table 14: Overall FRI for the city/urban scale; for flood initiated by storm surges and the current status of the flood protection – Free and Hanseatic City of Hamburg, Germany

Free and Hanseatic City of Hamburg	Indicators	Dimension index Σ(xi*wi)/Σwi	"Importance" Σwi/ Σw	Overall FRI
Natural Dimension	2	4	0,03	3,96
Physical Dimension	36	3,87	0,39	
Social Dimension	10	3,96	0,09	
Economic Dimension	16	3,71	0,17	
Institutional Dimension	27	4,20	0,31	

Results obtained in this analysis demand an interpretation in order to address all current issues regarding flood resilience.

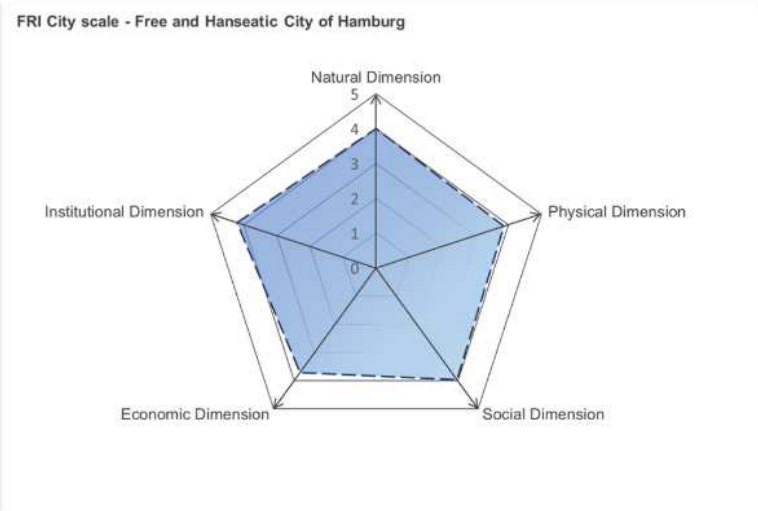


Figure 49: Radar chart presentation of FRI on city scale, for flood initiated by storm surges and the present status of the flood protection – Free and Hanseatic City of Hamburg, Germany

Results obtained using Matrix with 91 indicators give good interpretation about existing and needed assets and policies (laws, binding documents, etc.) that will contribute to increase flood resilience of analysed case study.

Natural dimension with index value 4 shows that the river network is able to accept the peak discharge from upstream. The discharge feeding the Lower Elbe from upstream can be controlled by the weir in Geesthacht. In the areas being less densely populated or in areas which are originally under agricultural use, polder areas are provided, which can capture certain amount of water in case of a storm surge approaching the city of Hamburg.

Social dimension with index value 3.96 shows that there is an intense exchange of knowledge between the planning, legislative and executive (especially with respect to the flood protection) disciplines. During the devastating storm surge of 1962 the public, the legislator and the executive agency learned their lessons. As a result, there was a change of the dike law, a repeated increase of the design water levels (taking into account the climate change), an

improvement of the cross section of the flood protection dikes and the implementation further manifold flood protection measures. Nowadays, there are clear-cut responsibilities within the civil protection. Furthermore, the public, living in flood prone areas, is kept informed regularly about the recent regulations of civil protection and evacuation process.

The economic dimension has a comparatively low index value of 3.71. The main reason can be seen in the missing financial support from insurances. There is only a limited possibility to effect an insurance against inundation. In general, material damages resulting from inflowing surface water are insured. Material damages resulting from storm surges cannot be insured. However, financial support for flood-adapted construction is available. There is no tax deduction for people living in flood prone areas.

Institutional dimension with index value 4.2 shows that recent flood protection concept of Hamburg is well positioned with respect to the institutional dimension. There are detailed civil protection and evacuation plans and clear-cut responsibilities. Nowadays, the planning of the public and private flood protection relies on the results from inundation simulation under consideration of the climate change. The stakeholders, especially those who are responsible of the flood protection, are in close co-ordination. Also, they rely on the recent research findings for the derivation of flood vulnerability, flood maps, flood risk maps, which are open in parts to the public.

Physical dimension received an index value of 3.87. The physical flood protection infrastructure comprising dikes, sluices, walls and gates etc. has been adapted and improved repeatedly during the years after the storm surges of 1962 and 1976. The flood protection infrastructure proved its protective effect against storm surges and flood as the surge “Xaver” (2013) showed. Possible future adaption of the flood protection infrastructure to changing hydro-meteorological conditions is included in the planning process of the flood protection, so that future increase e.g. of the dike height can be carried out easily.

In the following step, the FRI will be discussed with the key stakeholders within the phase 3 of the LAA method in order to increase the objectiveness of the results but also to increase the awareness among the stakeholders of all relevant aspects to consider when improving the flood resilience in urban (and coastal) areas.

The overall flood resilience index of 3.96 shows that the flood protection of the city of Hamburg is already at a considerable level, mainly due to the well-established flood management planning practices and efficiently assigned responsibilities and roles for different tasks of flood management. Still, flood management is a dynamic process and must be continuously adapted to the future conditions

T5.3.1

The Elbe Estuary and the City of Hamburg are protected by a continuous line of flood protection infrastructure along the river Elbe. The layout of the flood protection infrastructure in the City of Hamburg is indicated in Figure 20. All three federal states responsible for the Elbe Estuary (Hamburg, Schleswig Holstein and Lower Saxony) have high safety standards reflected in the design water level, that is derived in each federal states according to their own methods and statistics (personal communication with the Ministries from all three federal states).

In Hamburg, the reinforcement and improvement of the existing flood protection line is performed within Construction Programs (Bauprogramme). Within the Program started 2007, the flood proteciton infrastrcuture is being elevated and reinforced in avare for 1,0 m (LSBG, 2007) referring to the design water level at the St. Pauli gauging station of NN+7,30 m. Depending on their locaiton and the considered loads (e.g. wind direction) the heigth of the infrastructure is between NN+ 7,60- NN+ 9,00 m.

However, the reliability of the design parameters are continuously being checked, as due to climate change or changes in the landuse, the current practices and flood proteciotn strategies might be inappropriate for the furture conditions.

In order to assess the hydrodynamic effects on the Low Elbe in case of storm surges, the present situation with the current flood protection infrastrcuture has been incorporated into the 2D HDN model of the Elbe estuary (see D6.2, D4.1). Storm surges hydrographs derived in WP2 or measured storm surges hydrographs (e.g. Xaver in 2013) are used as hydrodynamic boundary conditions.

A preliminary assessment of the historic situation, without the continuous dike line along the Elbe estuary assuming the storm surge event “Xaver”, showed on the one hand, that the water level at the gauge Hamburg St. Pauli are significantly lower compared to the recent situation (Figure 50).

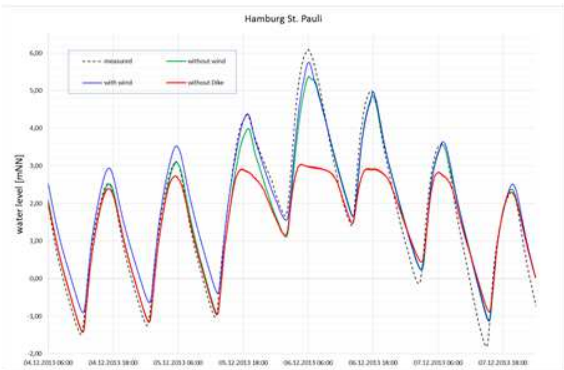


Figure 50: Comparison of the water levels at the gauge Hamburg St. Pauli for the historic situation without a continuous dike line (red line) and the recent situation and additional flood protection infrastructure (black dashed line)

On the other, the water levels along the Low Elbe during a storm surge event (e.g. Xaver) are higher than the average terrain elevation of the hinterland (Figure 51) resulting in large inundated areas.

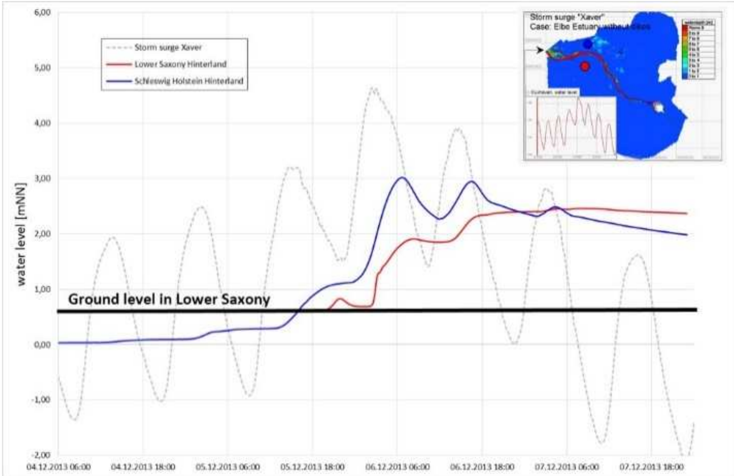


Figure 51: Comparison of the water levels at two randomly selected points in the hinterland of the Elbe estuary (dark blue – Schleswig-Holstein, red – Lower Saxony) with the water levels of the storm surge Xaver.

These preliminary results illustrate advantages and disandvantages of the recent flood protection infrastructure along the Elbe estuary. Protection of low lying hinterland areas in Schleswig-Holstein and Lower Saxony against large scale inundations is beneficial (see Figure 51). However, the high level flood protection infrastructure along the Elbe river leads to higher storm surge water levels in the Hamburg city area (see Figure 50), due to missing space for the river in case of high water levels in the river.

Therefore, appropriate adaptation measures have to be developed (see Table 15).

Witihn PEARL, the alternative or complementary measures and strategies, including the Nature Based Solutions (NBS) have been studies and their potential to mitigate the flood hazard and risk analysed.

Those strategies are summaried in Table 15.

Table 15: Adaptation measure assessed with respect to their effect on an enhanced flood protection

Catalogue of adaptation measures					
Type of adaptation measure	**Adaptation Measure**		**Description**		**Status**
Static	**M1**	**Narrowing of the cross section**	M101	90% Narrowing near Brunsbüttel	In Progress
			M102	60% Narrowing near Brunsbüttel	In Progress
			M103	75% Narrowing near Brunsbüttel	In Progress
	M2	**Re-aligment of dikes**	M201	100m	In Progress
			M202	250m	In Progress
			M203	500m	In Progress
			M204	750m	In Progress
			M20X	>750m	In Progress
Dynamic	**M3**	**Flood protection polder**	M301	Location/Size A	
			M30X	Location/Size B	
	M4	**Elbe flood barrier**	M401	Closing time A	
			M40X	Closiing time B	
	M5	**Integration of old tributaries**	M501	Historical conditions (1930)	In Progress
			M502	Wischhafener Süderelbe	
			M503	Haseldorfer Binnenelbe	
			M504	Borsteler Binnenelbe	
			M505	Alte Süderelbe	
			M506	Dove-Elbe	
			M507	all	
	M6	**Integration of tributaries**	M601	Oste	
			M602	Stör	
			M603	Krückau	
			M604	Pinnau	
			M605	Schwinge	
			M606	Lühe	
			M607	Este	
			M608	all	

Re-alignment of the continuous dike line by 250 m and 500 m have been investigated (Figure 52) until the due date of the deliverable. The preliminary results shows that a re-alignment of the dikes lead to a decrease of the water levels (Figure 53).

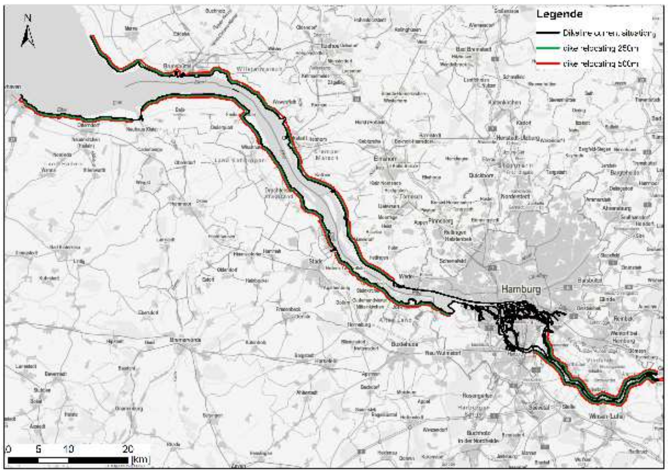


Figure 52: Investigated re-alignment scenarios i) 250 m – green line, ii) 500 m – red line

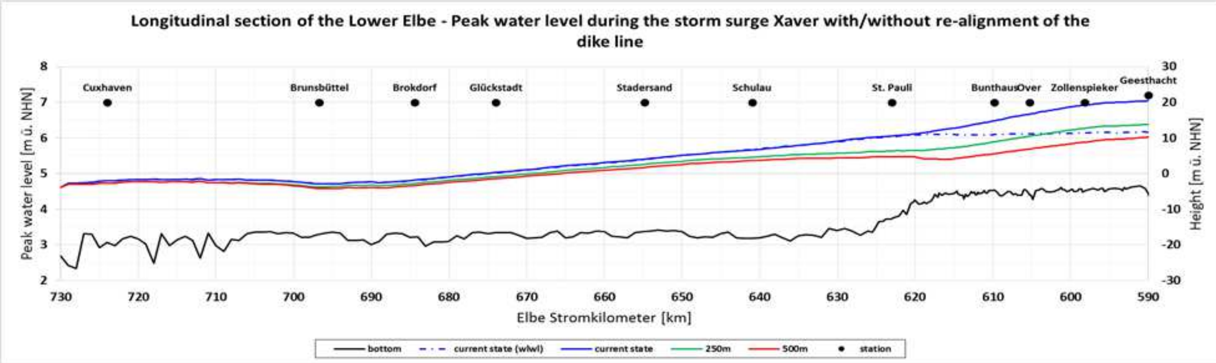


Figure 53: Longitudinal section of the Lower Elbe showing the peak water levels during the storm surge Xaver 2013

Further analysis of the strategies will be further performed and discussed and reassessed togehter with the key stakeholders within the LAA process in the following reporting period.

3.3 Additional research activities and results

3.3.1 WP1- Understanding formation of vulnerabilities and risk in coastal regions

In order to assess the risk formation over time, giving it a historic perspective a FORIN desk study is performed.

Taking into account the results from the stakeholder analysis of the present flood risk management, a historical analysis of the roles and decisions of the key stakeholders have been performed based on the desk study and semi structured interviews with the selected key stekeholders.

The preliminary results are visualised in Figure 54.

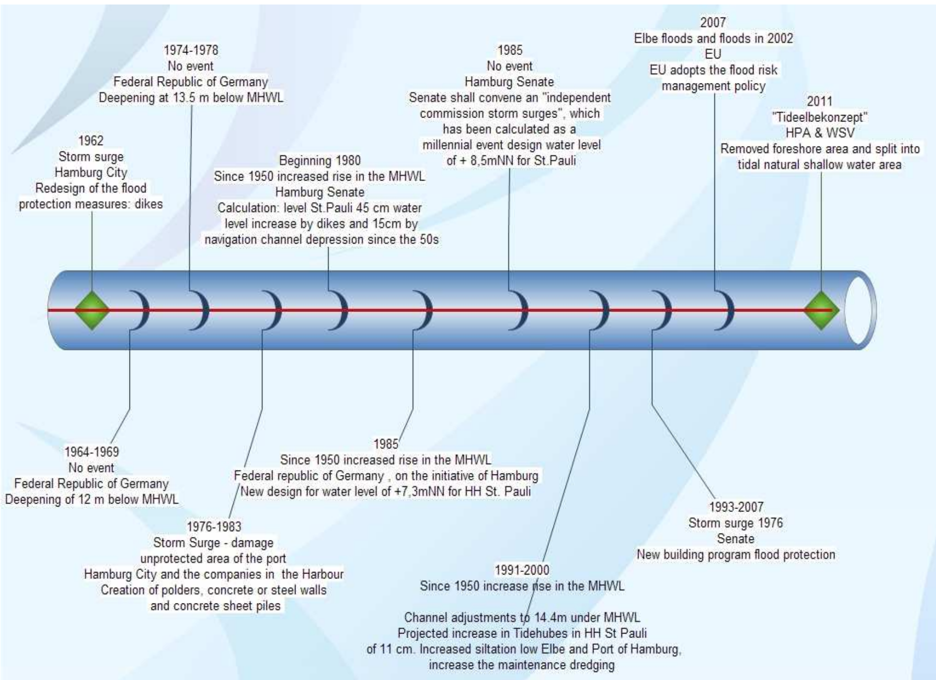


Figure 54 Actor time line for the stakeholders of Elbe Estuary

Further, in order to be able to give a holistic perspective of the measures implemented and the decision makers a causal loop diagram has been created (Figure 55). Each of the causes, in this case the trigger events have been represented in a rectangle, which is connected through a thick arrow to the measure adopted. The measures have been written in bold. The decision makers have been indicated in a round shape and are connected to the measures through a blue dash arrow. The effect has been suggested through a dash arrow and derives from the measure. The events have been illustrated in a chronological order. Each arrow has been assigned with a positive or negative sign based on the link between the elements. The figure considered the main cause of floods the water level rise since 1950, which constitutes the trigger factor for the following events. The most significant flood event has been considered the storm surge from 1962, which is connected to the water level rise. It is considered to have a positive sign, due to the fact that both have a negative impact. The measures adopted have been the redesign of the flood protection by heightening the dikes, which it has negative sign because the two items are moving in a opposite direction. It is considered that the storm surge produces a negative impact, while the measures, in this case the dikes generate a positive impact, by reducing the future floods. Further on, the measure is connected to the effect, which has a positive sign due to the reduction of the flood event from 1976. The effect can be connected to the storm surge and it has a negative sign. The measures have been implemented by Hamburg City and it is considered to have a positive sign. To this event, later over the years have been implemented other two measures.

Some of the measures have been adopted between the years 1980-2000 as consequences of the water level rise from 1950. All these measures have negative signs that suggests an opposition of the impacts reflected by each items. The measures effects are considered to have a positive sign as both have the goal the reduction of flood risks in the future.

By analysing the causal loop it can be seen that the main actors involved have been: Hamburg City and Hamburg Senate (included as Political body represented at the local authority), Federal Republic of Germany, Companies in Harbour (considered to be private stakeholders), HPA and WSV, EU. The decision makers have been assigned with a positive sign, due to the fact that they are considered to move in the same direction with the measures.

In the next step, a more detailed analysis of the processes, actors, consequences based on the desk study and further interviews where required, will be performed and will directly feed into the holistic risk assessment.

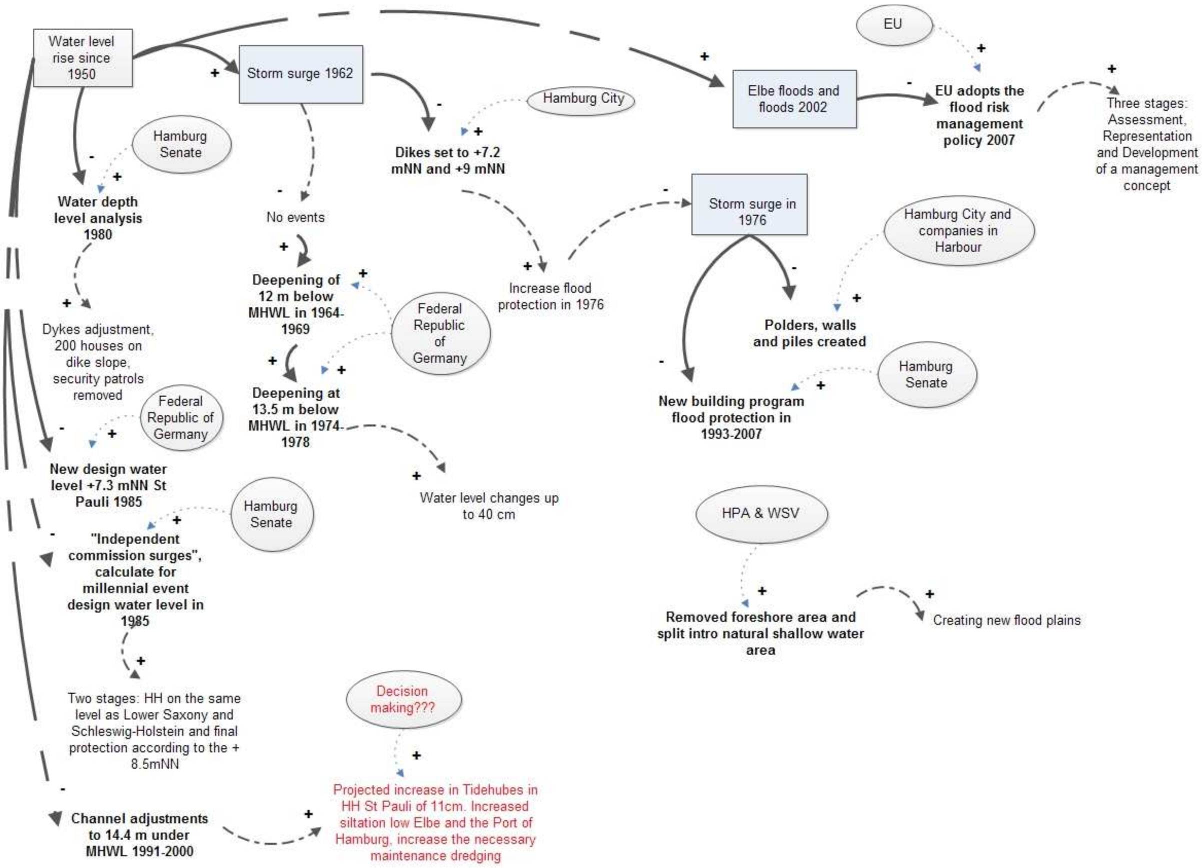


Figure 55 Stakeholders and measures illustrated through causal loop

3.4 Summary and lessons learned

Researc activities for the Hamburg/Elbe estuary are focussed on the WP 2, WP3 and WP4. Within WP2 hydro-meteorological loads (e.g. storm surge water levels, precipitation, river run-off), relevant for the case study area have been analysed. Scenarios for exreme events, individual events and combinations of events, as input for risk assessment approaches in WP3 have been defined. To be able to model extreme events individually and in coincedence a 2D hydrodynamic numerical model of the Elbe estuary has bee set-up. The 2D-HDN model is the basis for the risk assessment activities in WP3 and the water level forecast system developed in WP4. Impact and risk assessment investigations (WP3) are carried out for the built environment, public and private transportation sector and the seaport, as part of the superordinate supra-regional transportation system. Preliminary results on the impact of extreme events have been gained using different approaches. Considering the island of Wilhemsburg for the assessment of flood impact to the built environment, enable one to assess the development of the flood risk over time. Research results from previous projects (FP7 Project CORFU, BMBF project XtremRisK) have been the basis for the comparison of the flood risk. In the scope of the WP4, which deals with flood forecasting and early warning system for coastal regions, a water level forecast systems for the Elbe estuary have been developed, based on the 2D-HDN model, adapted to the special purpose of water level forecasting. Water level forecast data from the Federal Maritime and Hydrographic Agency (BSH) are assimilated to the hydrodynamic model aiming at the transformation of the pointwise data into a spatial forecast of the water level. At the present level of development, water levels are forecasted twice per hour for a forecast period of 18 hours. Results of the forecast runs are presented on a website (http://pearl.wb.tu-harburg.de/forecast/). An evacuation model for Wilhelmsburg has been developed as well, which has been used to develop the overall evacuation concept for Wilhelmsburg. The key element of the evacuation concept, being the pedestrian evacuation, a prototype model has been set-up. A spatially continuous force-based model is the basis for simulating pedestrian dynamics, taking into account the interaction between pedestrians themselves, their respective relative velocities and pedestrians and obstacles. Building stock of Wilhelmsburg, population data and the distribution of collecting points/refuges, representing the targets for the pedestrians, are used as input parameters for the pedestrian evacuation model. The pedestrian evacuation model simulates the arrival times of the pedestrians at the collecting points/refuges. The arrival times are used as input data for further evacuation processes (e.g. evacuation by bus, train or private cars). Related to WP5, the Elbe estuary area as PEARL case study implements the PEARL LAA methodological framework. But, due to the specific features of the stakeholder involvement in the area, the local culture and the level of risk awareness, the overall concept has been adjusted to suit the local needs. Stakeholder involvement takes place in a tailored approach by conducting face-to-face meeting instead of comprehensive LAAs or stakeholder workshops. Within WP5 the effect of different adaptation measures along the Elbe estuary. Amongst others, nature-based solutions (e.g. re-alignment of dikes, reactivation of old tributaries, polders), narrowing of river cross section and flood barriers at the mouth of the estuary are assessed. Preliminary results are available. Furthermore, the flood resilience index for the city of Hamburg was assessed, showing that Hamburg is rather well prepared.

In WP1 the research work has been performed although initially not stated in the DoW. Here, the initial causal-loop diagrams have been developed based on the desk study and punctual semi-structured interviews with the key stakeholders. This work will be further developed in the following reporting period and will directly feed into the holistic risk assessment.

Lessons learned

Several extreme events hit the Elbe estuary and the city of Hamburg in the past (e.g. 1962, 1976). The devestating storm surge event in 1962 gave the authorities and the public a reality check. The awarness for extreme hydro-meteorological events and their adverce impact rose and responsible stakeholders (authorities) and the public have been sensitized over the years. Intensive engagement of the stakeholders in previous initiatives and participatory planning actions undertaken in several national and international projects (BMBF KLIMZUG-Nord and XtremRisK projects or FP7 Project CORFU) related to climate change and flood took place over the years, which has, as a consequence, higher awareness for the relevance of the issue. At the same time fatigue towards such stakeholder engagement activities arrived. Therefore, engagement of the key stakeholder must be tailored to their specific needs and interest, resulting in an adjusted LAA approach, being (regular) face-to-face meetings. Furthermore, key stakeholders are actively involved in the design and development of the PEARL methods and tools. The water level forecast system developed in WP4 is an example (collaboration with the BSH).

In the aftermath of the events in 1962 and 1976 flood protection infrastructure has been redesigned and constantly improved over the last decades, being now at a rather advanced level. But nevertheless, there is the awareness of flood protection as a permanent task.

4 Case Study – Les Boucholeurs, France

4.1 Introduction to the case study area

4.1.1 General description of the case study area

The two cities of the Charente-Maritime department, “Les Boucholeurs” is a district of Châtelaillon-Plage located on the limit of Yves (Figure 56). District count approximately 600 houses and have an important activity in oyster and mussel farming.

Figure 56: Initial case study area Les Boucholeurs, Chantellailon-Plage, France

The Atlantic coast is threatened by storm surges and potentially by the sea level rise. Those events could contribute to the failure mechanisms of the embankments and could generate some important water level on the rear part of this area, which is lower that the coast line itself.

This was the case on 27th-28th February 2010, when Xynthia Storm reaches the French Atlantic coast. The Charente-Maritime department was highly affected by this events which generated € 1,4 billions of damages and 53 fatalities in France (2 on the site “Les Boucholeurs”). After this event, in the hurry, the place “Les Boucholeurs” was designed as one of the main“Black Area” where all the houses should be destroyed. This impacted local community a lot due to their farming activities and living places.

Further discussions as well as strong participation of local stakeholders changed the marking “Black Area” into “Orange or Yellow Area”. Currently the new strategy for this area is created. This relates to reconstruction on the embankment system. After this event, a large plan of protection measures was launched with some structural works: creation of breakwater, reinforcement of dikes, etc.

At the beginning of the project, the protection plan is ongoing but not all the protection measures were achieved.

One of the main challenges of the project is to help stakeholders to quantify the effects of the protection plan and allow some preliminary reflexions about the future measures which could be interesting to implement in the future to increase the resilience of the city. IN addition the case study area is enlarged to the whole city Châtelaillon-Plage

4.1.2 Hazard and risk situation in the case study area

The rare extreme event Xynthia occurred in early morning of 28th February 2010 as a result of atmospheric depression created on 27th February morning. This storm hint west coast of France causing large-scale floods with huge damages. Beside France, the storm hint Germany and the Benelux countries. In total 65 people died.

Described as an explosive storm with the depression of 20hpa in more than 24h, Xynthia went through the country very fast. Based on the meteorological parameters (atmospheric pressure Xynthia has not reached the exceptional storms Lothar and Martin in December 1999, neither Klaus in January 2009. Even so, the effect of Xynthia on flooding and erosion is significant, especially in the departement Vandee and Charente-Maritime.

Meteorological characteristics of the storm show that the wind gust speed of Xynthia was 242 km/h at the Pic du Midi d'Ossau in the Pyrenees and in the Charente Maritime at 140 km/h.

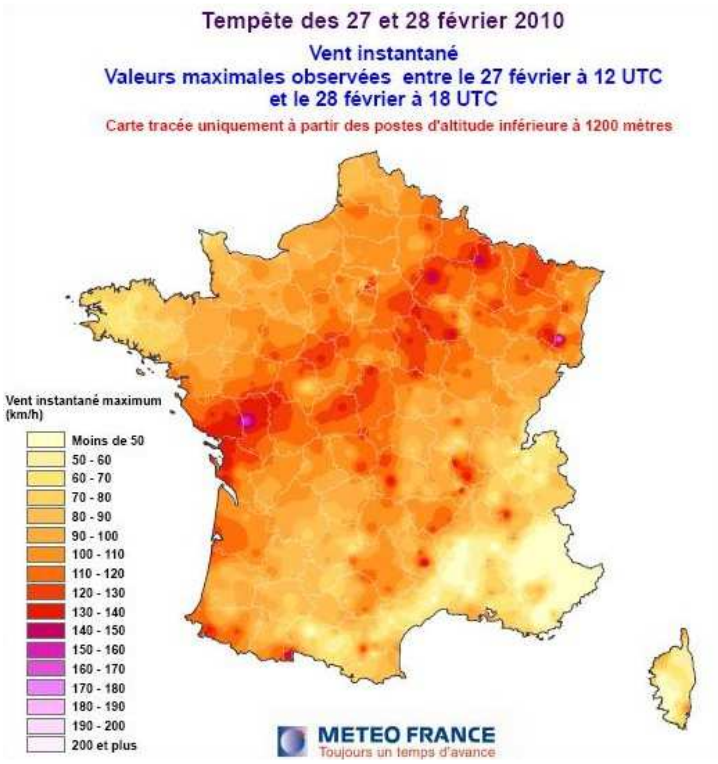


Figure 57: Maximal wind speed during the storm Xynthia (Source: Meteo France)

Figure *57* shows the maximal wind speeds during the storm Xynthia over France. The location of case study area is marked in the figure. The recorded wind speed relevant for case study is in the range from 120 km/h to 130 km/h. Excluding wind effect the tides created show significant values in heights. According to the BRGM (Bureau de Recherches Géologiques et Minières) the

measured level of 4.5 m NGF (General Levelling in France) recorded at la Rochelle (northern of case study area) correspond to the very high return period. Up to this moment there is no official statement regarding calculated or estimated return period of this storm. The major threat for the affected area was storm surge and big waves. The storm surge was 1.6 m and the tide approximately 2.75 m.

4.1.3 Current institutional and governance practice

Flood risk management planning in France shares responsibility from national to local level through different laws, plans and policies all in line with Water Framework Directive (WFD) and Flood Directive (FD) (Table 16). The implementation of Flood Directive (EU 2007) is started long before Xynthia event, but after this and similar events the revision of national strategy and policies related to flood risk management is done.

After Xynthia the national plans: PSR and PAPI are created and adopted by Government on february, 2011. Plan PSR or « fast submersions plan » is created after dreadfull consequences of storm Xynthia (41 dead) and flash flood in Draguignan (25 dead). The main objectives of this plan is to impulse actions to reduce the risks for human life in areas in danger of sea submersion, flash floods or levees failures, to anticipate the national strategy and to select operational projects to secure the population in low areas and to have an owner with the technical and financial skills for each dike. Plan also has four main directions: (i) Vulnerability reduction in flood exposed lands, (ii) Improving weather forecast, the observing, warning and alert system, (iii) Reinforcement of dikes, levees, seawalls and other protective systems, and (iv) culture of the risk.

Second plan, PAPI (Actions Programs for Flood Prevention) created for local projects. Actions defined in the plan are mainly under contract between the State and local authorities in order to reduce the damage connected to the floods. Of course this plan is in line with existing strategy and balanced actions, and with a coherence with the national and basin policy.

Table 16: Vertical scale for risk minimizing, France flood risk management as example

LEVEL	FLOOD MANAGEMENT
European	POLICY Flood risk management: Flood prevention, protection and mitigation Trans European Networks (TEN) (http://www.unece.org/) LAW Water Framework Directive (WFD) (http://ec.europa.eu) OTHER PLANNING INSTRUMENTS ICPR (IKSR) (http://www.iksr.org)

LEVEL	FLOOD MANAGEMENT
National	LAW Law on Natural Disasters (Loi relative aux catastrophes naturelles), (http://www.legifrance.gouv.fr) Law on Security, protection of forests against fire and prevention of major risks, (Loi relative à la sécurité, à la protection de la forêt contre l'incendie et à la prevention des risques majeurs), (http://www.legifrance.gouv.fr) Water Policy, (Loi sur l'eau), (http://legifrance.gouv.fr) Law on the prevention of natural and technological hazards, (Loi relative à la prévention des risqué naturels et technologiques), (http://www.legifrance.gouv.fr) Legislation transposing the Water Framework Directive (WFD), (Loi portant transposition de la directive cadre sur l'eau (WFD)), (http://www.legifrance.gouv.fr)
Regional	POLICY Master Plan development and Water management SDAGE/SAGE (Schéma Directeur d'Aménagement et de gestion de l'eau SDAGE / SAGE), (http://www.eaufrance.fr) Flood zone Atlas (Atlas des zones inondables), (http://www.rdbrmc-travaux.com) Management and Flood prevention Plans (Plan d'Aménagement et de Prévention des Inondations (PAPI)), (http://www.driee.ile-de-france.developpement-durable.gouv.fr)
Department	POLICY Plan for prevention of foreseeable natural risks of inundation (Plan de prevention des risqué naturels previsibles d'inundation PPRI) (http://www.alpes-maritimes.equipement-agriculture.gouv.fr)
Inter-municipal	POLICY River contract (Contrat de rivières), (http://www.eaufrance.fr)
Municipal	POLICY Local Development Plan (Plan local d'urbanisme, PLU), (http://www.chatelaillonplage.fr/)

4.1.4 Available data used for research activities

Data used for vulnerability assessment is taken from National Institute for Statistics and Economy studies (INSEE). While creating the framework for vulnerability the data availability is crucial. The framework for vulnerability is defined in order to have vulnerability mapping in Esri software. Based on available information about buildings following attributes are available:

- Building type - urban function
- Building height

Xynthia modelling is done using TELEMAC software. For this case study, the initial situation is the situation before Xynthia event. The main data collected to build the coastal flooding model are:

- The bathymetry of the Atlantic coast taken from some existing models in this area
- The topography of the landside comes from a LIDAR survey made
- The dike profile along the coast line

- The location of breaches during the Xynthia event.

Artelia use the modelling tools TELEMAC-2D and TOMAWAC to study the coastal submersions.

TOMAWAC, software which belongs to the TELEMAC chain, calculates the swell, the waves resulting in a sea level overvalue

TELEMAC-2D is a two dimensional hydrodynamic model which solves the Shallow Water Equations (also named Saint-Venant equations) with the Finite Element Method (FEM) or the Finite Volume Method (FVM). A computation mesh (not necessarily uniform) of triangular elements allows the refinement on the sensitive area of the study in order to obtain more precise results. TELEMAC-2D is applied for river and maritime hydraulics.

Moreover, several phenomena can be simulated with this software such as: the propagation of long waves, taking into account non-linear effects, the influence of Coriolis force, of meteorological factors: atmospheric pressure and wind, turbulence, dry areas in the computational domain: intertidal flats and flood plains, treatment of singular points: sills, dikes, pipes, …..

TELEMAC can handle the modelling from few square kilometres (very local and local scale) to several square kilometres (regional scale).

The model of coastal submersion simulation is built on a grid and the calculation is done on every points of the mesh. At a regional scale the aim is to see if the coast will be submerged and the global impacts. Then, there is no need to implement in the model all the complexities of the reality such as buildings.

The following figure represents the mesh used for the Xynthia simulation. The cell size depends on the details wanted in the results. Thus, the number of calculation points increases in city localization.

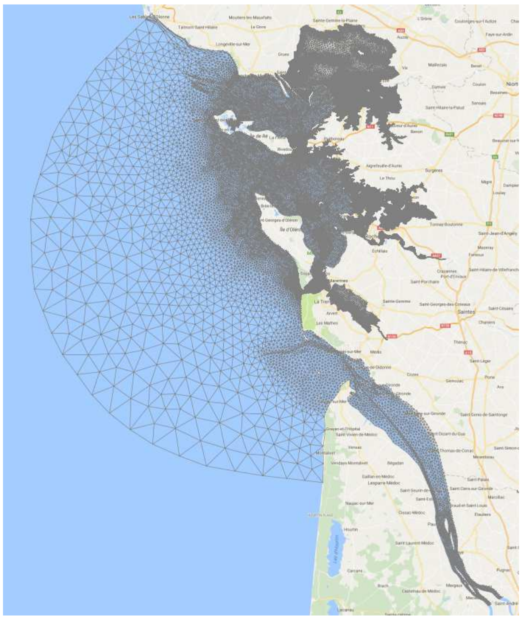


Figure 58: Developed mash for simulation of Xynthia event, Chantellailon-Plage, France

However, the change in scale in the model will influence the mesh. Indeed, if the studied area is focused on a very local part (e.g. Les Boucholeurs) as in the following figure, it becomes important to take into account all the infrastructures such as roads, culverts, buildings etc. to recreate

realistic flows. Thus, the calculation around these elements needs to be more precise. It is conveyed by more points of calculation carefully placed in these areas.

Figure 59: Developed mash over the infrastructure and roads, for Xynthia event, Chantellailon-Plage, France

The calibration and validation event on this area is the Xynthia storm. This is the most important recent event here. In 1999, another large storm event reached France but due to a different wind direction, the most impacted area was located on the Gironde estuary.

The following figures present comparison at the tide gauges of La Rochelle - La Pallice, Rochefort, Le Verdon, La Cotinière and Royan, between the records during this storm and the results of model integrating the astronomical tide and the influences of the surge offshore, the wind and the swell. The theoretical tidal obtained with the 2D on the same period model is also draw to illustrate the importance of surges generated at the coast for the hydro meteorological parameters associated with this storm.

It appears from the analysis of these charts the following remarks:

- The evolution of water observed in tide of La Rochelle - La Pallice is very well represented by the model. There is a slight shift in the flow before the peak of the event,
- The model underestimated the level of the peak to the tide of Rochefort. The phase observed for the tide is similar to that observed for the astronomical tide,
- The tide gauge of Le Verdon is not exploitable for the peak of the Xynthia event. The exploitable period of the registration shows the good representation of the evolution of the water for the model,
- For the tide of La Cotinière model underestimated about 25 cm the maximum water level observed in the storm Xynthia. A temporal shift is also observed for this tide,
- Data of Royan tide gauge is not consistent with data of Le Verdon, despite a near location on banks of the Gironde estuary.

Despite the low number of exploitable data, the model allows to precisely represent the maximum water level measured at the tide of La Rochelle - La Pallice. Outside the main study area, the model correctly represents the evolution of the water level, without offering such high level of precision.

On the study area, the model represents accurately the influence of the hydro meteorological parameters on the evolution of the water level (on maritime side).

4.2 Key research activities and results

The research activities for Chantellailon-Plage case study focuses on holistic risk assessment and flood resilience evaluation. Therefore, the activities were mainly on WP3 and WP5. The general objective after data collection and modelling phase was to focus on flood risk management with final goal to provide usable forms for communication with key stakeholders. The analysis and general definition of frameworks for vulnerability, risk and resilience needed to be applied within Arc GIS.

4.2.1 WP3- Holistic and Multiple Risk Assessment

Research activities are focused on vulnerability and risk mapping. However, the additional requirement was to have availability to map both risk and vulnerability. The framework developed for vulnerability takes into account *population vulnerability, socio-economic vulnerability and vulnerability of build environment*. This was chosen in order to have possibility to have spatial representation of results. Each vulnerability parameter has associated impact element.

Impact elements taken into account for population vulnerability (PV) are:

- PV_1 - population density,
- PV_2 - number of children, senior citizens, invalids,
- PV_3 - gender and
- PV_4 - mean income

Based on requirement we obtained data from INSEE in the form of tables. For this analysis impact elements or weights are defined arbitrary. Calculation of population vulnerability based on available data is done using relation below.

$PV = \omega_1 PV_1 + \omega_2 PV_2 + \omega_3 PV_3 + \omega_4 PV_4$	*Eq. 4*

Where values for the weights are:

- w_1=0.25
- w_2=0.15
- w_3=0.25
- w_4=0.35

Calculated value for population vulnerability is 3.8. Since we did not used population data available for each building this value will be assigned to overall vulnerability.

Socioeconomic vulnerability focuses on direct damages mainly. The indirect damages are left from analysis due to the fact that the mapping is not possible. For earlier classified land use the different vulnerability levels (from 1 to 5) are associated for each building. The table below represents the different vulnerability levels associated with different land use in the case study area.

Table 17: Assigned vulnerability levels for urban function mapped for case study

Urban functions		Vulnerability level
1	Housing	5
2	Education	4
3	Food	4
4	Working	5
5	Safety	5
6	Leisure	2
7	Religion	2
8	Health	5
9	transportation	4
10	railway	3
11	mixte	5

The mapping done within Arc GIS is presented in the figure below.

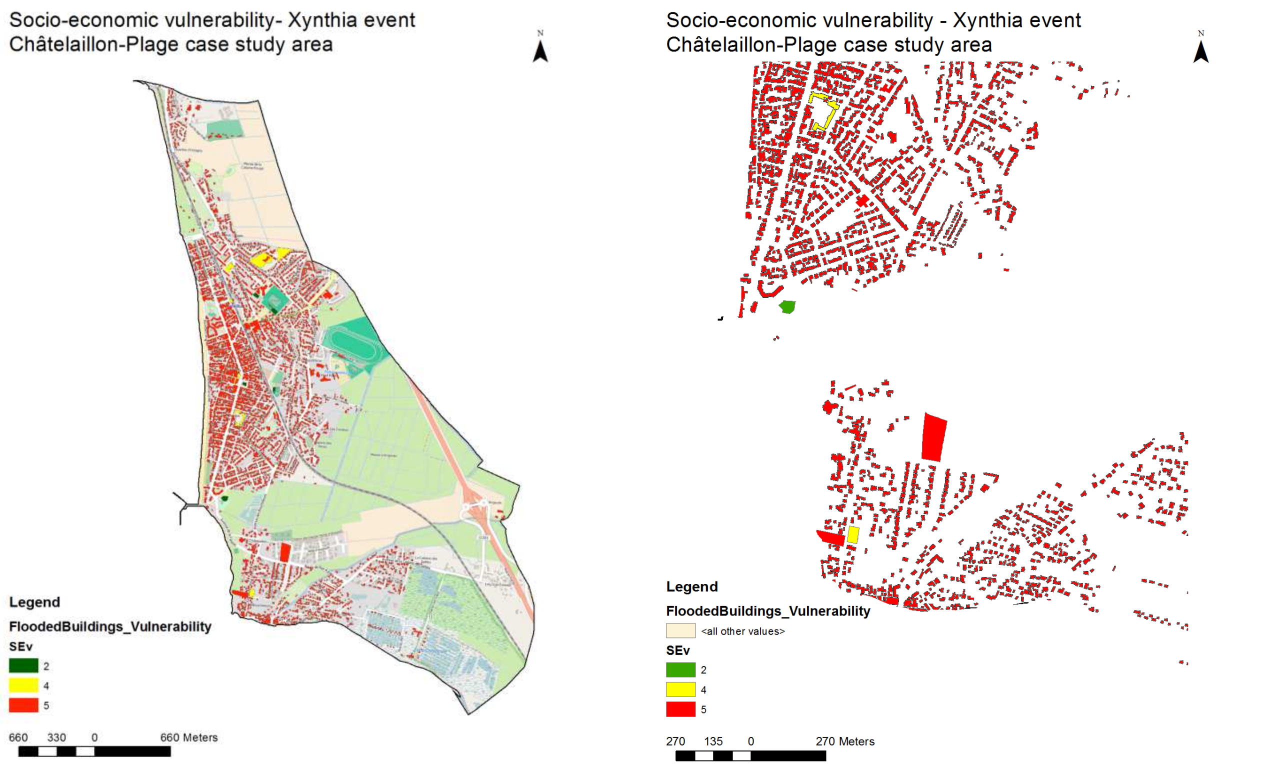


Figure 60: Socio-economic vulnerability mapped, for Xynthia event, Chantellailon-Plage, France (picture left whole area and picture right zoomed part)

Overall vulnerability is presented with the relation below:

$V = PV + SE$	*Eq. 5*

Following this the vulnerability is calculated for each building in the case study area. The maps below show vulnerability mapping for the Xynthia event in Chantellailon-Plage.

$V = \frac{V_p + V_{SE}}{2}$	*Eq. 6*

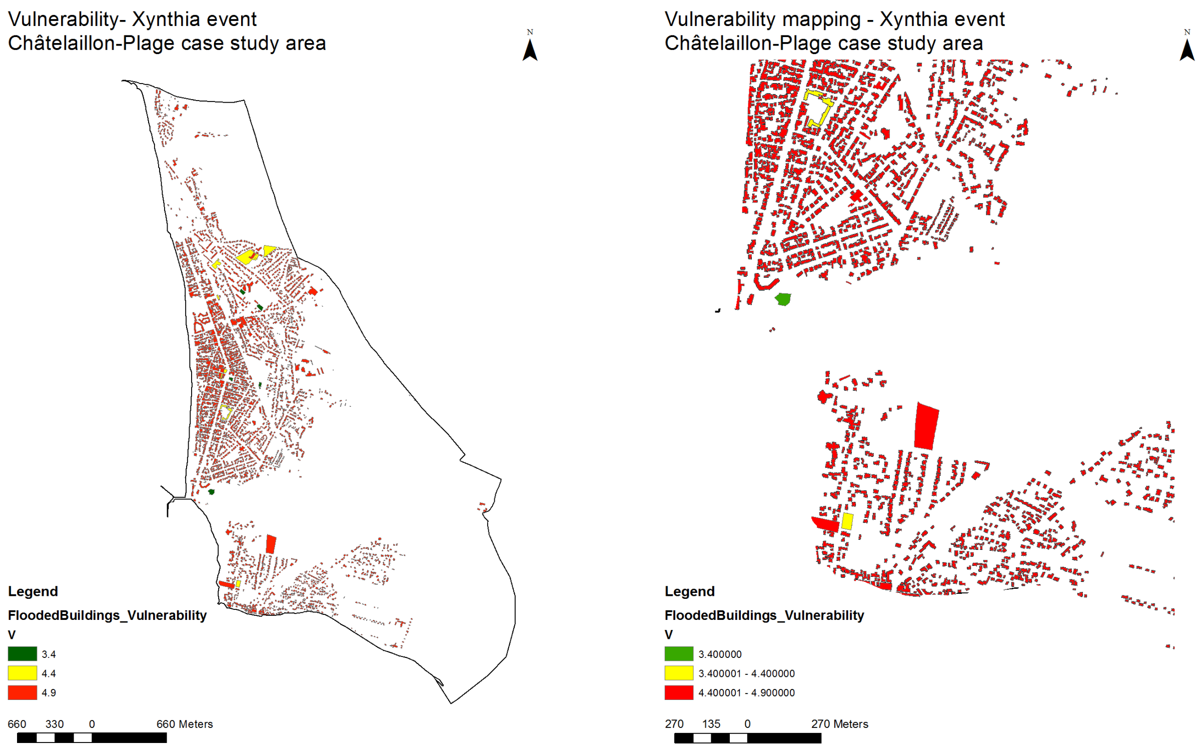


Figure 61: Vulnerability mapping for Xynthia event, Chantellailon-Plage, France (picture left whole area and picture right zoomed part)

Risk evaluation takes into account vulnerability, exposure and hazard. For hazard mapping the existing flood depths are classified and using ArcGis for each building object the unique flood depth is associated. By doing this the calculation of risk level for each building object is possible. In the figure below the different flood depths inside each flooded object is presented.

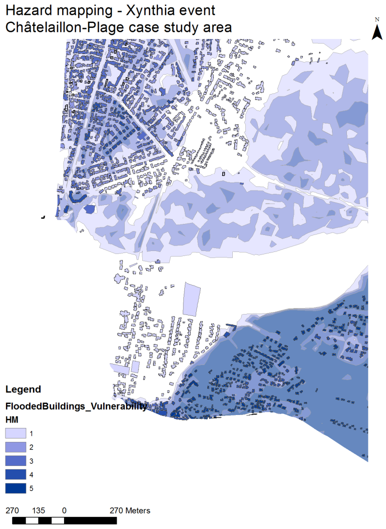


Figure 62: Hazard mapping (zoning) for Xynthia event, Chantellailon-Plage, France

Further, numeric value of risk is calculated as a product between vulnerability and hazard and divided by five.

$R = \frac{V \times HM}{5}$	*Eq. 7*

R is representing risk with the value range from 1 to 5 where 5 is high risk and value 1 is low risk.

Figure 63: Risk map of case s udy area for Xynthia event, Chantellailon-Plage, France

In addition the direct damages are calculated for each building with respect to existing hazard mapping. Based on available data the following parameters are needed.

- calculated area for each building
- flooded building classified
- depth damage curves

Flooded building are classified in GIS software are presented as layer. Depth damage curves are used from CORFU project. These curves are developed based on research with respect to different depth and different urban functions. Depth damage curves (Table 24) are also adapted to the rearranged land use. Since the land use is represented through different urban functions, therefore the created depth-damage functions are following the same procedure.

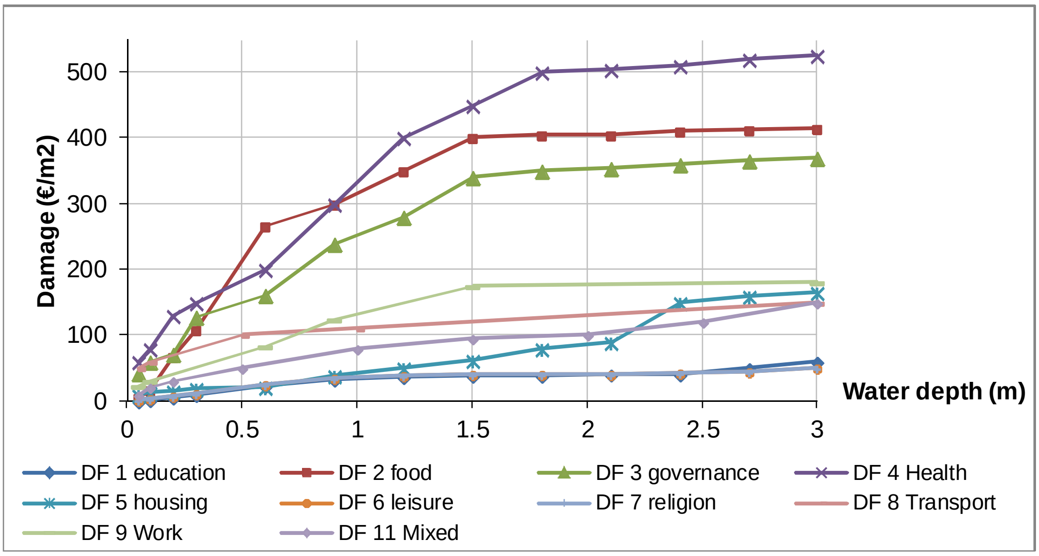


Figure 64: DDC applied for direct damage assessment for Xynthia event, Chantellailon-Plage, France

Direct damages are calculated in GIS evaluating the damage expressed in Euros per building. Three scenarios are applied for different flood maps.

Table 18: Different scenarios for direct damage assessment for Xynthia event, Chantellailon-Plage, France

Scenario 1	Xynthia	Xynthia	event
Scenario 2	X20_2016_ssBreches_classesH	Xynthia + 20cm	just overtopping possible
Scenario 3	X20_2016_PPR_classesH	Xynthia + 20cm (PPR)	with braches based on the rulles within PPR

Based on the calculations following results show that for scenario 1 1346 buildings are flooded with total direct damage of €14,974,616.91.

Table 19: Direct damages for Scenario 1

Urban Function	Number	Total Damage (Euro)
Education	2	€ 60,567.44
Food	3	€ 705,871.11
Governance	1	€ 36,293.48
Health	0	€ -
Housing	1315	€ 12,948,886.09
Leisure	2	€ 45,647.40
Religion	0	€ -
Transport	0	€ -
Working	9	€ 257,268.28
Mixed	14	€ 920,083.11

Sum	1346	€ 14,974,616.91

For scenario 2 1553 buildings are flooded with total direct damage of €10,693,836.89.

Table 20: Direct damages for Scenario 2

UF	Number	Total Damage (Euro)
Education	2	€ 60,567.44
Food	2	€ 453,626.34
Governance	1	€ 36,293.48
Health	0	€ -
Housing	1513	€ 8,789,795.58
Leisure	2	€ 56,943.22
Religion	1	€ 5,010.28
Transport	1	€ 34,862.60
Working	18	€ 588,899.61
Mixed	13	€ 667,838.35
Sum	1553	€ 10,693,836.89

Within scenario 3 have 1722 flooded buildings with total direct damage of € 21,311,024.79.

Table 21: Direct damage for Scenario 3

UF	Number	Total Damage (Euro)
Education	2	€ 94,941.18
Food	3	€ 705,871.11
Governance	5	€ 317,389.19
Health	0	€ -
Housing	1660	€ 17,795,886.84
Leisure	2	€ 56,943.22
Religion	1	€ 5,010.28
Transport	1	€ 34,862.60
Working	34	€ 1,380,037.26
Mixed	14	€ 920,083.11
Sum	1722	€ 21,311,024.79

Mapping of direct damages for different scenarios is done within GIS.

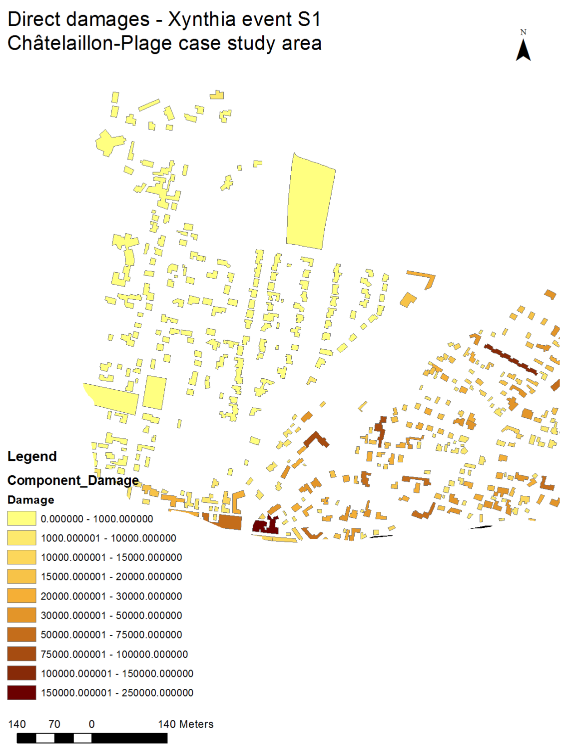


Figure 65: Direct damages mapped for S1, Xynthia event, Chantellailon-Plage, France

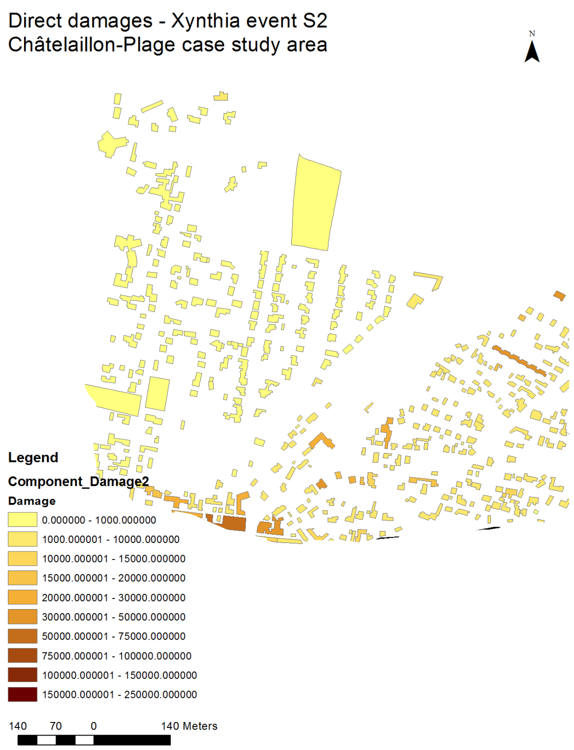


Figure 66: Direct damages mapped for S2, Xynthia event, Chantellailon-Plage, France

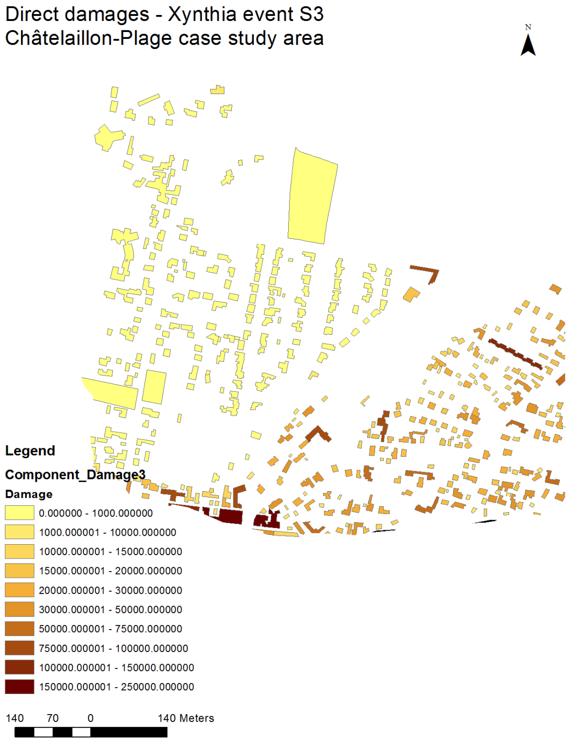


Figure 67: Direct damages mapped for S3, Xynthia event, Chantellailon-Plage, France

4.2.2 WP5- Decision support and policy development for strengthening resilience of coastal regions

The research within WP5 focuses on flood resileince assessment. The defined framework gathers multiscale assement and multidimension assessment. Case study area is analysed as urban system taking ino account different urban functions and services. The importance of these consideration is expalined within deliverable 5.2. The different scales for analysi are defined. based on available data, cases tudy Chantellailon-Plage is analised on three scales: building, block and city (urban scale). Developed framework for flood resilinece gives posibility to have flood resileince mapping for building and block scale. We used the oportunity and mapped cases study area. In the text below the short version of our analysis is presented as well as maps related to floor resileince evaulation.

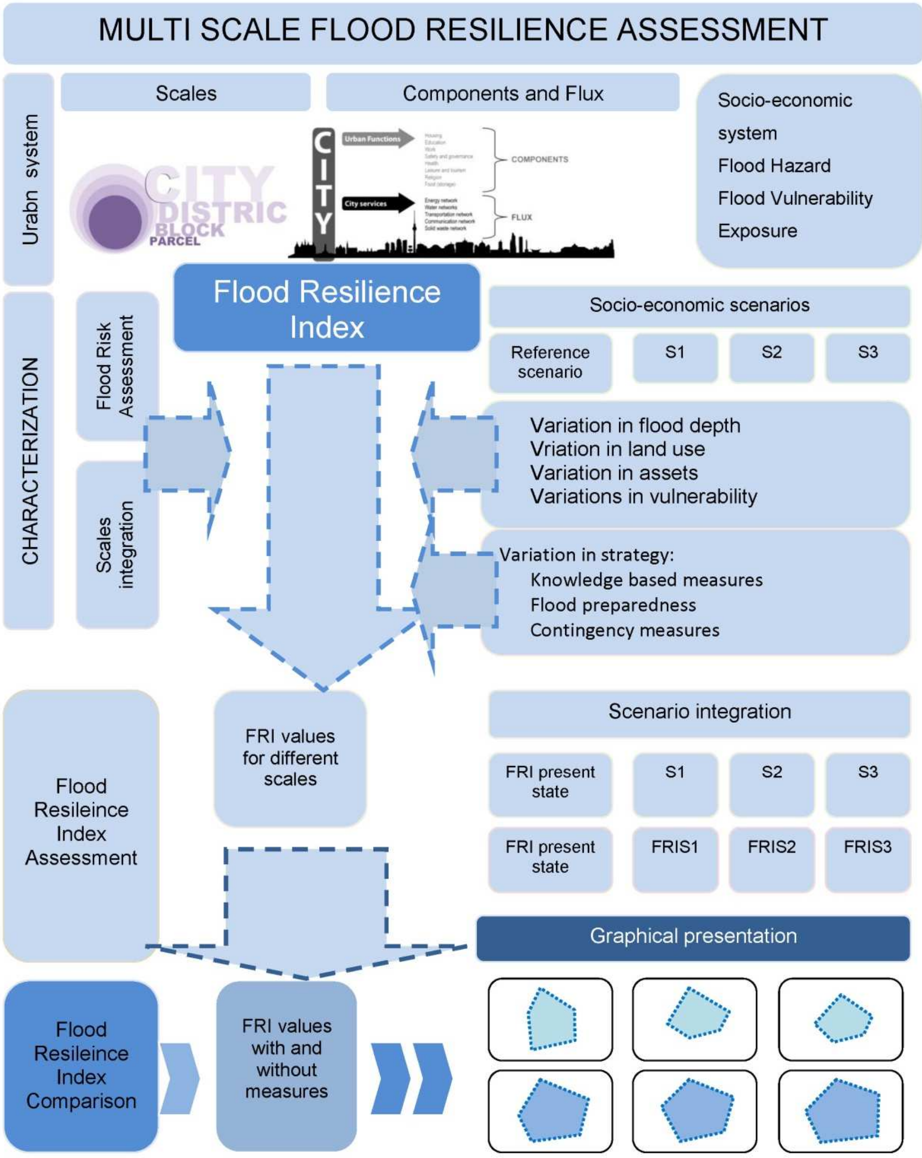
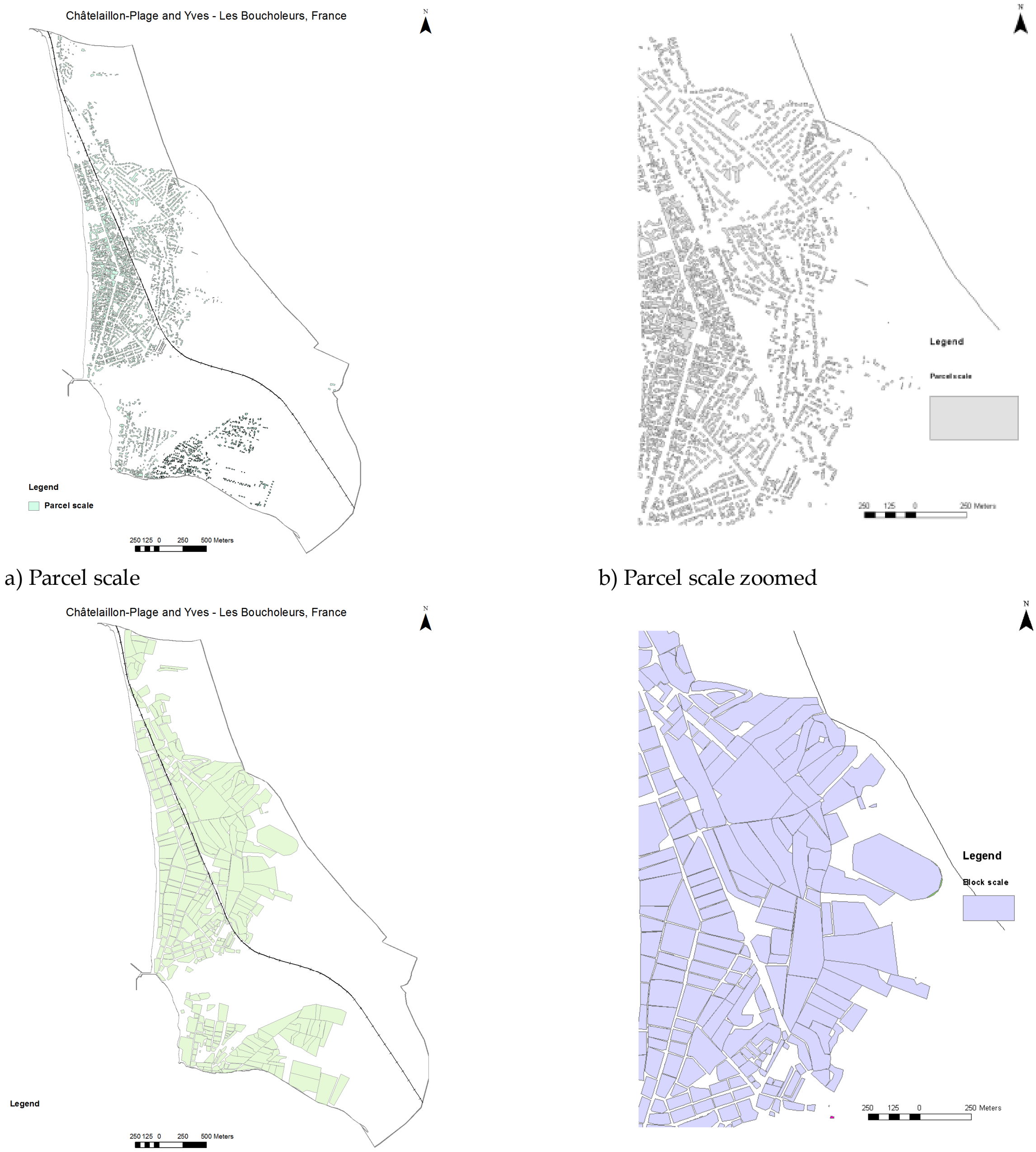


Figure 68: Proposed framework for multi scale flood resilience assessment

A set of data give by our partner ARTELIA have following layers necessary for FRI evaluation:

digital elevation model in resolution of 75m, shape files with information on different buildings, roads, water bodies, channels and a corresponding flood map with extracted minimal and maximal flood depths. A figure below shows the scaling of urban system. In total, there are 2295 objects in parcel scale and 286 block objects. Figure below presents 'decomposition of urban system' with parcel and block scale. As defined the block is presented with set of buildings (parcels) surrounded by street.



a) Parcel scale

b) Parcel scale zoomed

c) Block scale

d) Block scale zoomed

Figure 69: Urban system analysis - scaling of urban system - Chatelaillon-Plage, France

Next step in the flood resilience assessment after setting the scales for analysis and evaluation is mapping of urban systems. Within this step, the existing polygons that represent building with different typology are classified into eight urban functions and five city services. Figure below shows the mapped urban system following the classification of urban functions and city services.

a) Case study area b) Case study zoomed

Figure 70: Urban system analysis - mapping of urban system - Chatelaillon-Plage, France

Characterization

There are three components of flood risk assessment relevant for this analysis: (i) flood hazard, (ii) flood exposure and (iii) flood vulnerability. The system analysis for the France case study considers the type of flooding, its character and spatial distribution of the analyzed event.

In addition to this case study the scales chosen for flood resilience assessment are (i) city/urban (ii) block and (iii) property/building scale.

Nevertheless the data for analysis is divided with respect to different scales. In the figure below the data are separated according to chosen scale. The analysis and evaluation of FRI is supported by software Arc Gis 10.

Table 22: Analyzed data according to the chosen working scales

Data analysis	City/urban scale	Natural	Hydrological system, unsealed areas
		Physical	Hydraulic infrastructure, monitoring and warning systems, drainage system, GIS data
		Social	Awareness programs, knowledge exchange, education, communication, access to financial services, savings & insurance, and budget & subsidies
		Economic	GDP, funding, insurance, financial resources
		Institutional	Building codes, regulations, urban planning, emergency

			planning
	Block scale *based on the dominant urban function	External requirements	Data on energy, water, and waste networks Data on communication and transportation systems
		Internal requirements	Physical on-site inspection
	Property/building scale	External requirements	Data on energy, water, and waste networks Data on communication and transportation systems
		Internal requirements	Physical on-site inspection

Results obtained from analysis parcel scale

Presentation of FRI dynamics can be presented in the form of radar chart. In the figures below the values for FRI of different urban functions for different flood depth are presented.

It can be concluded that the influence on FRI values flooded and non-flooded urban functions is significant.

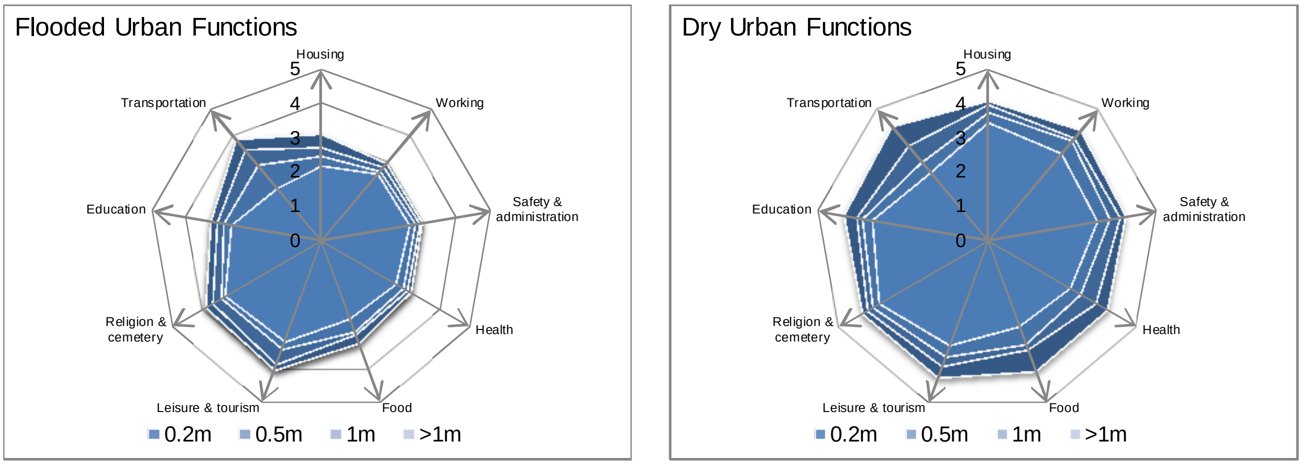


Figure 71: Dynamics of FRI for both flooded and dry urban functions for flood initiated by Xynthia storm-Châtelaillon-Plage, France

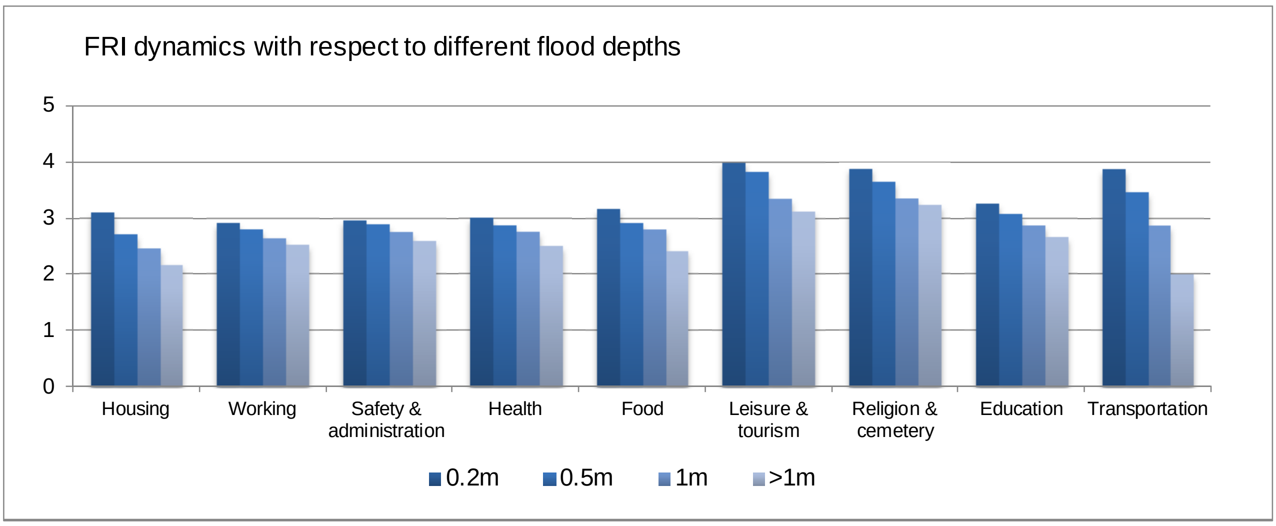


Figure 72: Urban function with decrease values of FRI for different flood depths for flood initiated by Xynthia storm- Châtelaillon-Plage, France

Further, the GIS presentation of preformed evaluation is presented below. The presentation is actually mapping the FRI to urban function for corresponding flood map on parcel scale.

Figure 73: FRI on parcel scale mapped for flood initiated by Xynthia storm- Châtelaillon-Plage, France

Results obtained from analysis block scale

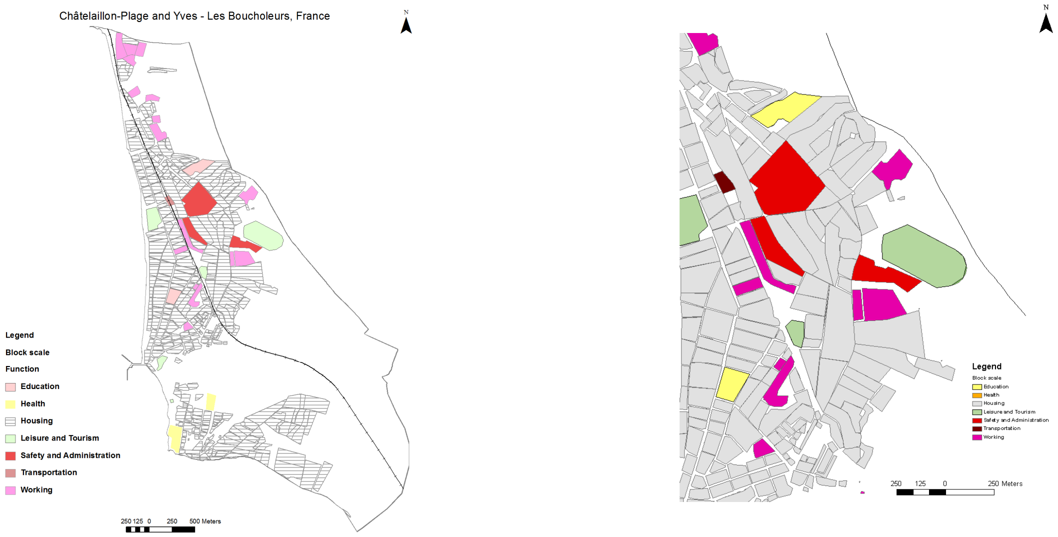
Method is the same as for parcel scale. Creation of block scale with Arc Gis involves creation of a new layer of polygons that are representing blocks. The blocks are created in order to separate a set of buildings surrounded by street pattern. In the figure 33 under c) and d) the blocks are presented. Further, each block inherited a dominant urban function. Figure below shows block structure with given topology inherited from .urban function within the block.

In total there are 286 blocks in the case study area from which 257 blocks housing, 2 health, 2 education, 5 leisure, 3 safety, 1 transportation and 16 working.

Table 23: Division within block scale with inherited urban function for Châtelaillon-Plage, France

Urban function	Number of blocks

Housing	257
Health	2
Education	2
Leisure and Tourism	5
Safety and Administration	3
Transportation	1
Working	16
Total	286



a) case study area b) zoomed case study area

Figure 74: Presentation of blocks with assigned urban function - Châtelaillon-Plage, France

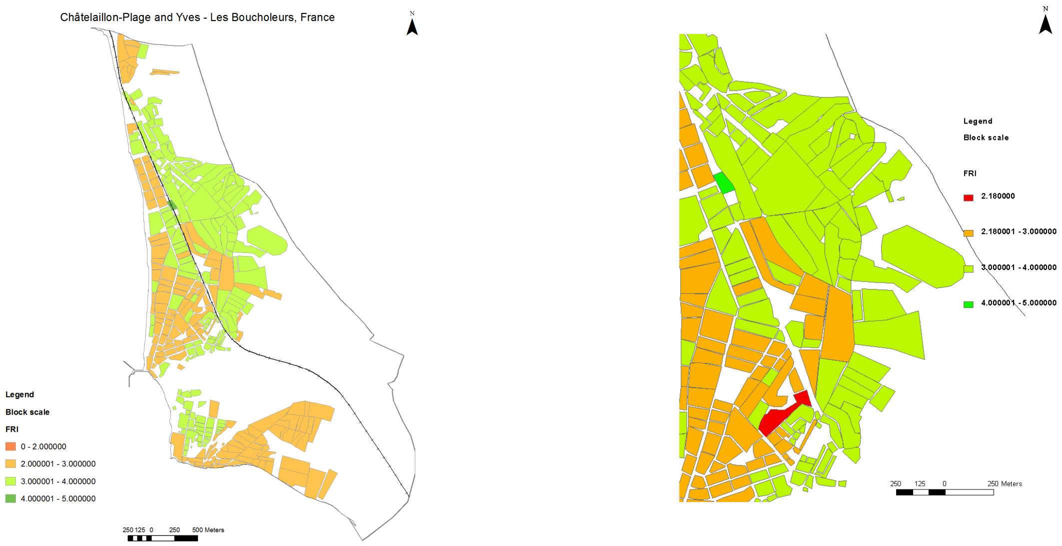


Figure 75: FRI on block scale mapped for flood initiated by Xynthia storm- Châtelaillon-Plage, France

Figure 75 present the FRI mapping for block scale for case study area. Comparison with FRI values on parcel scale shows that the connectivity is present and that due to aggregation of characteristics the resulting values of FRI correspond to results obtained in evaluation on parcel scale.

Results obtained from analysis city (urban) scale

The evaluation of FRI for big scale like district or larger urban scale in this case the whole city area includes five dimensions (natural, physical, social, economic and institutional). Here, the aggregation of all characteristic is translated on bigger scale. The movement for individual entity (building/urban function) is now moved to the whole system. Consequently, the focus is bigger and the urban system with its dynamic character is analyzed through five dimensions: natural, physical, social, economic and institutional. Within each dimension, the set of indicators is set for better characterization. The matrix with 91 indicators is developed and filled. The resulting flood resilience for case study area is presented as number with value from 1 to 5 (where 1 is low resilience and 5 is full resilience evaluated for particular event). The overall resilience is an averaged value of five values for resilience corresponding to different dimension (natural, social, economical, physical and institutional).

Evaluation of overall FRI is followed by assigning values to each indicator with their respective weights. For the given conditions, the FRI for the Châtelaillon-Plage is 2.38. The result in the form of table shows separate FRI for each dimension and the overall index.

Results obtained in this analysis demand an interpretation in order to address all the current issues regarding flood resilience.

Table 24: Overall FRI for the city/urban scale, for flood initiated by Xynthia storm- Châtelaillon-Plage, France

Châtelaillon-Plage	Indicators	not used categories	Dimension index $\sum((xi*wi)/\sum wi)$	Overall index
Natural dimension	2	0.00	2.50	2.38
Social dimension	10	0.00	2.35	
Economic dimension	16	0.00	2.19	
Institutional dimension	24	3.00	2.76	
Physical dimension	30	6.00	2.12	

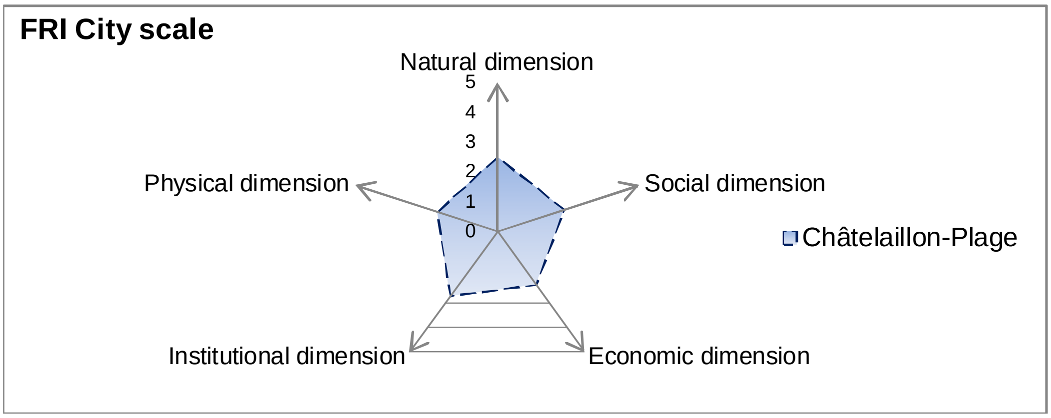


Figure 76: Radar chart presentation of FRI on city scale, for flood initiated by Xynthia storm- Châtelaillon-Plage, France

Results obtained using Matrix with 91 indicators give good interpretation about existing and needed assets and policies (laws, binding documents, etc) that will contribute to increase flood resilience of analyzed case study. The 82 indicators is used out of 91.

Natural dimension with index value 2.5 shows that available green space and existing channel network are not sufficient to avoid huge flooding or peak discharge. Measures that will contribute increasing the capacity of natural environment in accepting flood waves are recommended.

Social dimension with index value 2.35 shows lack in multilevel knowledge exchange between engineer, architect/urban planner, sociologist, economist, politician - city government, etc.

Economic dimension with index value 2.19 shows that availability of financial resources for protection of transportation network is not high. This also transfer influence on ability to provide quick rehabilitation of assets after flooding and insurance compensation.

Institutional dimension with index value 2.76 shows land use control although is important is not on the high level. This is in addition to existing houses and object on flood prone areas.

Physical dimension with index value 2.12 shows that there is an absence of dry and wet proofing in the existing buildings. Since the objects are located in the flood prone area the protection measures are lacking, and so endanger the existing facilities.

With the improvement in these segments the flood resilience of this community can be on higher level.

4.3 Additional research activities and results

4.3.1 WP1- Understanding formation of vulnerabilities and risk in coastal regions

The definition of vulnerability assessment is one of additional research activities we did not plan for this project. However the there was a need to map the results of analysis. This was also confirmed during the meeting with stakeholders and the importance of maps when there is a discussion about existing risks and vulnerabilities. The developed framework is applied on the case study area and presented under 4.2.1.

4.3.2 WP3- Holistic and Multiple Risk Assessment

The calculation of direct damages for each building in the case study area is done using developed depth damage curves. We have adapted the depth damage curves to fit our existing urban functions (land use). As a result the calculated damages are presented in the form of maps for three different scenarios (we had three different flood maps).

4.4 Summary and lessons learned

Research activities for Châtelaillon-Plage, French case study area focused on flood resilience, risk and vulnerability assessment. The case study team UNSA and ARTELIA defined frameworks for vulnerability, risk and flood resilience. In addition all results are available in the form of maps.

Lessons learned from this case study are mainly related to better communication among all actors. This can be done by mapping the communication roads. Creation should be done with caution since this area is very sensitive. The social component is very strong therefore constant collaboration with stakeholders remains the only way in increasing the risk perception and willingness to accept future flood risk management planning.

The real long-term lesson drawn from Xynthia is a need for a complete revision of the coastal settlements, which during last two centuries had little in common with a sustainable development. Finally, Xynthia and its repercussions demonsrated the weakness of the awareness of the risks on vulnerable coastal territories and the depth of the collective lack of responsibility (Chauveau et al. 2011).

5 Case Study – Genoa, Italy

5.1 Introduction to the case study area

5.1.1 General description of the case study area

Genova is the capital of Liguria region, situated in North western Italy, with a population of around 600.000 inhabitants. Italy's largest sea port is located in Genova. The case study concerns the coastal area and the Bisagno river basin. The focus of the case study is on the Bisagno mouth, streaming into urban area, and on the Fereggiano sub-basin.

Extreme events affecting the Bisagno river basin are heavy precipitation, cyclones, flash floods, pluvial and coastal floods as well as combination of floods. The Mediterranean region is a clear example where large-scale flows and topography are contributing factors to the occurrence of heavy precipitation events. In the study area of the Liguria region, localized extreme precipitation is produced by large-scale flow interaction with regional topography. Cyclones relate with a low pressure area, also referred to as Genova low, insisting on the Genova gulf. The depression bear rain, often intense, on the Liguria coast.

Recently Genova was hit by two major flash floods in November 2011 and October 2014, both resulting in fatalities, displacement of people and high financial damage.

The Genova case study is aimed to address the issue of heavy rainfall connected with urban drainage systems. Flooding in urban areas can be caused by flash floods, coastal floods or river floods, but there is also a specific flood type that is called urban flooding (http://www.floodsite.net/). This kind of flood is specific in the fact that the cause is a lack of drainage in an urban area. Heavy precipitation can cause flooding when the city sewage system does not have the necessary capacity to drain away the amounts of rain that are falling. All these phenomena occurred in the November 4, 2011 event in Genova.

5.1.2 Hazard and risk situation in the case study area

In general, urban drainage systems consist of three parts: the overland surface flow system, the sewer network, and the underground porous media drainage system. Traditionally, no design is considered for the urban porous media drainage part (Yen and Akan, 1999). Many areas of Genoa have separate sewers to take waste water and rain water, but in other areas, the sewer system is combined, meaning that waste water mixes with rainfall.

Urban flooding is the most frequent floods occurring in Genova. Their impact though is less severe than flash floods, but there are many areas that, in correspondence with heavy precipitation, flooded regularly for the lower floors and basements of buildings. Heavy rainfall can overwhelm the sewage system. When this happens, sewage can overflow from manholes and rainfall water flowing into city roads. For example these phenomena occurred before, during and after flood event of Fereggiano stream (drainage area 5 km^2), of Bisagno torrent (98 km^2) and of other small streams (e.g., Noci, Rovera, Chiappeto) in November 4, 2011.

Urban flooding are a great disturbance of Genova daily life. Roads can be blocked; people can't go to work or to schools. Some areas are on flat terrain and so the flow speed is low and you can still

see people driving car or scooter through ponding water. Other areas of the city are on sloping terrain and it's common that the water quickly flowing on the city streets due to high slopes. The streets become drainage networks and this flow doesn't go into the river due to banks or other obstacles. It's happen that water depth is not deep but velocity doesn't allow citizens to walk. The economic damages are high but the number of casualties is usually very limited, because of the nature of the flood. The propagation and extent of urban flooding in Genoa are obviously a function of the intensity of the event, but it is a fact that is sufficient a rainfall that does not cause a riverine flood.

5.1.3 Current institutional and governance practice

A number of River Basin Authorities (Autorità di Bacino, AdB) are established in Italy. They are responsible for the overall management of river basins, including the identification of i) the critical river sections and reaches which capacity, in terms of discharge, is below given thresholds; ii) the associated flood prone areas; and iii) the structural and non-structural interventions needed to reduce or to eradicate the risk. Usually, three thresholds are introduced in terms of flood return period (T=1/p, where p represents the event's annual probability of exceedance): high risk (T=50 years), medium risk (T=200 yrs) and low risk (T=500 yrs). The first two are used for both planning of the city development (e.g., urban plans) and the design of structural protection measures against the floods (e.g., levees, dikes). In this sense, any river should, in perspective, be able to carry the flow without flooding up to the discharge associated to T=200 yrs. The T=500 yrs boundary is identified for civil protection purposes and for non-structural measures aimed to the safety of the population and losses reduction (alerts, urban plans, insurance).

Unfortunately, most of the Italian rivers and torrents are not able to carry a flow discharge with T=200, without flooding their flood plains. This is the case also for the Genoa's torrents and streams here under consideration. Both the Bisagno and its small tributary Fereggiano are not able to safely drain the discharge with T=50, producing inundations in the urban area of the city. This is well recognised and described in the flood prone areas maps attached to the Piano di Bacino (Basin Plan) of the Bisagno torrent. Note that in both Bisagno and Fereggiano cases the areas recognised as subject to a possible inundation with T=50 yrs (yellow) present extensions not so different from those associated to T=500 yrs (green) (Figure 77).

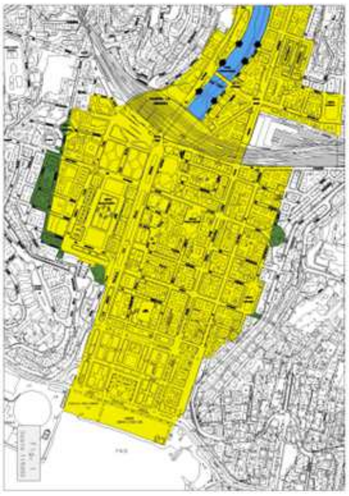


Figure 77: Bisagno drainage basis. Flood prone areas for different return periods (T = 50yrs – yellow, T = 200 yrs – orange, T = 500 yrs – green)

The Bisagno Basin Plan identifies a number of hydraulic structures and maintenance works to be performed to minimize the risk in urban areas. In brief, works for the complete re-building of the Bisagno cover in its final reach will be completed (Figure 78), sensitively increasing the maximum discharge of the river. Then, works for the diversion of Fereggiano river (a tributary of Bisagno) are also started, collecting waters from Fereggiano basin to the sea, avoiding in such a way to overload the Bisagno river discharge.

Figure 78: Work in progress along the Bisgano final reach

The Italian National Law 225/1992 institutes the National Service of Civil Protection. The aim is to safeguard human being, personal properties, settlements and the environment from natural catastrophes and other destroying events. It establishes that the Civil Protection has to issue forecasts, to carry out prevention activities, and to aid people during emergency situations.

The Law 267/98 started a very ambitious project: to develop the “Sistema Nazionale di Centri Funzionali (CF)”. This project is targeted to the defense from hydro-geological catastrophes and the mitigation of their effects. The idea is to create a coordinated network for the real-time exchange of data and information (forecasts and observations) needed to guarantee an efficient meteo-hydrological observation and warning system to assist the different political decisional levels in issuing warnings and alerts.

The “Direttiva Presidenza Consiglio dei Ministri” (DPCM) of February 27, 2004 gives operational instructions regarding the management of the national distributed alert system based on the CF network. In this context, emergency situations are faced through different phases: risk definition, prediction, dissemination and emergency management. Each operational CF includes three functional areas: one in charge of meteo-hydrological analysis, one in charge of data acquiring, validation and storing, and the last area devoted to maintain, update and repair machinery, hardware and software apparels, also in critical situations.

To facilitate the warning communication, Italy has been organized into Alert Zones, i.e. portions of the territory characterized by similar response to extreme events.

The National CFs issues a daily National Surveillance Bulletin and, when needed, a Criticality Bulletin. When a potential meteorological risk is foreseen, a predefined technical procedure is

activated. Meteorologists and hydrologists of National and Regional CFs join in an Alert Team, which evaluates the current situation, finally issuing a Hydrologic Bulletin.

The last part of this complex system is the communication to the people of the forecasted weather conditions, the consequent land effects and possible critic conditions. The Regional Civil Protection Department issues the alert bulletins through different means. Each City Major, Province President as well as other Government Territorial Bureau are informed daily. Citizens are informed via mass media (newspapers, television news, etc.), through messages displayed on electronic boards located in various parts of the city, through the web and via message services.

When the alert is declared, people and public organizations have to act according to the instructions received. Every Municipality has to follow the instructions contained in the Municipal Emergency Plan, which is expected to describe the measures to be taken during a risk situation. The Mayor is responsible for the Municipality. He/she has to manage the local Civil Protection resources, as suggested by the Emergency Plan and according to the alert level. On the other hand population have to activate self-protection measures in order to protect their own lives and personal goods.Available data used for research activities

5.1.4 Available data used for research activities

No.	Type of data	Brief description
1.	Rainfall	Time series of rainfall; Format: ASCII, xlsx; Resolution: 10 min
2.	Discharge	Time series of discharge; Format: ASCII, xlsx; Resolution: 10 min
3.	Flood prone area	Shape files of flood prone area; Return period: 50 yrs, 200 yrs, 500 yrs
4.	Digital elevation model	Digital elevation model; Format: ASCII, grid file; Resolution: 5m
5.	River profile sections	River profile sections; Format: CAD, xlsx
6.	Observed data	Observed data (rainfall, discharge) of Nov. 4th, 2011
7.	Census	Census data from 2011, Format: Shape file, xlsx
8.	Cartografia Tecnica Comunale	Format: CAD; Scales: 1:2000, 1:1000

5.2 Key research activities and results

5.2.1 WP1- Understanding formation of vulnerabilities and risk in coastal regions

Vulnerability assessment: Starting point of the vulnerability assessment in the Genova pilot was the Risk and Root Causes Assessment (RRCA), performed in the WP1. Furthermore an approach for vulnerability assessment was developed. The vulnerability assessment comprises a household survey, as well as a methodology for spatial vulnerability assessment with the calculation of a compound vulnerability index. The PEARL vulnerability index is based on a modular structure with three elements (susceptibility, coping capacity and adaptive capacity). These three elements in turn consist of several sub-indices.

However, the vulnerability assessment by means of the household survey conducted through the population of the pilot area can be considered as a stand-alone part of the work. The aim of this survey was to deduce vulnerability patterns of local households and to gather information on how the households respond before, during and after a hazard, in order to get an understanding on local risk management strategies. Results and conclusions from the vulnerability analysis in the Genova pilot are included into the milestone report 25, WP1. Furthermore Deliverable 1.2 comprises the final PEARL framework and sourcebook document with Genoa as a case study example. Deliverable 1.3 is final report describing the full RRCA methodology and its applicability and also focusses on vulnerability assessment in Genoa. Both Deliverables introduce the methodology and applicability of the techniques developed in WP1.

Root Cause Analysis was conducted for Genoa and the analysis drew on 17 semi-structured telephone interviews with key stakeholders to supplement a review of the vast existing literature in Italian on the floods and flood history in Genoa, including technical reports, planning documents, legal documents and scientific reports and articles as well as analysis of relevant media reports, which covered more than 150 articles published online between 2010 and 2015.

The RRCA focused on the flooding events of 2011 and 2014 in Genoa, Italy points up the vital role of early warning systems and structural mitigation works in protecting against rapid-onset flooding due to the complex morphology and climate of the city – which contains multiple river catchments with steep slopes and a small coastal fluvial plain. In particular, the analysis highlighted the governance issues that prevented structural mitigation projects planned as far back as the 1990s from being realised. The interplay between legal and financial issues generated a deadlock that prevented local authorities from effectively reducing risk. The progressive increase of extreme events and the presence of a flexible institutional structure allowed this root cause to be addressed through a change in the criteria for funding allocation and by creating new institutional units to reduce hydrogeological risk. The holistic nature of the Root Cause Analysis brought to the fore issues often hidden from local narratives about the flooding disasters, namely the human resources constraints for the authorities in charge of disaster risk management.

As mentioned above, the vulnerability assessment in PEARL comprises a survey on household level for Genoa, as well as an approach for spatial vulnerability assessment, including the calculation of a compound index.

The underlying questionnaire for the household survey was developed by the University of Stuttgart, Institute of Spatial and Environmental Planning (IREUS) with feedback and input from partners of WP1, WP3 and WP5. The survey was extended, compared to the initial description in the PEARL DoW (European Commission Directorate-General for Research and Innovation 2013). As described in Task 1.5 of the PEARL DoW, a sample size of about 100 participants for each case study were originally envisaged. This number was increased to ensure statistical validity and the survey now comprises approximately 500 questionnaires per case study, which were anonymously conducted and no names were used during the survey. In Genoa students of the University of Genoa were recruited to conduct the survey - externals had to be hired due to language problems; the hiring process was supported by the respective case study partners. The contracts for the household survey were signed by the end of November 2015 in Genoa. The local case study teams supported IREUS with the implementation of the household survey. Local interviewers were trained by IREUS for the collaboration. It was important to provide in-depth introduction to the topic and techniques needed for the survey to ensure methodological consistency across the case study methods. From this point, all necessary survey work was

carried out by the local interviewers. After finishing the field work, the hard copies were returned to IREUS for evaluation. In March 2016 the Italian data transfer was completed. In June 2016 an internal report on the findings of the household survey was provided as part of Milestone 25. Box 1 summarizes the main findings of the household survey for the Italian case study side.

Box 1: Main Findings from the household survey Genoa

The vast majority of interviewees have the respective national citizenship (Genoa 92 %). Furthermore, 77.8 % of Italian respondents indicate to originate from Genoa. The majority of respondents owns the accommodation they live in, however this condition is not automatically linked to the willingness to invest in flood protection measures. The most frequently cited hazard types for Genoa are floods (51.6 %), landslides (22.7 %) and storms (14.1 %).

More than half of the Italian respondents feels better prepared for future events. However, if researcher ask what respondents have actually undertaken to implement measures, it generally appears that they have a lack of understanding of how to independently achieve a higher level of preparedness to deal with extreme events in coastal regions. The most common precautionary measure is the avoidance of having property stored prone to flooding. Only 7.8 % of interviewees from Genoa autonomously installed better protection measures.

In general, the household survey reveals a severe knowledge and information deficit. In Genoa three quarters of respondents did not gather any information on flooding. Furthermore, about 64 % of interviewees from Genoa do not have knowledge on whether flood information is used or displayed in urban planning documents.

One of the main findings of the survey is that the number of respondents who received early warnings is alarming low. In Genoa only a third of those interviewed were forewarned. The situation is further aggravated by the circumstance that 85 % of interviewees in Genoa stated to not have any information on evacuation routes.

The main source of information regarding natural hazards is television (58.7 %). Presumably, there are more reliable and precise sources of information. As presented in detail in the Genoa RRCA report, a variety of official and unofficial communication tools are available.

In Genoa 78.4 % of respondents were not insured when the last flood hit.The majority of respondents had no insurance cover when the last flood hit, neither did they get insured after the event. Again, the RRCA provides important insights, it states that there is not a culture of private insurance schemes for natural disaster damages in Italy.

Even though respondents declare to primarily depend on family and friends in case of emergency rather than to trust in authorities, it becomes apparent by the preferences of chosen answers that the interviewees actually heavy rely on official bodies. The level of accounted liability ranges from local to national government (in order of frequency of response). The respondents named self-responsibility of citizens with less than 10 %. Based upon the responses to the questionnaire, people in Genoa think that bad urban planning (30.09 %) is the main driver of losses, followed by increased amount of precipitation (21.9 %), inefficient decision making (17.9 %) and steep slopes (14.9 %). Only 6 % of responses consider the lack of early warning, as well as the attitude of citizens as the most important reason for losses.

On the other hand, the interviewees were asked to name the most important actions to be taken from their individual perspective. The Italian respondents predominately named radical

restructuring of certain areas (58.8 %) and better protection measures (29.6 %), while only 5.4 % of them requested better financial support for citizens taking action.

Furthermore, a geo-referenced vulnerability assessment approach was developed. The purpose of the spatial vulnerability analysis is to display the results on maps, either as a compound index or parts. The advantage of this method is that all sub-indices can be represented separately or as a combination. In this way, a better understanding of the vulnerability structure can be achieved. The aggregation of numerous components into a single index allows to draw conclusions at one glance, because every spatial entity is assigned to one value. For the calculation of indicators information is required, starting with (1) geo spatial data and (2) spatially explicit statistical data on the respective scale. The results of the vulnerability assessment aim to be tractable to policy-makers and can be integrated in ongoing or future spatial planning or management processes. The vulnerability assessment in PEARL includes a methodology which is flexible in terms of the data and as such it can be applied for every case study area with regard to the availability of data. The concept and outcome is furthermore explained in D 1.3. To ensure optimal use of information, IREUS and UNESCO-IHE developed an extended approach of vulnerability assessment, which makes it possible to incorporate findings from the household survey in Genoa into the general vulnerability assessment scheme. It therefore comprises the combination of statistical data, deriving from the Census data in Genoa, geo-statistical data and information on household level.

5.2.2 WP2- Understanding formation of hazards under extreme events

Technical activities of GISIG (in collaboration with University of Genoa - DICCA) mainly focused on the study of the event that hit the city of Genoa (Liguria, Italy) on October 9, 2014. The workgroup also focused on October 25, 2011 event of Cinque Terre, modelling this extreme rainfall event in the Bisagno area.

In particular, on the topic of October 9, 2014 event, the workgroup focused on:

<u>Data collection</u> in terms of rainfall measurements for the Bisagno basin (CMIRL network), water level observed, discharge measurements, flooded area observed and Basin Authority flood prone areas, cross-sections for the part of the Bisagno river streaming in culvert and vectorial data to build a DEM model for 2D analyses

<u>Meteorological and statistics analysis</u> in term of study of the evolution of the event, mapping of the rainfall fields and valuation of the return period of the event and comparison with main flood events of the past such as the 2011 event

<u>Hydrological analysis</u> using a rainfall-runoff model named DriFt, developed by the University of Genoa, aims to estimate the flood hydrograph of October 9, 2014 event for some sub-catchments of interest and comparison with available discharge measurements.

<u>Hydraulic model</u> using Hec-Ras tools and the results of hydrological analysis in terms of flood hydrograph of the event. The aims was to simulate the floods event and create water depth maps to describe the evolution of the event.

<u>Creation of flood maps</u> by using a script developed into an ESRI environment calculating water depth for each point of the grid and in different time steps.

Meteorological and statistics analysis of October 9, 2014 event

The meteorological event of Genoa on October 9, 2014 is due to a frontal system able to generate a number of rainfall cells starting on the sea and rapidly moving from south-east to north-west, hitting the natural barrier formed by the mountainous of Liguria. The high amount of rainfall released by these sequences of thunderstorms is to be associated to an anomalously (for the season) high temperature of the Mediterranean, to the orographic lifting due to the mountains, and, for this specific event, to the "V-shaped" aspect of winds converging toward the city of Genoa. The centre of the storm was located on the Bisagno and Sturla basins (Figure 79).

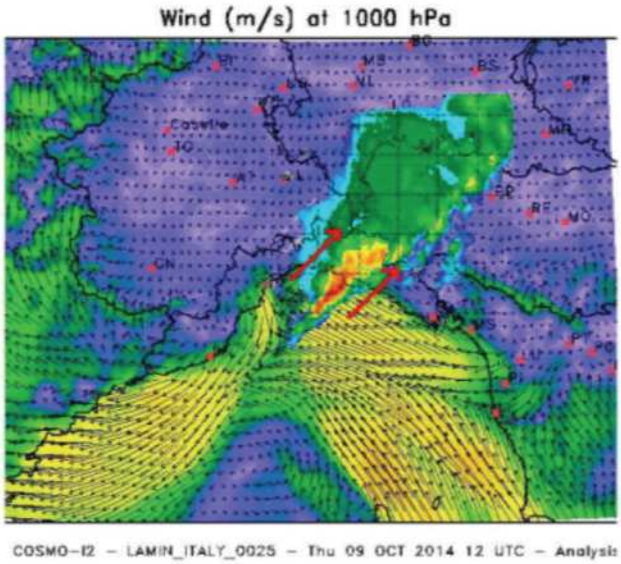


Figure 79: October 9th, 2014 – Rainfal radar reflectivity, 1000 and 700 hPa winds

The collection of rainfall measurements for the area are available from the professional (CMIRL) network (Figure 80). Stations are subject to regular maintenance, their location is decided following international standards and quite long time series are available.

Figure 80: CMIRL network and Bisagno basin in red

The CMIRL network recorded a maximum of 400 mm for a 24 hours duration cumulated rainfall and 135 mm for a 1 hour duration (Geirato station, Figure 81, Figure 82). These values can be quickly compared to the maximum recorded for the November 4, 2011 event: 605 mm for the 48 hours duration, 411 mm/12 hrs, and 181 mm/hr (Vicomorasso station).

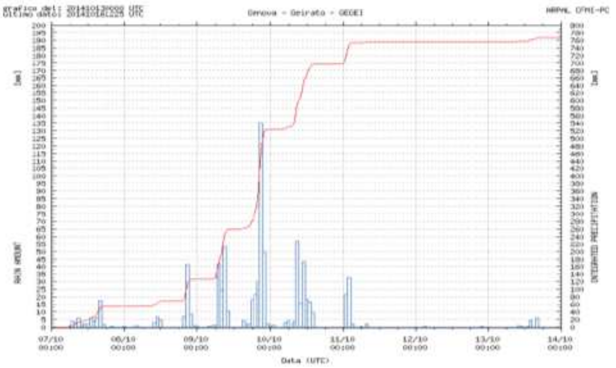


Figure 81: October 9th, 2014 – Rainfall record at Geirato raingauge station, CMIRL network

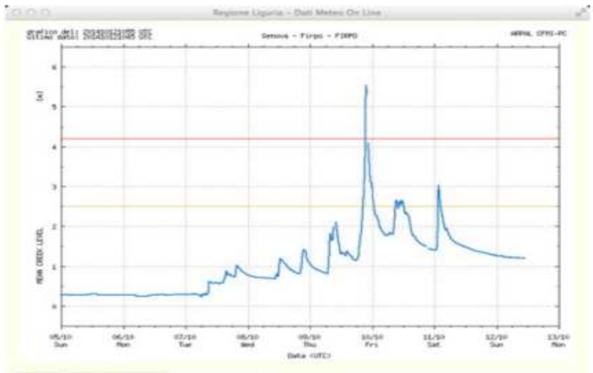


Figure 82: October 9th, 2014 – Water depth record at Firpo station, CMIRL network

In the following some of the results of the analyses performed are shown.

Figure 83: Comparison of flooded area observed during October 9th, 2014 event (red) and the basin authority flood prone areas (blue)

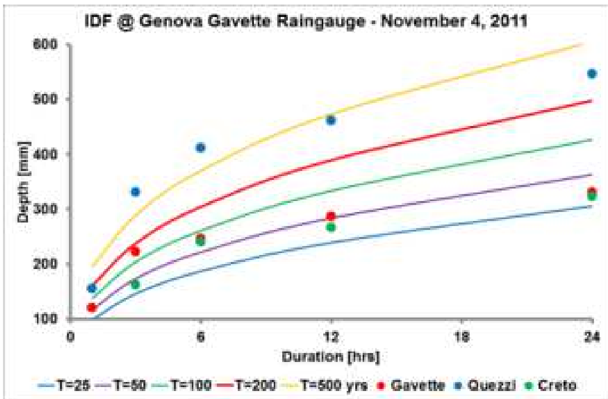


Figure 84: IDF curves for Genova Gavette rain gauge and comparison with November 4th, 2011 event

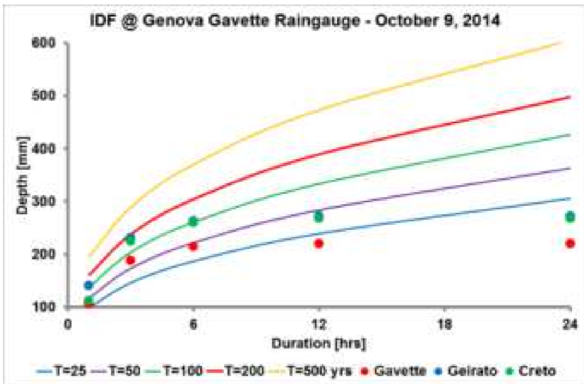


Figure 85: IDF cruves for Genovy Gavette rain gauge and comparison with October 9th, 2014 event

Hydrological and Hydraulic modelling of October 9, 2014 event

The Hydrologic model used is DRiFt (Discharge River Forecast), a semi-distributed event model based on a geomorphologic approach, has been used for the analysis. This model is focused on the efficient description of the drainage system (Figure 86) in its essential parts: hillslopes and channel networks are addressed with two kinematic scales, which determined the base of the geomorphologic response of the basin. The geomorphologic module is coupled with a simple distributed representation of soil infiltration properties, while the rainfall event is schematized with its variability in time and space. The run-off volume is routed with a time variant TUH (T-hour Unit Hydrograph) technique, which takes into account the runoff production variability. Parameters calibration and validation have been carried out using different intense rainfall events in different size basins. This robust and parsimonious model is able to predict consistently the main features of the hydrograph; the observed parameter invariance allows the reliable utilization for flood forecasting, especially in regions where many small non-gauged basins are present. DriFt was developed by University of Genoa (Giannoni et.al. 2000 and 2005).

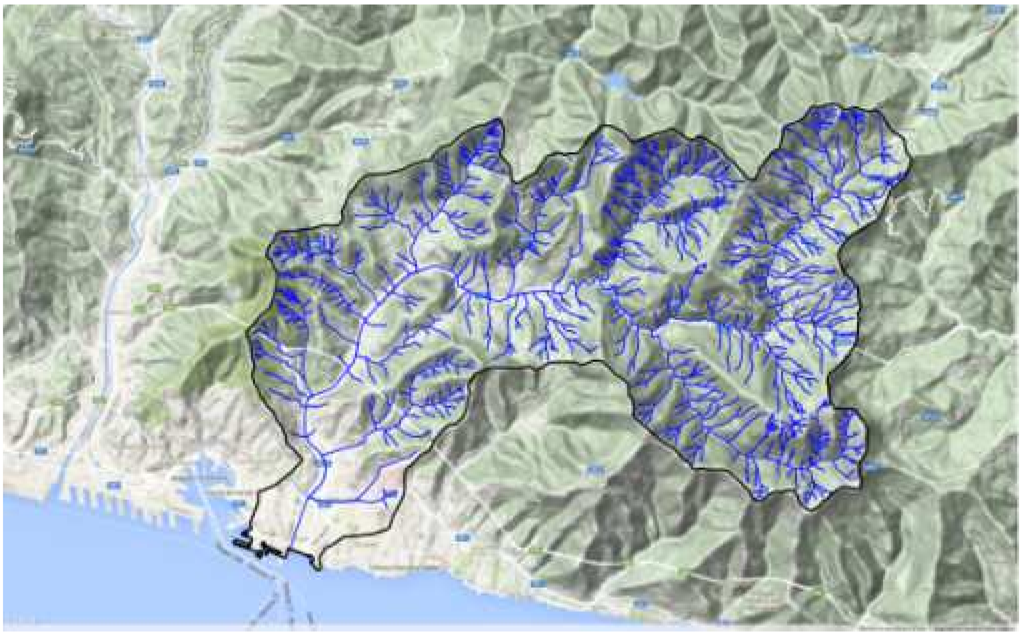


Figure 86: Bisgano river – Channel networks of Bisagno basin determined on the base of the geomorphology of the basin, using a slope and area filter.

In the following an example of the results of the analyses performed is shown:

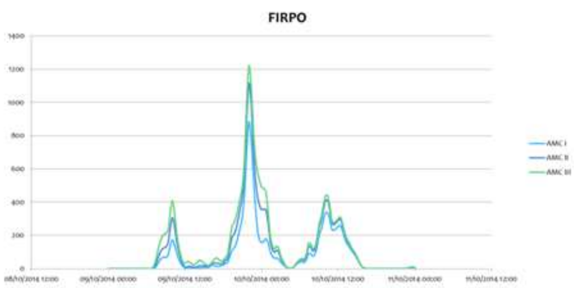


Figure 87: DRiFt model result – Hydrograph of October 9th, 2014 event at Firpo (Bisgno stream)

The Hydraulic model used for simulating the Bisagno River is HEC-RAS. It is designed to perform one-dimensional hydraulic calculations for a full network of natural and constructed channels.

For two-dimensional analyses it was used a GIS tool developed in an ESRI environment by GISIG, very similar to Hec Geo Ras tool. Water depth is calculated as the difference between the water height above the channel bottom and the value of the DEM in each cell of the grid.

Figure 88: Bisgano river – Planimetry of cross section of Bisgano river used to develop the hydraulic model in Hec-Ras

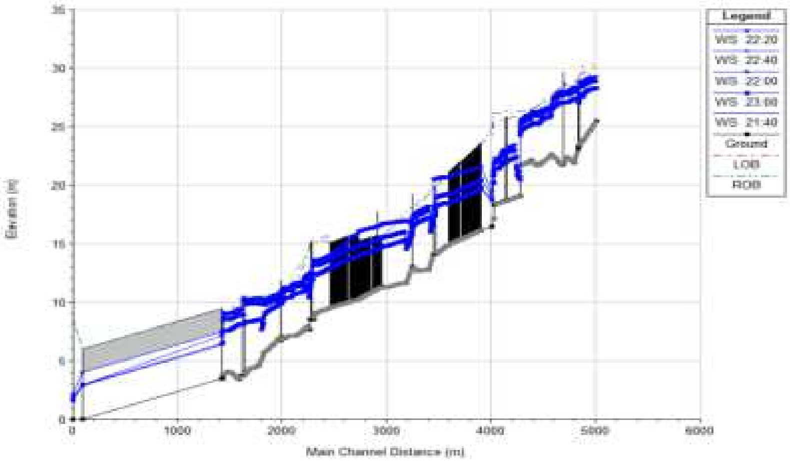


Figure 89: Bisagno river – Water profiles for the final reach of October 9th, event at different time

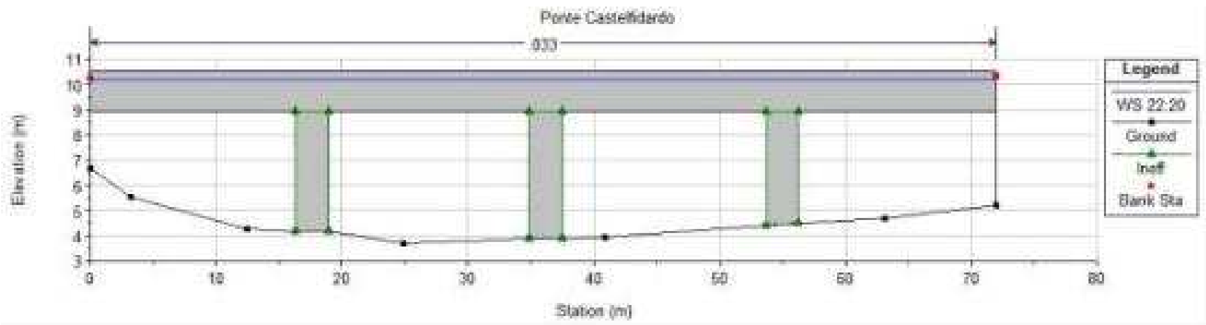


Figure 90: Bisgno river – Water level at Castelfidardo bridge at 10pm on October 9th, 2014

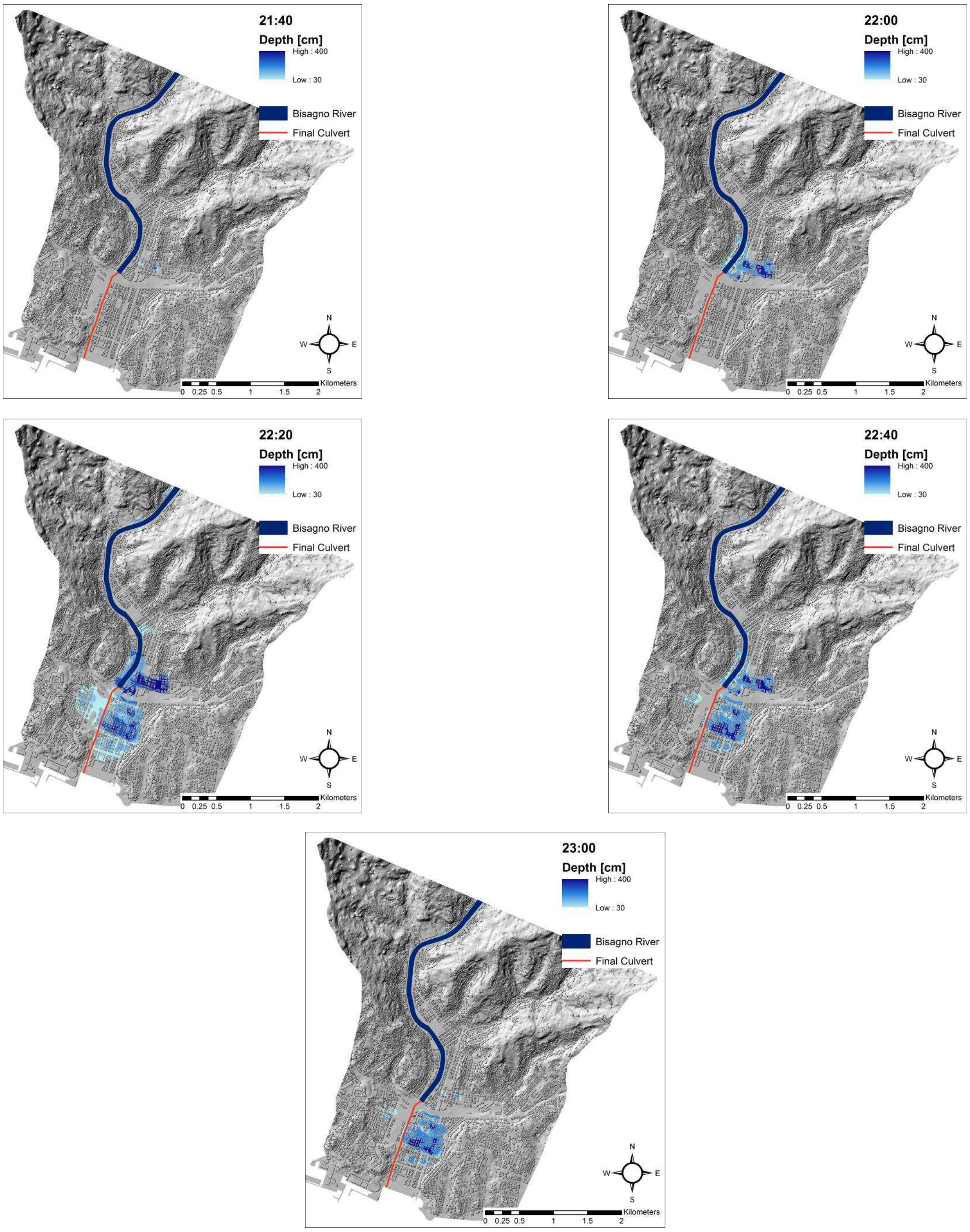


Figure 91: Bisagno river – Water depth map at different time steps on October 9th, 2014

Analysis of Brugnato/Cinque Terre event of October 25, 2011

On October, 25, 2011 heavy rainfall affected Cinque Terre and Val di Vara (Eastern Liguria, Italy). A cumulative daily rainfall of 539 mm was recorded by the Brugnato rain gauge, with intensity up to 153 mm/h and 328 mm/3h (CMIRL network, Figure 92), a truly record for Liguria Region. This event triggered several slope movements and floods, causing 13 casualties, severe structural and economic damages.

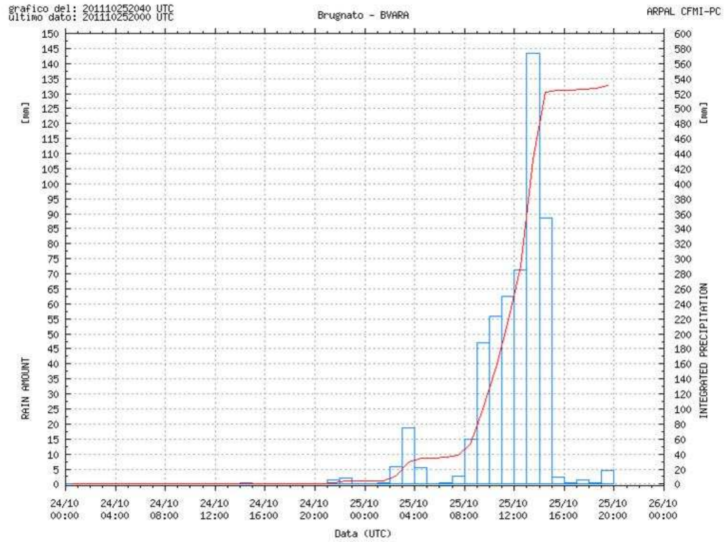


Figure 92: October 25th, 2011 – Rain fall record at Brugnato rain gauge, CMIRL network

In the PEARL research activities, rainfall event of Brugnato was applied to the Bisagno Basin. The aim was to develop water depth maps of the event to simulate the most important extreme event of Liguria Region of last years.

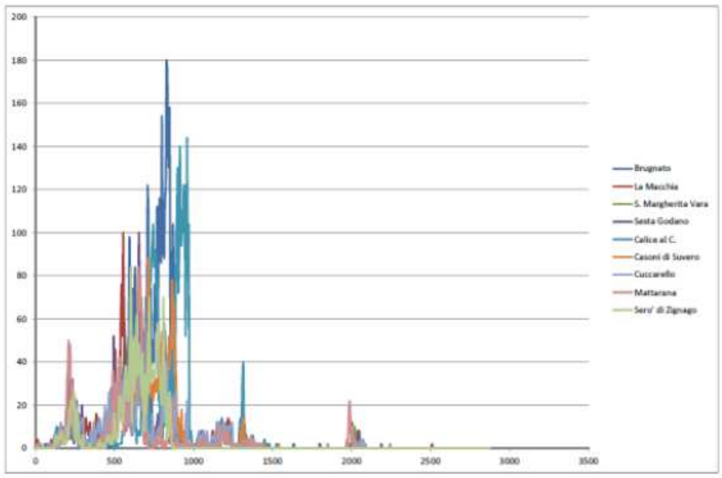


Figure 93: Ocotber 25th, 2011 – Rain fall record at different stations, used for the analyses

In the following some of the results of the analyses performed are shown:

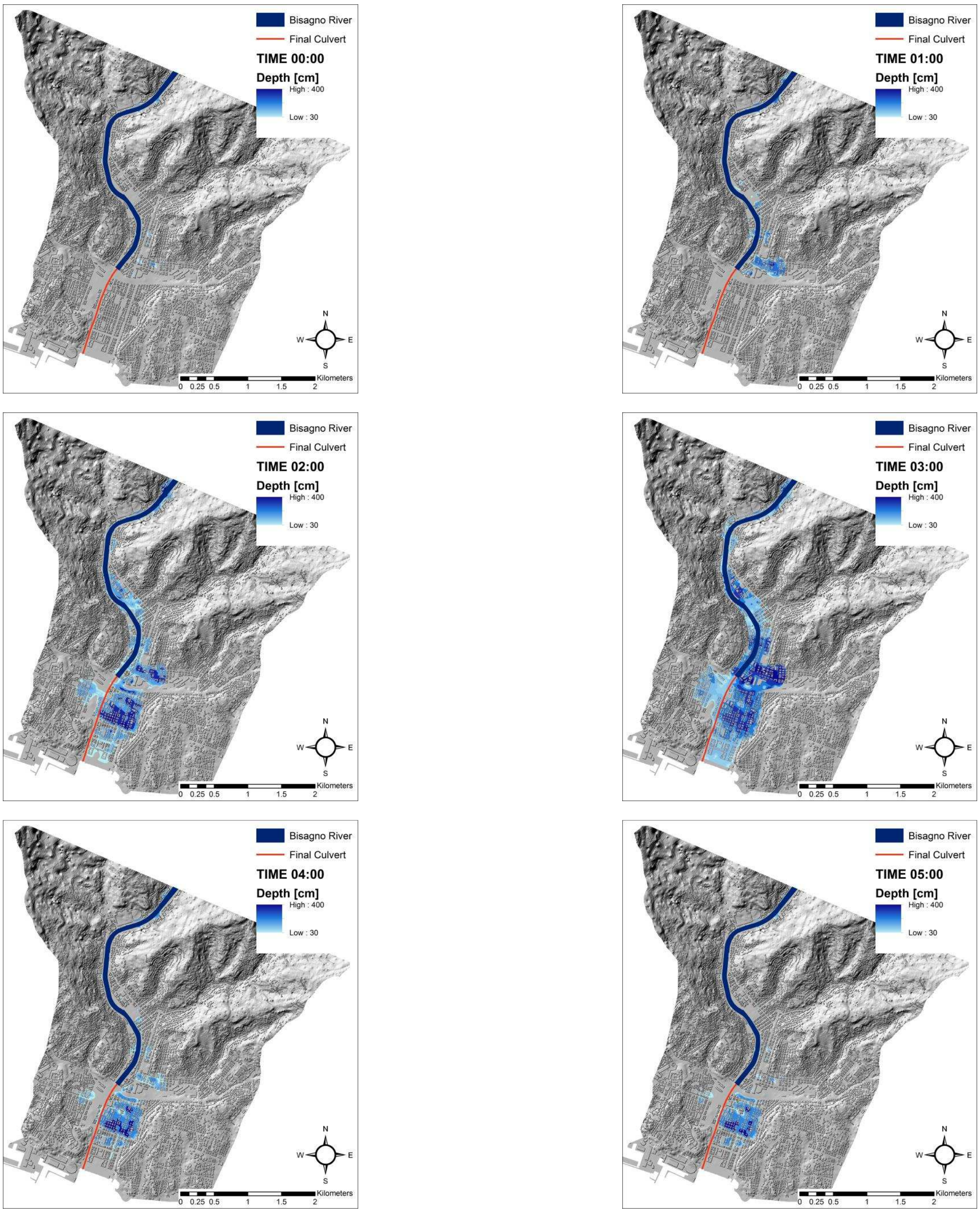


Figure 94: Bisagno river – Water depth maps at different time steps for the October 25th, 2011 event

Conclusions by the modelling work

Hydrological analysis, 1D hydraulic model and 2D flooding model have been implemented for the studied area and for two rainfall events.

Two scenarios have been simulated:

- The event of 9 October 2014, when the Bisagno flooded a great part of the downtown
- The event of 25 October 2011 occurred at Brugnato/Cinque Terre was applied to the Bisagno Basin to see what could happen in case a so severe event hit our pilot area

The results of the first scenario have been compared with observed results for that event, and the model calibrated.

Output of the 2D models are flood maps (with a fixed time step) representing water depth in cells with a 2m x 2m grid (format is integer grid 2 m x 2 m, exportable in geotiff).

Contribution by a storm surge as a constant value of 70 cm for the sea water level has been included in the model as a boundary condition

5.3 Additional research activities and results

5.3.1 WP3- Holistic and Multiple Risk Assessment

In the framework of the Italian case study of PEARL, located in the city of Genova, a 3D visualization tool was experimented and tested, with the purpose to integrate all the data coming from GIS analysis and hydraulic/hydrogeological modelling of the studied area and provide, at a client side, the possibility to identify buildings and infrastructures that could be impacted during the flood events in different meteorological conditions.

The first step in implementing the 3D visualization of a flood prone area is the selection of the most appropriate technological tool.

In order to choose the best software tool to perform 3D display in PEARL, it has been set a number of initial requirements such as being Open Source, easy to use for the user and cross-platform. For these reasons, the Cesium WebGL-based virtual globe and map engine was selected.

Cesium (Analytics Graphics, Inc., 2011) is an Open Source JavaScript library for creating 3D globes and 2D maps in modern web browser without install additional plugin. It uses WebGL for hardware-accelerated graphics, and is cross-platform, cross-browser, and tuned for dynamic-data visualization.

Cesium is open source under the Apache 2.0 license. It is the most suitable for dynamic geospatial data visualization with the help of Cesium Language (CZML). CZML is a JSON based schema, which describes geospatial data along with their properties that vary over the time.

Cesium can integrate layer imageries from different sources, including standard image files. Also external WMS (Web Mapping Service) can be integrated within. Each layer then can be visualized according to specific visualization properties (brightness, contrast or saturation).

Cesium supports also 3D models, including key-frame animation, skinning, and individual node picking, using glTF, an emerging industry-standard format for 3D models on the web. Cesium also provides a web-based tool to convert COLLADA models (COLLAborative Design Activity, an interchange file format for interactive 3D applications) to glTF for optimized use with Cesium.

With the advancement in 3D visualization techniques, it has been possible to develop 3D GIS analysis capabilities, which are quite helpful in urban planning, disaster management and environmental planning.

In the context of the PEARL Italian case study of Genova, GIS applications related to 3D city modelling have been deployed starting from regional technical maps 1:5000 (CTR 1:5000), to derive a DEM (Digital Elevation Model) composed by two different layers such as the DTM (Digital Terrain Model) and the extruded buildings. This datasets are used in Cesium for a 3D territorial representation of the studied area, that is located in final part of the Bisagno River Basin.

The work developed in PEARL is propaedeutic for further applications, such as the visualizazion of flood hazard maps and flooded area and a 3D visualization and analysis to identify vulnerable buildings and their categorization (with the help of colors) according to their exposure to the flooding event.

Other risk maps derived by the elaboration of the data from the modelling activities can be as well visualized with a 3D technique.

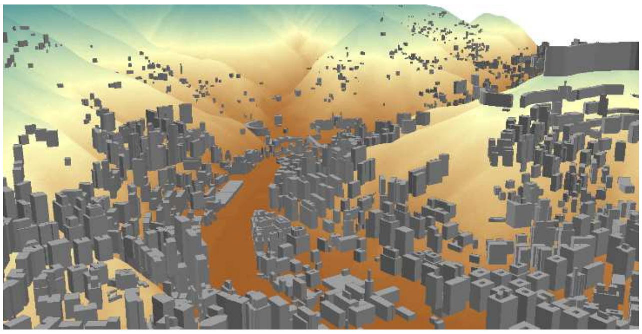


Figure 95: Visualization of the Genova digital elevation model (terrain model and buildings) through the ESRI tool ArcScene

5.3.2 WP5- Decision support and policy development for strengthening resilience of coastal regions

T5.1

Different meetings with local stakeholders were organized by GISIG, partner of the PEARL project and responsible for the implementation of the Genova pilot in the Bisagno basin. Local partner of the clustered RISC KIT project, Fondazione CIMA, collaborated with GISIG to organize these meeting and to define the agenda and the points of discussion. Hence, the meetings in subject can be also seen as clustering initiatives between the two projects (PEARL and RISC KIT), as highly recommended by the European Commission.

Moreover, Fondazione CIMA is the research centre of National Civil Protection in Italy, tightly connected with the emergency planning and management within the municipality of Genova, and can be considered as one of the most important stakeholders in the Genova pilot.

Preliminary LAAs meeting with few main stakeholders of the pilot, were informally held to foster the connection with the PEARL project and the establishment of an interest group for the project results.

An official LAA meeting was then organized in 15th July 2015, at the presence of representatives from:

- Genova Municipality – Civil Protection
- Fondazione CIMA – RISC KIT local partner, responsible for a pilot case in Magra Basin, and operational branch of National Civil Protection.
- IREN – the water and gas company of the city of Genova, in the person responsible for the management of network services in emergency situations (including floods).
- University of Genova - Hydrology and Hydraulic Engineer Department

The meeting was opened by GISIG with a short presentation of the Association and its main activities and a general presentation of PEARL, the Bisagno pilot and all the related activities carried out within the project in different WPs. GISIG outlined also the goals of the presented meeting, that were (1) the constitution of a stakeholders group for the project and the pilot area; (2) the enforcement of the liaison with RISC KIT project; (3) the presentation of the current status of PEARL works and available results; (3) the individuation of common visions and hints for new collaborations; (4) the individuation of common objectives, needs and to propose future activities inside or outside PEARL.

An important outreach of this LAAS meeting was to have put the basis for a dialogue between GISIG and the Municipality of Genova / Civil Protection in order to tune future activities and project expected results with the needs and expectations of Genova Municipality, to assure the exploitation of project results and optimize the project funding, so addressing the activities to cope with real problems and real needs.

Basing on the LAAs meeting of July 2015, in November 2015 there was also an another meeting between PEARL and Municipality of Genova, this time more operationally oriented and having the aim to train the students in charge for the household interviews (see research activities in WP1) on how to approach the public and obtain answers for the questionnaires. In the occasion, the "students" were also trained by an expert from the Civil Protection Dpt. about the new warning system in force in Genova, with the aim to diffuse to the citizens, during the interviews, also knowledge and information material on the innovation in the regional warning system.

Results from the household survey, as well as experience and methodology followed in carried out the work, were of high interest for the Municipality of Genova and for the deputy major to Civil Protection and Public Works.

Another important meeting with local and national stakeholders in the field of natural risks, civil protection, territorial management and planning was held in Genova in November 2016, in the framework of the Final Workshop of LIFE+IMAGINE project (www.life-imagine.eu). The workshop, that mainly coped with the availability and usability of data for the coastal zone management and prevention of extreme events. The workshop was participated by more than 50 "motivated" stakeholders, coming from the most important local public and private institutions (National Environmental Agency, Liguria and Toscana Regions, Municipality of Genova, Civil Protection, Regional Environmental Protection Agency, University, National Research

T5.2

For the calculation of the FRI, weights were assigned to each indicator having the following considerations:

- Natural indicators are assigned a weight of 3 and 5.
- Emergency evacuation & warning, and accessibility are given an importance of 4 and 5
- Land use and urban expansion have a weight of 5, as well as protected critical facilities
- Volunteers and solid waste management are assigned a weight of 5 and 3.

Following the method defined by Batica et al., 2013 and presented in this report, the three characteristics are taken into account in the evaluation of FRI (i) environment, (ii) estimated risk and (iii) price. The weights are assigned after consultations with researchers at our organisation and stakeholders from case study and literature review related to the analyzed event.

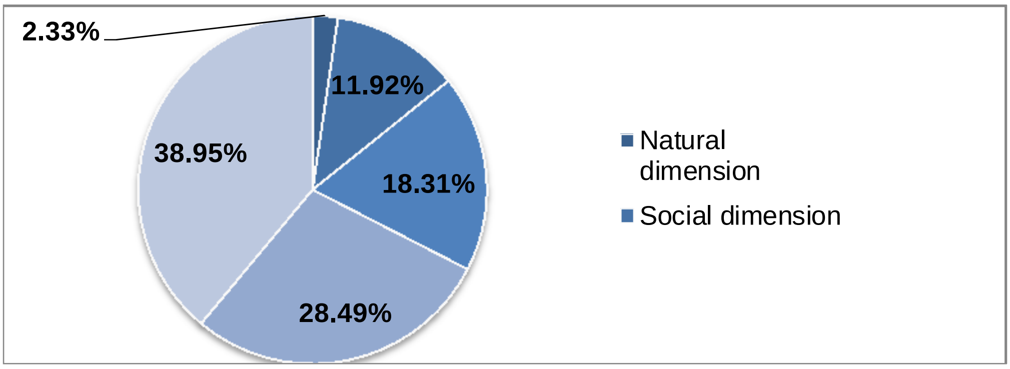


Figure 96: Weight of each dimension on the overall FRI

As presented in Figure 96 the importance of each dimension varies from 2.33% for natural to 38.95% for physical dimension.

Evaluation of overall FRI followed by assigning values to each indicator with their respective weights. For the given conditions, the FRI for Genoa is 2.14. The result in the form of table shows separate FRI for each dimension and the overall index.

Results obtained in this analysis demand an interpretation in order to address all the current issues regarding flood resilience.

Table 25: Overall FRI for the city/urban scale, Genoa, Italy

Genoa	Indicators	not used categories	Dimension index ∑((xi*wi)/ ∑wi)	Overall index
Natural dimension	2	0.00	1.88	2.14
Social dimension	10	0.00	3.39	
Economic dimension	16	0.00	2.38	
Institutional dimension	27	0.00	2.00	
Physical dimension	35	1.00	1.76	

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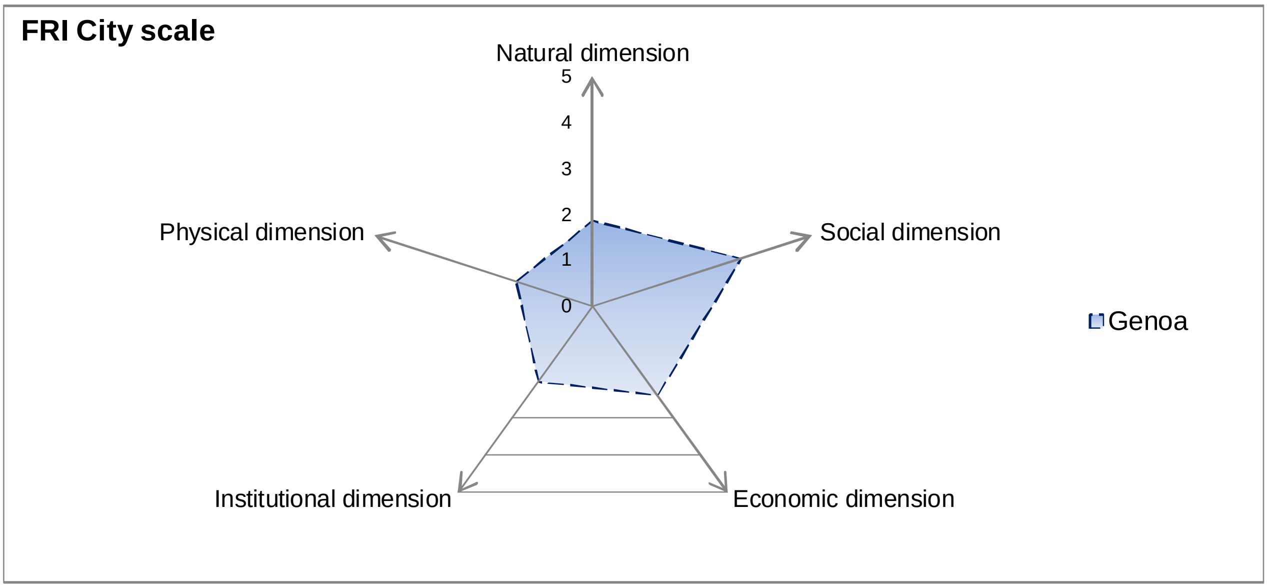


Figure 97: Radar chart presentation of FRI on city scale, for case study Genoa, Italy

Results obtained using Matrix with 91 indicators give good interpretation about existing and needed assets and policies (laws, binding documents, etc.) that will contribute to increase flood resilience of analysed case study. The 90 indicators is used out of 91.

Natural dimension with index value 1.88 shows that channel conveyance is too small to accept floodwater. Measures that will contribute increasing the capacity of natural environment in accepting flood waves are recommended.

Social dimension with index value 3.39 shows that even with the big weights the knowledge exchange is missing or it is not on the proper level. Regarding flood awareness, some additional measures should include flood risk education, flood risk communication management and in multilevel knowledge exchange between engineer, architect/urban planner, sociologist, economist, politician - city government, etc.

Economic dimension with index value 2.38 shows that availability of financial resources for people affected in flood. In addition, the compensation after flood in the form of tax reduction is missing or it is on very low level.

Institutional dimension with index value 2.00 shows that there is an absence of FRM plans in city urban planning. In addition, the participation of community in the flood risk management plans is on the low level.

Physical dimension with index value 1.76 shows that there is an absence of any dry and wet proofing in the existing buildings. There is also absence of hydraulic structures within flood risk managment plans

With the improvement in these segments, the flood resilience of this community can be on higher level.

5.4 Summary and lessons learned

Summary of research activities

Research activities were mainly focused on:

- Investigation and assessment of hazards by extreme rainfall events in the last part of the Bisagno basin, where a high urbanization and population can increase vulnerability and risks value.
- Analysis of the vulnerability in the studied area, carried out with the use of territorial data, statistical data, and data acquired for the project purposes coming from 500 interviews to local population.
- Calculation of the Flood Resilience Index for the October, 2014 event.

Description of lessons learned

Scientific and technological level to study and describe the rainfall events is high, and allows a good knowledge of the territory and its reactions to them. Often, the territory itself is not able to correctly manage these events, in particular if more extreme and frequent than in the past due to climate changes.

Works to prevent cities from floods are good and advisable, but a residual risk will last.

In such a context, important is to create awareness in the population living in flood prone areas, in order to provide them with adequate instruments and knowledge to cope with these risks, to activate auto-protection measures and to become part of the management system.

Special emphasis

Institutional/governance practices

Hydraulic works, that are going to be finalized in the Bisagno area, have the benefit to minimize the risk in these areas but not to eliminate. Citizens and administrations will have to cope with a residual risk, which will be lower, but a risk that must be managed and kept under control.

As said, a culture of resilience in the population must be built, so as the production of participatory Emergency Plans, where the citizens can get information on the environment and related risks.

Important is also to push toward the installation of self-protection measures, to be funded with public incentives. Finally, it is highly recommended the de-localisation of infrastructures at risks.

Lessons learned on risk management and risk governance

Genova flood history is too young to be able to shortly generate a culture of risk among the population. Important hydraulic works, such as the new cover of the Bisagno mouth and the Fereggiano diversor, will decrease the flood risk in the city, but not totally. For that, to generate in the population a culture of the resilience is highly important and the administrations are working for that.

In the PEARL project, GISIG partner, which is responsible for the implementation of the Genova pilot, collaborated with the Municipality of Genova, Civil Protection Department, to create awareness about the risks among the population of the pilot area. The students in charge for carrying out the household surveys, in fact, before starting their activity, have been trained by an officer of the Municipality of Genova about the self-protection measures and the new warning system in force in the Region, with the aim to diffuse these knowledge to the citizens during the interviews. A leaflet, explaining the warning system and the different degrees of warning (from green – no warning - to red – maximum warning) was distributed during the interviews.

6 Case Study – Marbella, Spain

6.1 Introduction to the case study area

6.1.1 General description of the case study area

Marbella is a city that belongs to the province of Malaga and it is part of the “Costa del Sol”. It is located in the south of Spain, in the region called Andalucía (Figure 98). The city extends for 117 km^2 and (according to the Spanish Statistical Office in 2015) 138,679 habitants live there with a density of almost 1,200 hab/km^2.The city is between a small mountain range and the sea. The case study is limited to the city centre where there is two main water streams, Represa channel and Huelo River.

Marbella presents a typically Mediterranean topography with high slopes on the upper part of the basin and very flat areas close to the sea. Three main river streams cross the surrounding area: Guadalmina (28 Km, 68 Km^2), Guadaiza (22 Km, 45 Km^2) and Rio Verde (35 Km, 150 Km^2). As a Mediterranean city, it benefits with wet-warm cool winter and ever-drier hot summer, with a mean annual temperature of 18 °C. The mean annual rainfall is 625 l/m^2, which the main part occurs during the months of summers and autumn. These rainfalls present great intensities in very short time.

Since the city involves around 44 Km of coastline, many beaches and recreational ports are present in Marbella. The main economic activity is the tourism, which mainly involves wealthy people, therefore assets and properties are characterized by high economic value. An example is given by the presence of high-class resorts, recreational ports, golf clubs and many other luxurious facilities.

Figure 98: Marbella map and location

6.1.2 Hazard and risk situation in the case study area

Main challenges that threaten Marbella are due to its particular topography. In fact, the city is characterized by different kinds of morphological elements, like extensive coastal plains that come

from previous mountains eroded during the centuries and high mountain elements like Sierra Blanca Mountain, which contrasts to its flat morphology.

These different morphological elements promoted the development of short rivers along the city, characterized by steep banks that put Marbella at risk of flash floods.

Situation results even worse because of the irregular nature of rainfall events in Marbella.

"Gota fría" is a significant meteorological phenomenon that characterizes the case study. It is generated by cold air fronts that penetrate into warm air ones at high altitude. The consequence is given by high intensity precipitations and strong storms, which mainly take place in fall.

These rainfall events provoke urban flood events characterized by short lead times, therefore significant runoff values that are not manageable by the existing drainage network, which does not have such a capacity to drain the whole runoff. This kind of flood, characterized by strong high values of discharge that happen in very short time, are called flash floods and represent a serious threat to pedestrian, properties and goods.

The severity of Marbella's condition is increased by the presence of many small fluvial streams that cross the city. These ones contribute to provoke flash flood events under "gota fría" conditions.

Another challenge for the city is given by storm surges, which often provoke important problems in recreational ports and increase erosion activity in the several beaches of the city. There are two additional factors that may exacerbate the cited conditions:

- High density of people
- Commercial activities in the lower part of the basin.

The first one takes place in the upper part of the basin because there are not enough protection structures (in terms of sediment traps or storm water tanks), therefore the sediments produced by erosion phenomenon enter freely into the conduits through the urban drainage structures along streets and often cause disruption of the sewage connections.

The high density of people and commercial activities in the lower part of the basin, instead, contributes to increase the risk level of the case study area because that part of the basin is characterized by flat topography and so it is prone to be flooded.

Therefore, the main challenges that have been identified in Marbella city are flash flood, storm surge and collapse of the sewer network due to the incapacity of the conduits. These events are characterized by high potential to create huge damages to people, assets and natural landscape.

The risk is even increased when flash flood and storm surge occur at the same time because, in this case, water runoff cannot be discharged into the sea. The main consequences are higher water depth and velocity values, so higher damages to assets and people.

Climate change is expected to accentuate the risk. Some effects have been already identified, like the jellyfish bloom, which has been jeopardizing tourism in recent times.

Some of the most recent events that created many damages in the study area happened in 2006, 2007, 2011, 2014 and still during this last November 2016 as it is shown Figure 103 and Figure 104.

6.1.3 Current institutional and governance practice

The current governance in Marbella aims to integrate flood risk management and urban planning in order to stop fighting against water and adapt to live with it. To get this objective it is necessary to create networks of stakeholders, engineers, professionals and decision makers who can cooperate, share interests and ideas, generate knowledge and results that allow adapting the city of Marbella to the new climatic challenges.

Stakeholders analysis have been conducted in the context of a past meeting that took place in order to ensure the maximum participation of the local stakeholders and to facilitate the participation of entities from other municipalities. These stakeholders' analysis led to several findings.

About exposure and impact on assets and population, Marbella's most significant critical issues are related with natural water courses that were urbanized. In particular, main critical events in Marbella are flash floods, which therefore are characterized by hourly time scale. The lack of inlets cause an underuse of the underground channelized steams and sewers networks, which would be able to accept more water in case of heavy rainfall events.Other types of structures able to fight floods like detention tanks are not present in the city.

About post-flood event analysis, in Marbella it has been found that post-flood effects usually last for days and affect at very local scale because convective storms occur locally. Typical damages to assets are accounted for cleaning, repainting and changing skirting boards and some furniture close to the floor reparation or substitution. These damages are usually repaired directly by the owners since insurance companies do not pay for them. Furthermore, in the case of commercial activities, there is a higher economic loss because the affected businesses use to close during cleaning and restoration.

The stakeholders' analysis, begun during that past meeting, involves also preparedness and early warning systems in case of urban flooding. In theory, there are two early warning systems, named WiCast and Cowama, for flooding forecasting and bathing water, which still need calibration and precision improvements. Moreover, Aemet (national meteorological agency) provides a national system useful for early warning system.

Overall, people were unaware about the previous systems, which are known just by the responsible entities. There is not enough flood risk awareness among people and information about what to do in case of flood events in critical streets is often lacking.

The analysis about decision-making processes and procedures in case of flood event detected civil protection and local police as authorities in charge to inform population. Warnings are transmitted by local media, although the situation is further exacerbated because of tourists who are not aware of the major flood risk in the city.

6.1.4 Available data used for research activities

The research was conducted in order to evaluate the damage due to flood events in the case study of Marbella.

Many data were used to obtain the expected annual damage. Mainly, this estimation assumes the knowledge of two necessary sets of information: hazard and vulnerability.

The first one, hazard, has been assessed thanks to the availability of the following data:

1. Real time series of rainfall and flow depth respectively provided by 1 rain gage and 3 limnimeters located in the Marbella's sewer network. They allow to capture real time data for specific events.
2. Digital terrain model (following DTM), which was provided by the National Geographic Institute with cell size of 2x2 squared meters and an elevation resolution of 20 cm. It was used to create the 2D surface hydraulic model of the coupled model carried out using Infoworks ICM software.
3. Sewer network data, which were collected through topographic and georeferenced data.
4. Rainfall historical series, which consists of 72 years of maximum daily rainfall data and 34 years of maximum short duration data (from 10 minutes to 12 hours) from Malaga airport station provided by the Spanish weather agency AEMET.
5. Climate scenarios data, which consists of a regional climate model developed by the Max-Planck-Institute that provided results for two different scenarios (RCP4.5 and RCP8.5) for the period 2006-2100.
6. Rainfall historical model data for the period 1960-2005, provided by the Max-Planck-Institute.

Vulnerability has been assessed using the data reported below:

1. Land use data, which consists of the cadastral information corresponding to any properties in the case study. Primarily, use of the building, dimensions and situation.
2. Census areas data, provided by INE (Spanish Statistical Office), which involves data about density, immigration and sensitive categories of people living in the case study area.

Then, in order to assess risk, the following data have been used:

1. Direct damage data, which have been provided by CCS (Spanish national reinsurer) from 1995 to 2014 for the spatial extension of the Malaga region.
2. Economic input-output tables of the year 2010 for the spatial extension of Andalucía region and of the whole Spain provided by INE.
3. Labour force per economic sector data of the year 2011 for the spatial extension of Andalucía region disaggregated in provinces provided by INE.
4. Indirect damage data obtained through the application of the input-output tables, from 1995 to 2014 for the spatial extension of Marbella city.

The hydraulic data have been obtained through a new sewer sensors system that has been installed within the studied sewer network. It consists in 3 water level sensors and 1 rain gauge that have been used to calibrate the model (Figure 99). The rain gauge is located downstream of the highway and, the water level sensors are located inside an 800 mm conduit of diameter at the upper part of the city inside the Represa's channel, upstream and downstream the Huelo river junction.

Figure 99: Location of the sensors within the sewer network

6.2 Key research activities and results

6.2.1 WP2- Understanding formation of hazards under extreme events

In the framework of this work package, extreme events scenarios are analysed. This analysis can be done thanks to a coupled 1D/2D model of Represa subcatchment that has been developed by AQUATEC. The software used for the creation of the model is InfoWorks ICM by Innovyze (2016).

For this study, a specific 2 m^2 resolution DTM was used. This DTM, was generated through LIDAR data with a minimum density of 0.5 points/m^2 and precision of 20 cm in terms of ground elevation. It covers 10.6 km^2 of the municipality land involving 68 km of sewers.

Regarding the calibration process of the model, the main parameters stablished were:

- Hydrological losses: For pervious areas the Horton method considered the same parameters of a similar experience in a closed area (initial infiltration = 20mm/h, residual infiltration = 7.2mm/h, decay constant = 0.043h^{-1} and recovery constant = 0.108h^{-1}) (Russo et al., 2015). Impervious areas (roofs and roads) have been directly connected to the sewer network (according to the existent situation).
- Surface roughness coefficients: Two different coefficients were taken into account depending on the type of surface considered, streets and roads (0.016 s/m^3) and rural areas (0.025 s/m^3).
- Routing parameters: Building were excluded by 2D domain (as said runoff was directly connected to undergound network), while other infrastructures (like roads and train railways) that suppose an interruption of the surface flow and most of time were modelled considering independent drainage structures and using vertical walls to represent them.

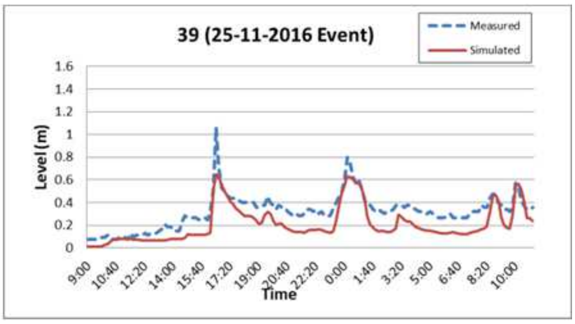
- Characterization of the surface drainage structures through ICM 'Gully 2D' nodes. These elements were hydraulically characterized on the basis of experimental data carried out in the UPC hydraulic laboratory (Gómez & Russo, 2011).
- Rainfall and flow-depths records for the adjustments of the model parameters in the calibration phase and for the results validation. The existence of 1 rain gauges and 3 water level sensors (installed within the PEARL framework) in the analysed catchmentis allowing detailed calibration and validation processes. Rainfall and water level time series were processed in order to obtain, respectively, five and one minutes time series.

Before calibration and validation processes, several modifications of the Marbella 1D model have been undertaken due to the several modifications that have taken place in the period 2013-2016.

Calibration is the procedure for ensuring an acceptable level of confidence in a model's ability to accurately represent the real system. It refers to the whole process of ensuring that a model behaves in a manner similar to the real system as possible. For urban surface runoff models, it is recommended that at least three events are used (DHI 2002). In this case, 3 events have been used to estimate parameters calibration so far (Table 26):

Table 26: Events selected for calibration of 1D/2D flood model (Marbella case study

Date event	Cumulative rainfall (mm)	Maximum rainfall intensity in 10 minutes (mm/h)	Function of the event
19/05/2011*	46	80.4	2D calibration
25/11/2016	77	34.8	1D calibration
04/12/2016	198.5	56.3	1D calibration
14/12/2016	15	33.4	1D calibration
For these event, the new rain gauge was not yet installed, so that the data used was provided from another rain gauge (MARBELLA-CAPOBINO) from AEMET, 15 km far away of the case study.			



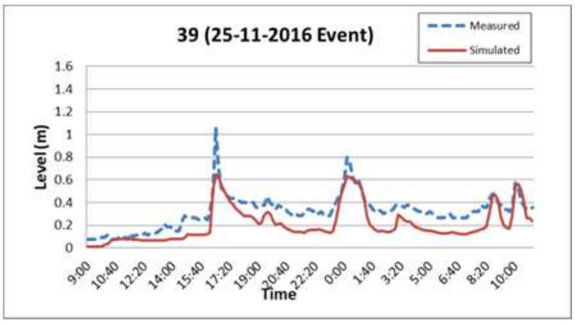


Figure 100: Results (event 25/11/2016) for Represa's channel, upstream (left), downstream (right) Huelo's river junction

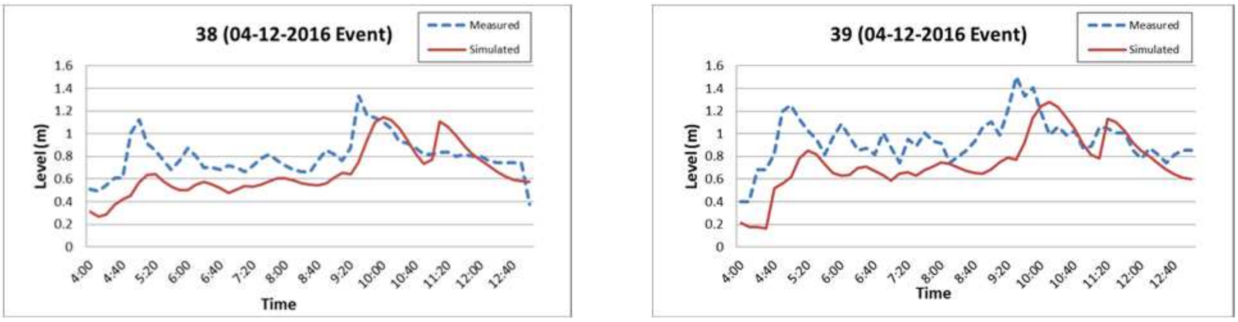


Figure 101: Results (event 04/12/2016) for Represa's channel, upstream (left), downstream (right) Huelo's river juntion

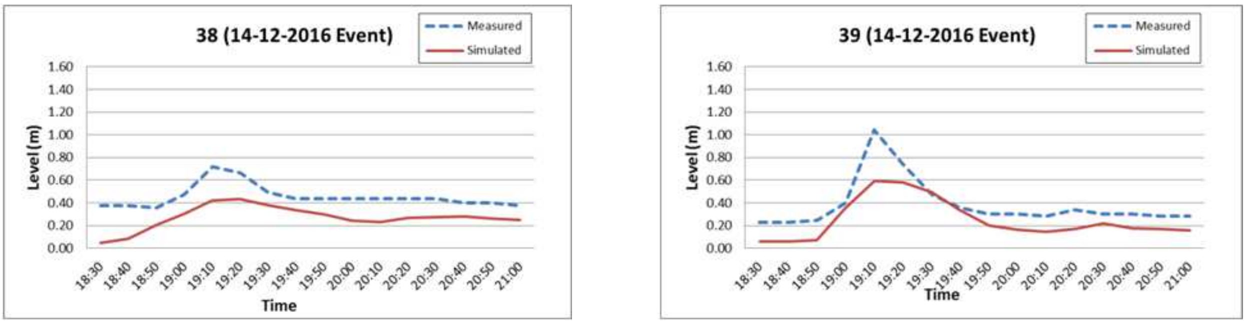


Figure 102: Results (event 14/12/2016) for Represa's channel, uptstream (left), downstream (right) Huelo's river junction

Common statistical analysis was carried out in order to evaluate the calibration processes (Table 27).

Table 27: Statistical parameters related to calibration processes for the sewer facilities used in this study

Code	Location	Coeficient of determination R^2	Root mean squared RMSE	Measured peak level (m)	Simulated peak level (m)	Peak Error (m)	Time to Peak Error (minutes)
Calibration event: 25/11/2016							
38	Upstream Huelo's river junction	0.92	0.07	0.68	0.47	0.21	0
39	Downstream Huelo's river junction	0.92	0.11	1.07	0.65	0.41	0
Calibration event: 04/12/2016							
38	Upstream Huelo's river junction	0.62	0.23	1.33	1.15	0.18	30
39	Downstream Huelo's river junction	0.56	0.29	1.50	1.28	0.22	40
Calibration event: 14/12/2016							
38	Upstream Huelo's river junction	0.75	0.20	0.72	0.43	0.29	10
39	Downstream Huelo's river junction	0.88	0.17	1.05	0.60	0.45	0

Other sources of information, such as emergency reports from police officers, firefighters and the affected population during the heavy storm events, were also used for the calibration/validation processes. This type of data is a very useful information for the calibration of the model in case of surface flooding as well as for the detection of critical points of the network where there are no surface water level sensors (as commonly in urban drainage).

The following figures show the possibility to use these data as a way to validate the model.

Figure 103: Calibration for Nabeul Avenue – Flow depths provided for the model for the event of November 25th, 2016 were compared to images recorded during the event. On the right, it is possible to observe the water depth map in the ceöös around Nabeul Avenue. On the left, a photo from a local newspaper shows water depth just above the kerb

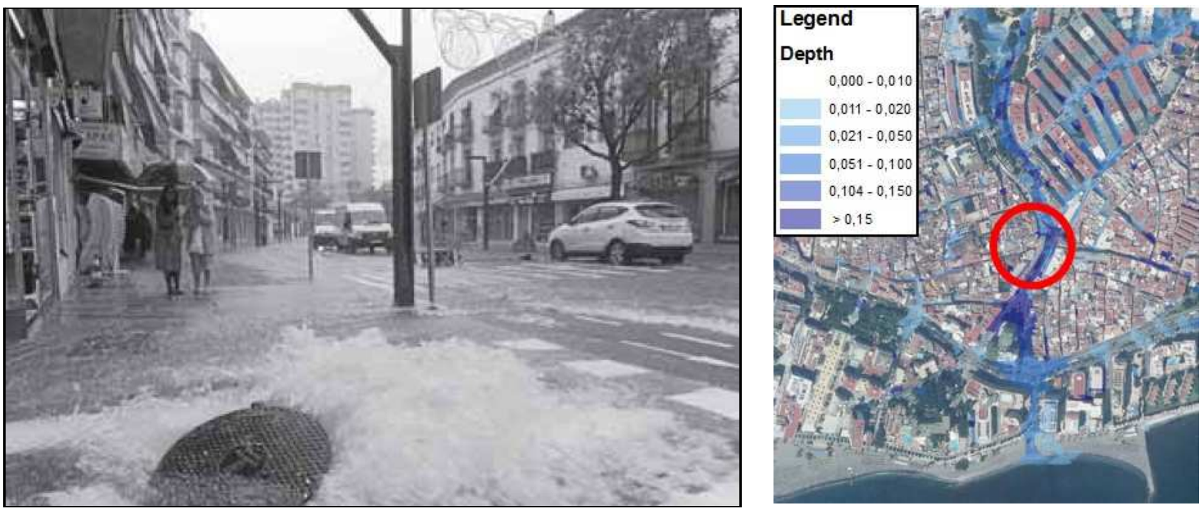


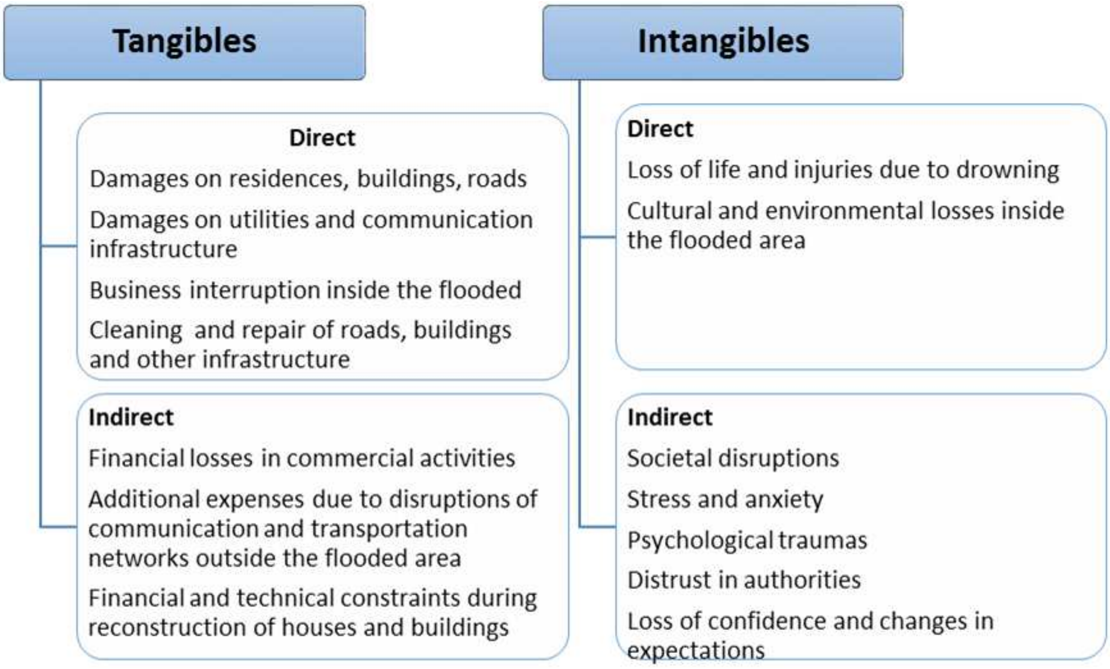
Figure 104: Calibration results for Nabeul Avenue – Flow depth provided for the model for the event December 4th, 2016 were compared to images recorded during this event. On the right, it is possible to observe the water depth map in the cells around Nabeul Avenue. On the left, a photo from a local newspaper shows runoff over the roadway and overflow from the sewer network

6.2.2 WP3- Holistic and Multiple Risk Assessment

The aims of work package 3 in the Marbella Case Study are to assess the economic impacts due to flood events, both the direct and indirect tangible damages, and make the assessment replicable

in order to apply it in other case studies. The methodology used to assess the direct damage was developed in CORFU[3] project (Velasco et al., 2015), but in PEARL a new way of creating Depth Damage Curves has been developed. In contrast, to assess indirecet damages, a completely new methodology has been created. Further information about the methodologies and its the theoretical explanation of it can be found in D3.1 of this project.

Table 28: Damages classification and categorisation (*Jonkman, Bočkarjova et al. 2008; Vojinovic and Abbott 2012)*



Direct damages

For the assessment of the direct damages three different types of data are required: land use information, flood maps and depth damage curves. Land use information capture the type, morphology and use of the builguings in the study case area. Flood maps gather the information about the rainfall events. Depth damage curves are functions that relate the type of building and its characteristics with the depth of floods to account the damages produced by each flood event.

Firstly, for the land use information INE (Spanish Statistical Office) was consulted. Data at building level can be found and are public and free in the INE website. The kind of floods that affect Marbella cause that the only data necessary are related to ground floor and the basement floor. Thus, the following maps were produced with the information regarding the type of use, the dimension of the builduings and the situation within the case study area (Figure 105).

[3] Collaborative Research on Flood Resilience in Urban areas (CORFU) is a major project involving 15 European and Asian institutions, funded by a grant from the European Commission, Seventh Framework Programme. http://www.corfu7.eu/theproject/

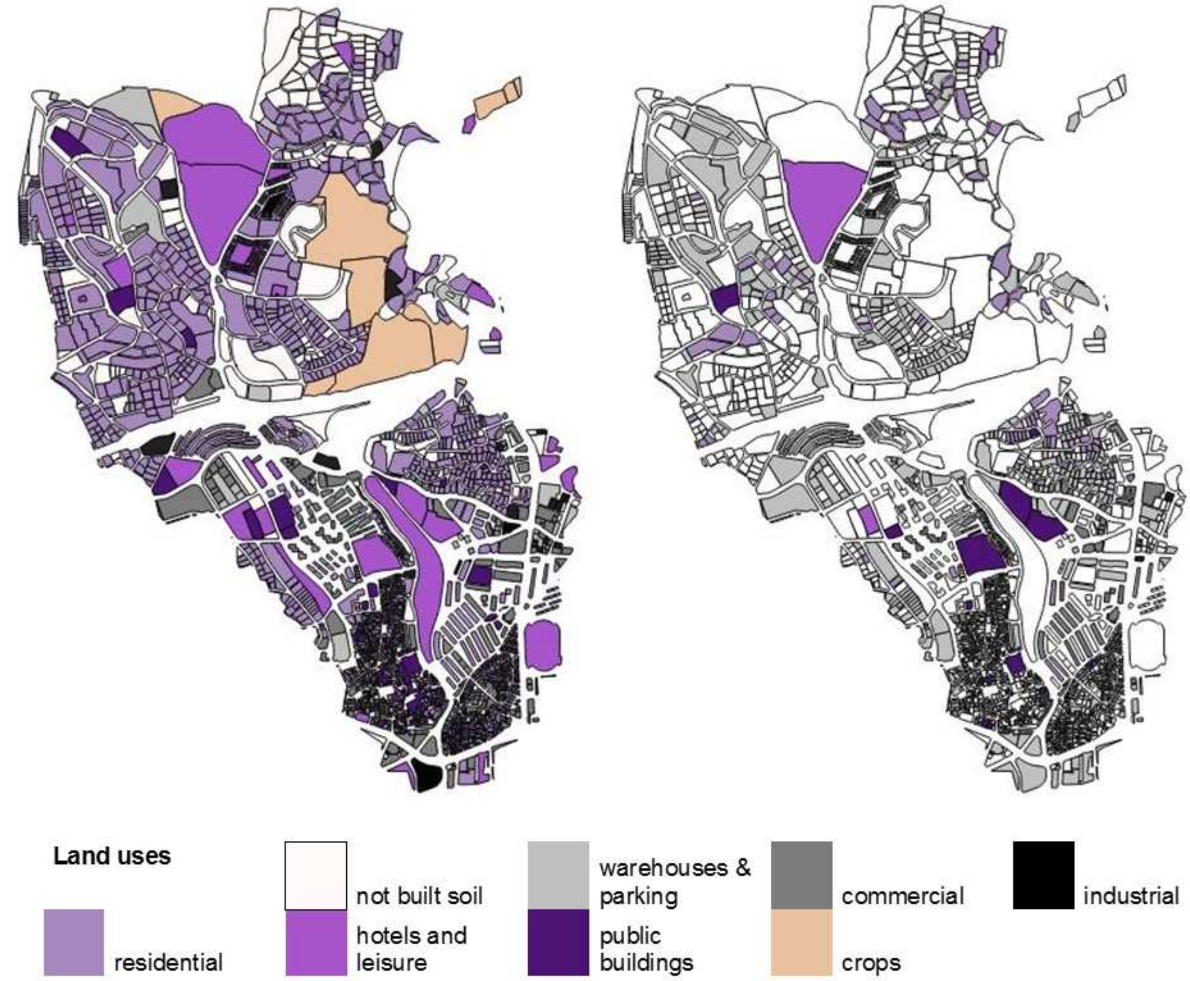


Figure 105: Land use maps for Marbella Case Study, ground floor (left) and basement (right)

Secondly, flood maps were created using the 1D-2D model in order to assess the water depth per each building. Flood maps were produced per 1, 10 and 100 years return period rainfall. As it can be seen in the following figure, the most affected areas are the Huelo and Represa streams. The system manages quite good the 1 year return period rainfall, but it is also noticeable that for the 10 year return period the sewage system starts to collapse, causing a considerable runoff. For the case of 100 year return period, it can be seen that the situation is of a very high risk.

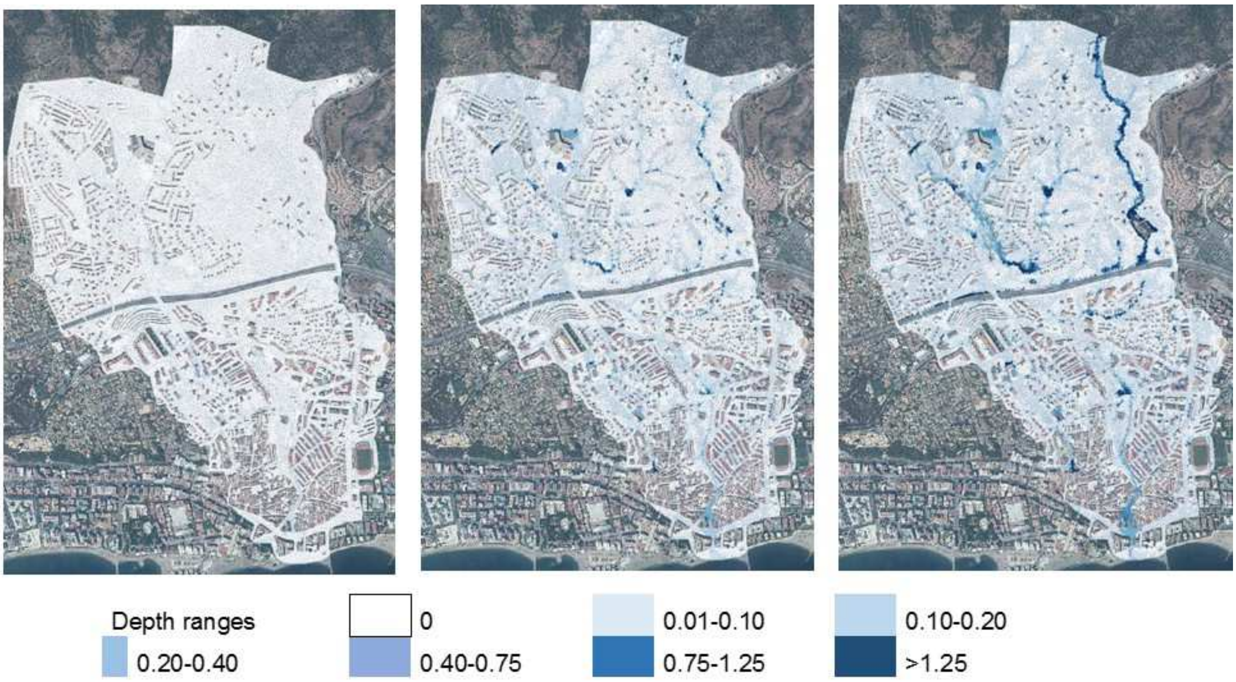


Figure 106: Water depth maps [m] for Marbella Case Study for 1 yr (left), 10 yrs (middle) and 100 yrs (right) return period

The flood maps were obtanined on the basis of an unustructured mesh that covers all the streets of the analyzed catchment. A specific methodology has to be followed to translate the depth from the streets to the buildings. Thus, the depth per each building is assessed taking into account all the depth poligons of the mesh that are in contact with the building. Using the average value of the different polygons to assess the depth in the building the following maps have been produced:

Figure 107: Water depths [m] in buildings for Marbella Case Study for 1 yr (left), 10 yrs (middle) and 100 yrs (right) return period

Last but not least, to assess the direct economic damage it is necessary to have the depth damage curve per each type of land use. Depth damage curves (DDC) are functions that relates the depth

of the water in each kind of land use with the damage per square meter. Moreover, the depth damage curves are developed for contents and for buildings. A detailed study of the past flood consequences using data from CCS (Spanish national reinsurer) was done in order to develop DDC. Per each type of building a typical example is defined. Then, the expected damages for the typical example are assessed both for the building and for the content to create two different DDC. Finally, the DDC were normalized per square meter in order to apply it in every building of each type. An example of the depth damage curves for Marbella is shown in Figure 108.

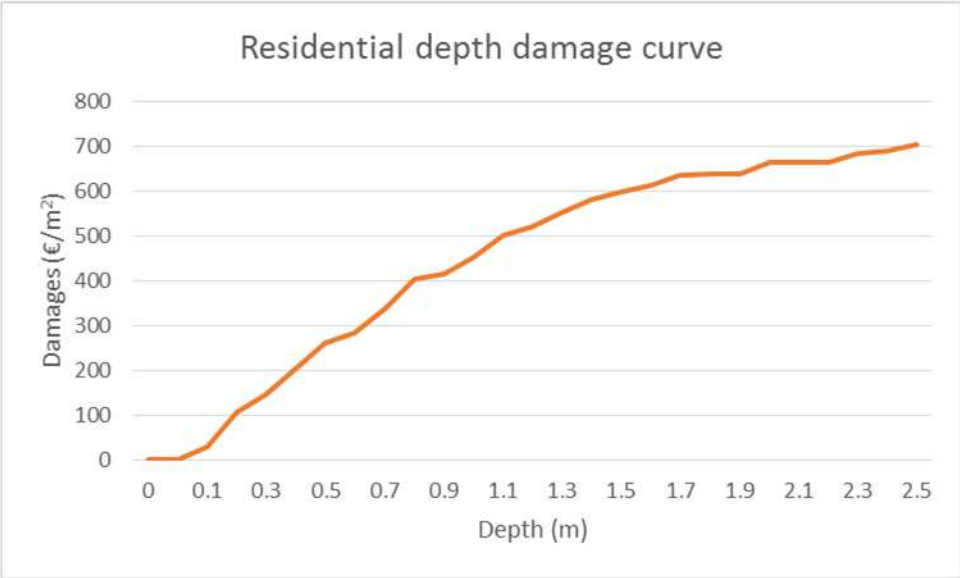


Figure 108: Residential land use depth damage curve for Marbella Case Study

However, the traditional methodology to develop depth damages curves make the replicability of the methodology difficult and costly in terms of time and data. This traditional method implies first a definition of the typical building per each case study, then the definition of the expected damages and the expected costs of reparation or substitutions either for contents and buildings. In order to improve the applicability of the methodology in the other case studies, an alternative methodology for the development of the depth damage curves is proposed. This new methodology consists in taking the most similar depth damage curves available in the state of the art, and using some economic indicators, adapt it to the new case study. This methodology has been applied in the Marbella case study using the depth damage curves developed for Barcelona in CORFU project (Velasco *et al*., 2015). The economic indicators selected for the adaptation were GDP per capita, GDP per declarant, construction prices and land registry data. The first and the second ones were selected by the capacity to assess the purchasing power, while the third and the last ones are chosen due to their capacity to reflect building carachteristics. Then, the results has been compared with the one produced by the traditional methodology in order to define the best indicators for the following case studies. The result of the adaptation and a comparison made with the new methodology will be done in the last year of the PEARL project.

Finally, the expected annual damage (EAD) is shown in Figure 110. EAD is the aggreggation of the expected damage per each return period, taking into account the occurrence probability of each event. EAD is calculated as the area below the curve in Figure 110. The results of the application of the direct damages methodology is shown in the following maps:

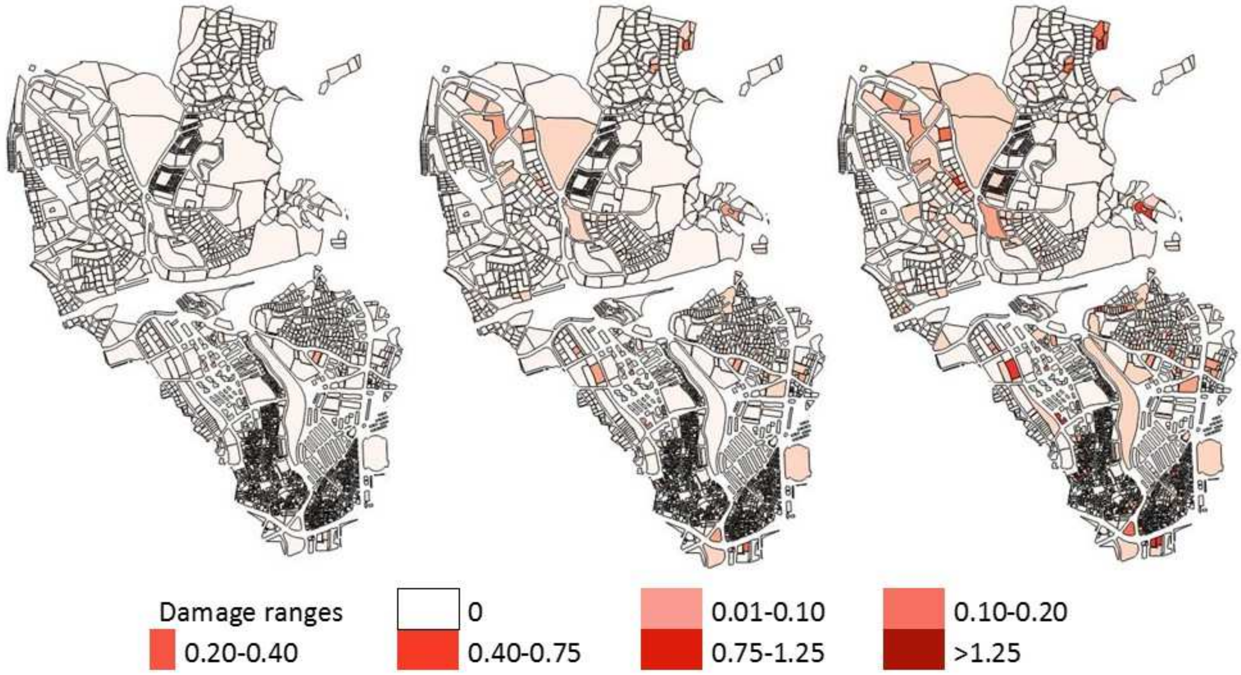


Figure 109: Direct damages (€/m²) for Marbella Case Study for 1 yr (left), 10 yrs (middle) and 100 yrs (right) return period

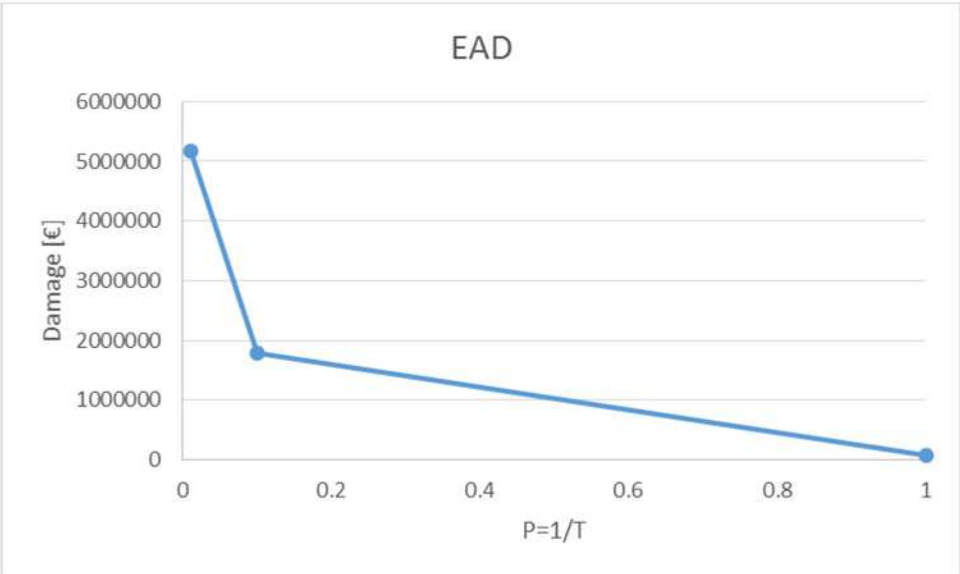


Figure 110: EAD for Marbella Case Study

The result of the EAD for the Marbella case study is 1,159,083.71 € (Figure 110). EAD is used as an idicator of the magnitude of flooding events. It is useful to compare adaptation measure strategies one from another in order to take more informed decisions in urban planing.

Indirect damages

The indirect damages are a cascading effect of the direct damages. The indirect damages try to assess how the direct damages are spread across the closer economic agents. There are several existing methodologies to assess them, but while some are very data and resource demanding, the others are not enough accurate. A complete state of the art review was done within the project. In this environment, a new methodology to assess indirect damages is considered necessary.

This new methodology is based on the current Input-Output methodology. First, a panel of data was created using the I/O methodology since there are not available specific data for the Marbella case study. I/O methodology was choosen because of the high level of accuracy that it provides. Then, using the results of the direct damages assessment per each type of land use and the calculated indirect damages data, and econometric model was created. The aim of this model is to make possible to apply the indirect damages assessment only using the input and output data of the Direct Damages Assessment. But, as the model is based on an I/O table panel of data, the expected accuracy of the model is higher than in a traditional econometric model.

The panel data used for the estimations is attached in the annex 2. Four different methodologies were used to estimate the model: Ordinary Least Squares (OLS), Pseudo-Maximum Likelihood estimator (PPML), random effects and fixed effects. The latter two are techniques within the context of panel data. In all cases, we account for the potential existence of heterocedasticity and autocorrelation. Indeed, standard errors are robust to heterocedasticity and autocorrelation is handled it by applying clusters at the flood event level. Using econometric criteria the most suitable regression was selected and is shown following with the model Eq. 8:

$$
\begin{aligned}
Indirect\ costs_{it} &= \alpha + \beta_1 Direct\ costs_{it} + \beta_2 Unemployment_{it} + \beta_3 Time\ trend_t \\
&+ \mu' D^{Season} + \mu'' D^{Activities}{}_t + \varepsilon_{kt}
\end{aligned}
\qquad \text{Eq. 8}
$$

Table 29: Econometric model coefficients, standard errors and significance; Standard errors are robust to heterocedasticity and clustered by event. Statistical significance at 1% (***), 5% (**), 10% (*). The reference case for the seasonal dummies is winter, while the reference case for the dummies of activities is arts.

	Dependent variable: Indirect costs
Explanatory variables	**OLS**
Direct Costs	0.96 (0.32)***
Unemployment	1350.51 (179.02)***
Time_trend	-9546.88 (840.47)***
Summer	11532.38 (2948.76)***
Spring	284830.3 (29463.3)***
Autumn	44726.98 (6931.75)***
Agriculture	457.19 (155.71)***
Manufacturing	-13339.74 (4543.74)***
Construction	-29174.25 (9936.66)***
Retailing	-85052.89 (28968.75)***
Information	-8.20e-11 (1.75e-10)
Finance	-1.90e-10 (1.98e-10)
Real State	-1.63e-10 (1.89e-10)
Professional activities	-1.35e-10 (1.93e-10)
Public Administration	-1.58e-10 (1.92e-10)
Intercept	-26.85 (2.56)***
R^2	0.44
Number obs.	600

Finally, the selected regression was added to the GIS tool in order to do the indirect damage assessment as the following step of a direct damage assessment.

The damage methodology, including direct and indirect damages, will now be tested and validated through the application in some of the project case studies. The results of applications will be shown in the coming deliverables.

6.2.3 WP4- Flood forecasting and early warning systems for coastal regions

The aim of WP4 in the Marbella Case Study site is to develop new methodologies and tools to achieve fast simulations and to improve early warning. With this purpose, the efforts focused on two main issues:

- The se of GPUs (high performance graphic cards) to achieve faster simulations that allow the simulations of a 1D+2D hydraulic model in real time every time that new precipitation data is available.
- The development of an EWS (Early Warning System) based on radar-nowcasting that allow increasing anticipation in the flood warning.

Use of GPU for faster simulations

The 1D/2D hydraulic model developed using Infoworks ICM for Marbella (see previous sections) has been deployed in a computer with a high-performance graphics card (GPU). The specifications of this computer are the following:

- CPU: Intel Core I7-5820K 3.3GHz
- 32GB RAM DDR4 2133
- Graphic card: Gigabyte GeForce GTX 980 WindForce 3X (4GB DDR5)

- HDD 3.5" 3TB SATA3 and SSD OCZ Vector 128GB SATA3

This configuration allowed to run the full model in real time in less than 5 minutes using the GPU compilation of Infoworks. This run time opens the possibility to run the model in real time (every time that new rainfall information is available: every 10 minutes in the case of the AEMET – Spanish Meteorological Agency– radar network, which covers the Marbella Case Study).

Details of the deployment of the model in the computer with high-performance GPU and the link with the EWS can be found in the Deliverable 4.2.

EWS based on radar nowcasting

Within WP4 an Early Warning System [EWS] for flood forecasting has been implemented in Marbella in order to issue flood warnings.

It uses radar precipitation estimates to calculate radar precipitation forecasting (the following 2h: now casting). With the forecasted rainfall intensities it calculates accumulations over different temporal supports over an intelligent region which automatically adapts itself to the precipitation characteristics (direction and velocity) in order to issue warnings (SMS and e-mail) for forecasted values and reduce false alarms. Details of the radar-based EWS can be found in Llort et al. (2014). Figure 111 and Figure 112 show the radar-based EWS (24h accumulation precipitation field and rainfall intensities field respectively). Those images show one of the most significant events in November 25th, 2016 (used also for calibration purposes in the hydraulic model), where warning based on forecasted precipitation were issued from the developed EWS.

Information of local sensors (rain gauges) has also been incorporated into the EWS and used to issue warnings on their values. Figure 113 shows the registered values for the same day in a rain gauge located at Marbella centre. Warning based on thresholds on sensor registered values are calculated and disseminated in the EWS to confirm the forecast warnings based on radar now casting.

Precipitation information of both rain gauges and radar (observed and forecasted) is used to feed a hydraulic model to issue warning over specific elements of the sewer network in real time (thanks to the use of GPUs in the calculation).

Details of the radar-EWS as well as its link with the hydraulic model will be available in Deliverable 4.5 on M45.

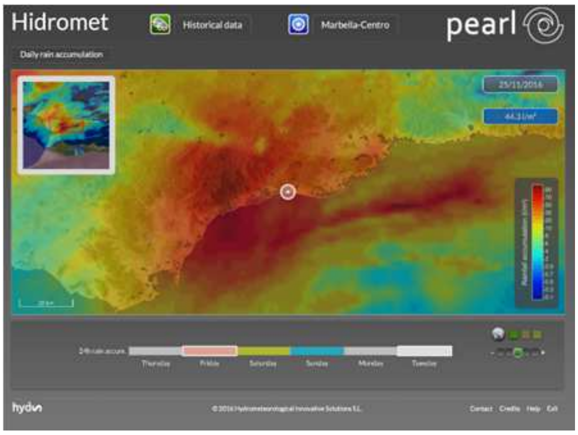


Figure 111: Daily rain accumulation (observed by the radar network) for November 25th, 2016

Figure 112: Instantaneous precipitation values registered by the radar network on November 25th, 2016

Figure 113: Registered values by a rain gauge located at Marbelle on November 25th, 2016

6.2.4 WP5- Decision support and policy development for strengthening resilience of coastal regions

LAAs, Learning and Action Alliances, were set up in order to bring stakeholders together voluntarily, to generate factual knowledge, to share interests and ambitions, but also to analyse the addressing problems, to develop and propose solutions.

Therefore, LAAs are an important tool to change the usual practices adopted by engineers, professionals, stakeholders and decision makers so far. In particular, the main target of LAAs aims to include in the decision making process organizations and people who are indirectly involved in it.

LAAs, so, represent an important bridge between science and stakeholders, because it involves people, organizations, communities and politicians that have interest in implementation, decisions and objectives of the project.

Therefore, LAAs play a key role in providing an interactive tool that might guide the decision-making process. So, LAAs have to be included in projects in order to get an overview of challenges, constraints, objectives and possible strategies.

Definition, setup and functioning of LAAs have been widely analysed in previous deliverables done in 2016, therefore it is suggested to refer to those documents for further information (1st LAA Meeting Marbella 20160202 and Report on 1st stakeholder meeting in Marbella-12 January 2016-Cetaqua).

The overall number of workshops about LAAs planned for the PEARL project is three.

The first one took place in Marbella on January 12st 2016 at the Palacio de Congresos. The LAA organization has been conducted according to the general guidelines, but local requirements have been considered in the final agenda drafting.

Participants were more than 60. The main aims of that workshop were to create an interaction between stakeholders, define issues, share knowledge and ambitions (Report on 1st stakeholder meeting in Marbella-12 January 2016-Cetaqua).

Several stakeholders provided interesting outcomes regarding all the discussion areas and many of those results were similar, therefore a general consensus about the main issues has been observed. The overall balance of the first workshop was definitely positive and it was possible to identify the main issues related to flooding and the main strategies to improve the flood management in Marbella.

The first workshop set the basis for the two following ones that are going to be hold in 2017. Their aim will be to guide stakeholders in order to create a common vision of the city using the outputs from this first meeting to obtain a roadmap that addresses the main issues for the city (Report on 1st stakeholder meeting in Marbella-12 January 2016-Cetaqua). The future meeting are, then, addressed towards a long term vision for the city, which will be developed through the results obtained in the first meeting plus new outputs of several WPs.

6.3 Additional research activities and results

6.3.1 WP2- Understanding formation of hazards under extreme events

In Marbella Case Study the hazard for pedestrians is going to be assessed according the methodology proposed by Martínez-Gomariz et al., (2016a). This procedure takes into account to specific flow parameters (water depth and velocity), which will be obtained thanks a fully coupled 1D/2D hydraulic and hydrological model. This model has been developed for the context of PEARL project involving 68 km of sewers, more than 2,800 manholes and a 2D unstructured mesh with more than 60 thousand cells in basis of a detailed digital terrain model (DTM).

The proposed limits for hazard delimitation are: Low Hazard below the product $(v \cdot y)=0.16 m^2/s$, Medium Hazard for the values $(v \cdot y)$ compressed between 0.16 m^2/s and 0.22 m^2/s, and High Hazard beyond $(v \cdot y)=0.22 m^2/s$. The maximum accepted water depth is proposed to be 0.5 m according to Cox et al. (2010), who considered that threshold as a limiting depth for children stability in a stream. Therefore, Low and Medium Hazard hydraulic conditions are both found below a water depth of 0.5 m.

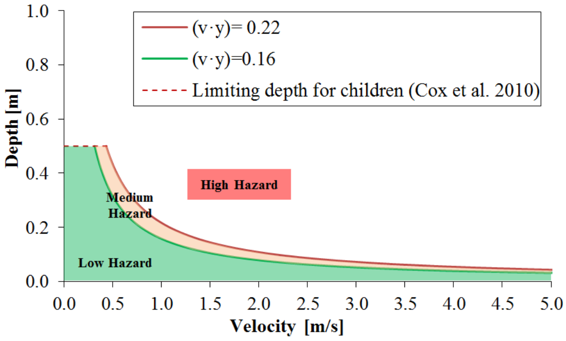


Figure 114: Hazard levels proposed based on the results of Russo et.al. (2009, 2010) and Martinez et.al. (2016c)

For Marbella Case Study 3 synthetic events have been simulated and the results are shown in the following figure:

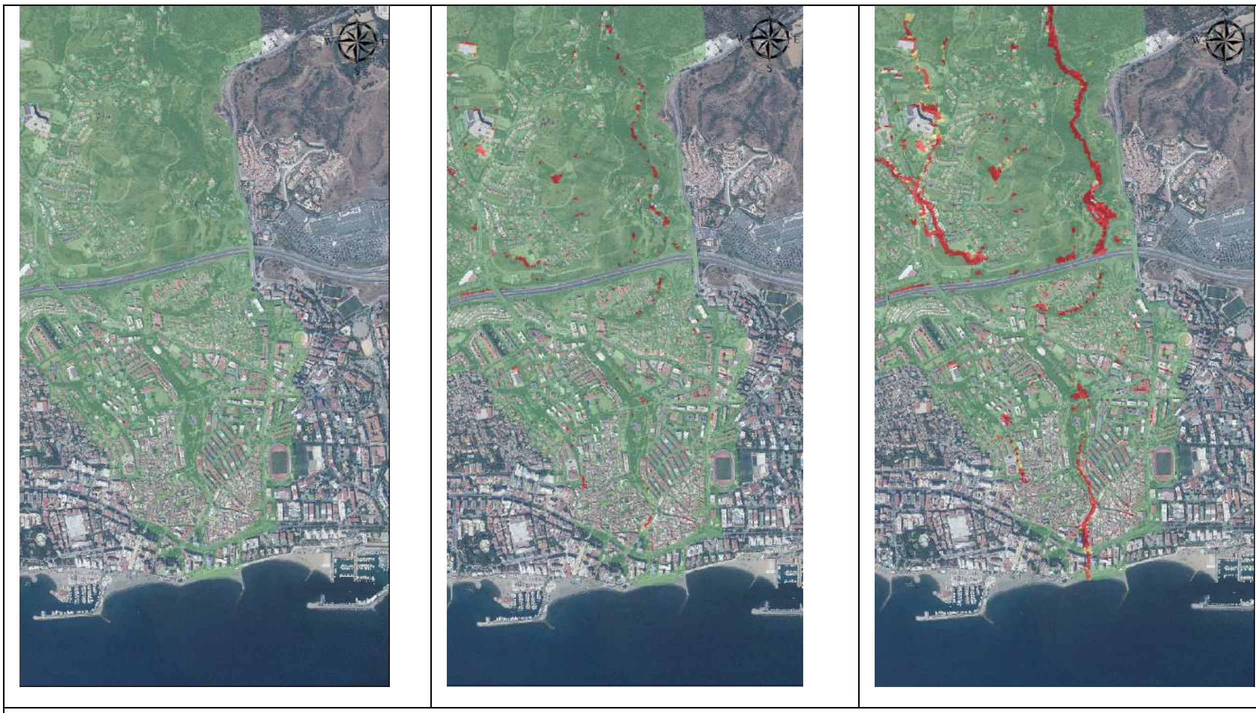


Figure 115: Hazard maps for Marbella Case Study for 1 yr (left), 10 yrs (middle) and 100 yrs (right) return period. The high hazard correspond with the red colour, medium hazards with yellow colour and low hazards with green colour

As can be seen in Figure 115 the most dangerous zones are the stream paths, that within the downtown corresponds to main roads of the city.

6.3.2 *WP3- Holistic and Multiple Risk Assessment*

Indirect damages assessment consists of two different models: the **indirect damages model for business interruption** and the **model for traffic disruption**.

- The former is an econometric model which needs the following inputs: the land uses (i.e. commercial, industrial, residential…) and the direct damages allocation. As a result, it computes the expected indirect damages due to business interruption.
- The traffic disruption model is a SUMO model that computes the increase in distance, time and fuel consumption due to disruptions in traffic as a consequence of a flood.

In this section, a methodology to quantify the outputs of the SUMO model is proposed. As a result of the traffic disruption an increase in the ground transport travel cost is expected (e.g. by car, by train or on bike). It is assumed that commuters use always the more efficient (optimal) itinerary, so that a disruption always causes an increase in costs. This increase in cost is caused by three vectors: an **increase in pollution**, caused by an **increase of fuel consumption** and an **increase in time** spent to reach the destination. In the same way than all the models proposed in the PEARL project, this methodology aims to be easily replicable, so that it can be useful in different places and different times. Therefore, the methodology will not give a number, a price or an equation to monetize these impacts, but will provide recommendations on how to do the assessment and what kind of prices or equations apply. An application example will be exposed using the output of the SUMO case application.

Pollution increase

The effect of Greenhouse Gases (GHG) and Climate Change are an important challenge right now and the studies of their impacts in the economy are increasing. It is also clear that these impacts in the economy increase over time because future emissions are expected to produce larger incremental damages as physical and economic systems become more stressed in response to greater Climate Change impact (IWGSCC 2013). Thus, the first impact to be monetized is the **pollution increase** between the normal traffic situation and the situation in case of flood.

In this study, only the CO_2 emissions from the combustion engines are included, as it is the most relevant GHG emitted in this kind of engines. Exhaust gases from combustion engines can create several other environmental impacts; however, it has been decided to assess only the GHG contribution as it is already an output from the SUMO model. On the other hand, increase in other exhaust gases such as SOx or NOx cannot be obtained from the SUMO model and therefore are outside the scope of this study. In addition, contribution to Climate Change from other GHG such as CH_4 and N_2O are considered irrelevant when compared to CO_2 emissions.

In order to internalize the damage produced by the companies some governments are introducing systems for pricing carbon. There are two main types of carbon pricing: tax on carbon emissions and emissions trading systems, also referred as cap-and-trade systems. The first consists of setting a price on carbon by defining a tax rate on GHG emissions (Pollutant pay principle). By contrast, the latter caps the total level of GHG emissions, to later on distribute permits based on historical pollution rates between the companies included in the system (e.g. in Europe only the highest pollutants are included, which suppose about 40% of the emissions). Then, a market for trading allowances is created, in which the most efficient companies can sell their unused permits, giving them a comparative advantage against the enterprises that need to buy more permits to cover their emissions. In order to increase the efficiency of the companies and reduce the pollution, the cap is then lowered every year. The aim of both systems is to reduce the GHG emissions by internalizing the costs and impacts that they produce. Several countries, states and unions build up tax or cap-and-trade systems. In Europe, there is the EU ETS system that is the larger cap-and-

trade system in the world, accounting for about to 40% of the emissions in the Union. Nevertheless, the number of places where carbon is priced or taxed is increasing over time.

However, these systems only reflect the costs of emitting one tonne of CO_2 rather than the impact of this tonne in the whole economy, due to the prices depending on the supply and demand in the market created for the allowances. The Interagency Working Group on Social Cost of Carbon (SC-CO_2), from the USA, tried to account the effective cost of the emission of one tonne of CO_2 in 2010 (IWGSCC 2010). The study includes (but is not limited to) changes in: net agricultural productivity, human health, property damages from increased flood risk, and the value of ecosystem services due to climate change. Later on, in 2013 and 2015, two revisions where performed to address some issues regarding the models used in the first assessment.

But these studies are not out of discussion: Moore and Diaz (2015) introduced some changes in the Integrated Assessment Models (IAM) used to calculate the SC-CO_2 and it resulted in an increase of more than 400% of the impact caused by 1 single tonne of CO_2. Moore and Diaz found that the impact of a tonne is about 220$ instead of the 37$, which is the average of the different scenarios in the first study.

Taking into account that the goal of the several models developed within the PEARL framework is to assess the effective impact of flood events, it is recommended to use the SC-CO_2 rather than the carbon price. Thus, it is recommended to use the last updated version of the Interagency Working Group on Social Cost of Carbon, which are the figures used in several EPA studies[4]. Four different scenarios are considered in the review, corresponding to different discount rates: average 2.5%, average 3%, average 5% and 95th percentile 3%; and the calculations are done for every year from 2010 to 2050 in 2007€ per metric ton of CO_2. The estimation selected should be consistent with the discount rate used in the overall assessment and the year of the event. The table with the estimations is attached in the Annex, an adaptation is made to convert 2007$ to 2007€ using the annual average EUR/USD rate.

Fuel consumption

Regarding the **fuel consumption** increase, as it is a commodity and its price is dependent on a lot of factors, the recommendation is to look for a price in the time and space when and where the event happens.

Time increase

Finally, the **increase in time** is going to be valued using the methodology of Travel Cost Method (TCM), as the time increase is spent in travel. Note that the increase in time spent travelling is considered leisure time as the working time lost is included in the business damages model. Even though a lot of research was and is made in TCM, a consensus is far from being reached (Czajkowski 2015). A broadly accepted approach is a fraction of wage rate, which is found in

[4] As an example:
- The Joint EPA/Department of Transportation Rulemaking to establish Light-Duty Vehicle GHG Emission Standards and Corporate Average Fuel Economy Standards (2012-2016).
- Amendments to the National Emission Standards for Hazardous Air Pollutants and New Source Performance Standards (NSPS) for the Portland Cement Manufacturing Industry.
- Regulatory Impact Results for the Reconsideration Proposal for National Emission Standards for Hazardous Air Pollutants for Industrial, Commercial, and Institutional Boilers and Process Heaters at Major Source.

several examples Egan et al. (2009), Langemeyer et al. (2015) and Jala & Nandagiri (2015). Different fractions of the wage rate are found in the different studies: from the 0.33 of Egan et al. (2009) to the 0.5 of Langemeyer et al. (2015). Hein et al. (2006) reported rates from 0.3 to 0.6. Thus, a wage is needed to apply the methodology. To assess the wage of all the affected drivers would be time and resources intensive, so this is not considered a feasible option. Thus, the average wage will be used to assess the opportunity cost of travel time. Using the average wage of the area affected by the flood event is recommended, taking into account that the closer the average wage area is to the flood affected area, the better. Concerning the wage rate to be applied, it is recommended to use 0.5 of the net wage, as it is commonly used in some articles (e.g. Langemeyer et al. 2015) and seems a good compromise.

6.3.3 WP5- Decision support and policy development for strengthening resilience of coastal regions

Within WP5, it has been developed a plugin for the web learning and planning platform following the specifications and methodology documents distributed by NTUA and SATWAYS. This plugin links the EWS based on radar in real time with the web learning and planning platform, showing in this last platform, the areas forecasted to have rain accumulations over predefined thresholds in the following hour or two hours (see Figure 116).

In the information of the plugin, besides information of the process followed to calculate radar nowcasting and the areas affected, the user can change the forecasted horizon (1h or 2h) and the accumulation threshold to display. The map shows then the corresponding areas in real time (updated every 10 minutes) covering, not only the Marbella case study, but all the radar coverage.

More details about the EWS generating the radar nowcasts and the areas exceeding the threshold for accumulations will be available at Deliverable 4.5, while information about the plugin itself is available in Deliverable 5.5.

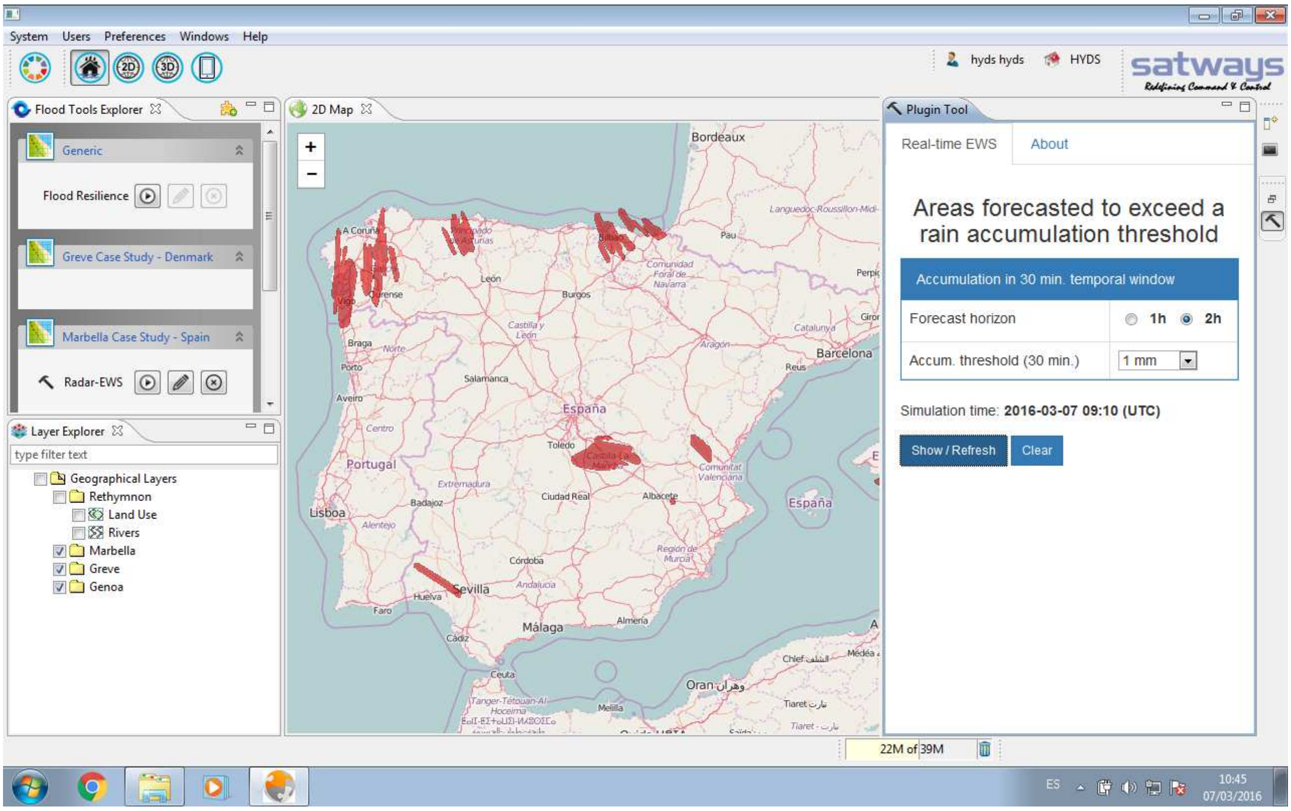


Figure 116: Scree-shot of the Plugin developed for the web learning and planning platform, showing the areas forecasted to be over given thresholds

6.4 Summary and lessons learned

Briefly, the present research activity allowed to have an overall view of the potential damage provoked to properties and assets by flood events characterized by a set of synthetic storms with several return periods.

In order to achieve this outcome, hazard and vulnerability analysis have been conducted obtaining the correspondent maps, which have played a key role to define in detail the economic risk in the analysed catchment. This last result is necessary for the correct flood management in Marbella city due to old and recent flooding problems. The main consequences of typical heavy rainfall events in Marbella are that flooding can happen in a very short time and significant discharges are produced in few hours or minutes. Furthermore, in the recent period, the damage has been increasing exponentially, therefore urgent measures have to be taken as soon as possible in order to avoid losses and to save economical resources which have been spent to recover previous conditions so far.

Besides the hazard increase, Marbella has been also experiencing a raise of vulnerability because of the increasing urban population.

Furthermore, Marbella conditions are further exacerbated because the economic activity of the city relies a lot on tourism, which is heavily affected and damaged by the extreme events that happen with a more and more high frequency in Marbella.

Hazard and vulnerability increases imply that risk has been growing as well. Therefore, in order to manage the flooding risk, more tools have to be available for decision makers.

Then, it is clear that this difficult situation needs measures to be solved and the risk analysis can be considered as a first important step towards the definition of a management strategy that includes efficient measures capable of reducing risk and extreme events frequency or, at least, their consequences on people.

In this context, our research focuses on the need of new efficient and accurate tools. Risk analysis represents a new way of thinking about flooding management because municipalities, companies, organizations and people are now able to have an overall view of the risks that threat their lives, properties and assets.

7 Case Study – Crete, Greece

7.1 Introduction to the case study area

7.1.1 General description of the case study area

Rethymno is one more EU case study examined within the PEARL project with the aim to develop a holistic risk reduction framework that can indentify multi-stressor risk assessment, risk cascading processes and strengthen risk governance by enabling an active role for key actors (Makropoulos C. et al., 2014). Having such an aim, an integrated modelling framework has been developed and applied, enhanced with active stakeholder involvment making at the same time progrees in assisting the flood risk management of Rethymno's coastal community. The area under study is sited at the Region of Crete in Greece and its population stands at 32,468 inhabitants according to Census 2011 (Hellenic Statistical Authority, 2011) with a density 140.12 population/km^2. As the 3rd most populous urban area in the island of Crete, commercial, administrative, cultural and tourist activities are being developed along the north coast where the city is located. The mean absolute altitude is 15 m and the length along the coastline of the area under study is 8 km (Makropoulos C. et al., 2015).

Figure 117: Location of Rethymno case study, Crete, Greece

7.1.2 Hazard and risk situation in the case study area

Multiple stressors have always posed flood threats for the city of Rethymno in Crete. The flow of stormwater through the city, the large number of streams that cross it and the rapid transition from the steep slopes at the upstream rural areas to the flat urban zone imposed significant pressure to flood defences. The coastal zone is also exposed throughout the years to strong N and NW winds resulting in the development of waves, which often overtop the harbour infrastructure and erode recreational beaches. Historic flood events led to adverse human, material, economic and environmental effects and eventually to the selection of engineering prevention and mitigation measures. Major historic flood events with high impact to the city's life and infrastructure occurred on *February 29th, 1968, February 6th, 1984, October 28th, 1991 and November 10th, 1999*. Primarily cause of those flood events was heavy precipitation along with insufficient flood protection infrastructure. Nevertheless, the multiple forcing variables from the urban and coastal area still result in flood problems as it was evidenced by recent flood events. On January 1st and 13th, 2015 and on February 10th, 2015 the flood problems took place at the adjacent areas of the port and in

parts in the Old Town of Rethymno as a result of storm surges and extreme violent wave overtopping of port infrastructures.

Desk based study, data collection and field visits enabled the researchers to initiate flood risk assessment of Rethymno case study, but understanding flood problems through the stakeholders' perspective was of primary importance for the actual comprehension of flood risk. While hosting the 1st official LAA workshop in Rethymno (October 1st and 2nd, 2015, please refer to Gourgoura P., Lykou A., and Koutiva I. (2015)) an activity was carried out aiming at "establishing facts" and grasping stakeholders' risk perception. By marking on a city's map along with comments, information was gathered in terms of hazards e.g. places where flood problems occur, types of flood, frequency, etc. Figure 118 below depicts the areas which are under risk today according to stakeholders' perspective and Table 30 provides a brief description.

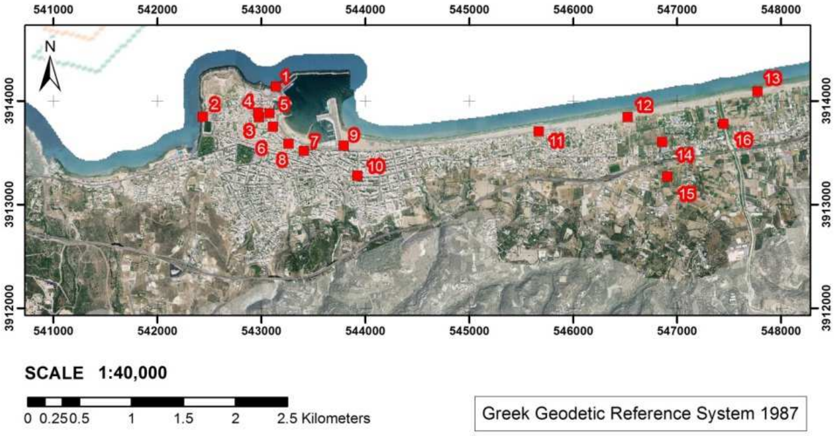


Figure 118: Rethymno flood problems as described and identified by stakeholders

Table 30: Area of occurrence and flood problems of Rethymno as described and identified by stakeholders

ID	Problem	Area of Problem	Brief description provided by authorities
1	Wave Overtopping	Parking Area of Port Facilities	Inundation of the Old Town of Rethymno
2	Wave Overtopping	Sochora Area, Peripheral Road	Inundation of Peripheral Road
3	Pluvial Flooding	Old Town of Rethymno	Coverage of drainage inlets, low lying areas
4	Pluvial, Drain & Sewer Flooding	Loggia Area	Elevation +0.60, coverage of drainage inlets
5	Pluvial, Drain & Sewer Flooding	Museum Area	Low lying areas & low capacity of drainage network
6	Pluvial, Drain & Sewer Flooding	Arkadiou str.	Low lying areas & low capacity of drainage network
7	Pluvial Flooding	Agnostou Stratioti Square & Arkadiou str.	Low lying areas, accumulation of stormwater
8	Fluvial, Drain & Sewer Flooding	Outlet of Kamaraki - Kallergi & Arkadiou str.	Old Lavirinthos, 06/02/1984 & 1999 flood event
9	Pluvial, Fluvial & Coastal Flooding, Sedimentation	Delphini building, Technical Department premises	Flooding of the building, sedimentation of outlet
10	Fluvial, Drain & Sewer Flooding	Sinatsaki stream	Overflow during high discharges
11	Coastal Flooding	Perivolia, west area of Pearl Hotel	Flooding of houses & plots
12	-	Interchange of Amari	Concerns for future flood problems that might occur due to new road infrastructures
13	Coastal Flooding	Missiria & Platania area	Sea intrusion, construction of small sand dikes
14	Pluvial Flooding	Missiria area, upstream &	Low lying areas, gentle slopes, no flow

		downstream of National Road	
15	Pluvial Flooding	Missiria area, upstream & downstream of National Road	Low lying areas, gentle slopes, no flow
16	Fluvial	Platanias river	Overflow at river at the part between the National Road to the sea

7.1.3 Current institutional and governance practice

The legal framework concerning flood protection and relevant management plans in Greece is formulated by the policies, priorities and responsibilities of authorities as described in the following legal international and national documents. Those documents are:

- The EU Floods Directive 2007/60/EC
- The Strategic plan on the Greek National Platform for Disaster Risk Reduction (Hyogo Framework of Action)
- The Circular for planning and action of Civil Protection to tackle flood risks produced and circulated by the General Secretariat of Civil Protection

The **Floods Directive** (Floods Directive 2007/60/EC) of the European Parliament, which was officially entered into force on November 26th, 2007, aims at the reduction and management of flood risks that affect human health, environment, cultural heritage and economic activities. Through the directive EU Member States are engaged to proceed to: assessment of the potential flooding risks of all water courses and coast lines; mapping of the floods extent, assets and humans at risk in these areas; and promotion of implementation of adequate and coordinated measures for the reduction of those risks. The Directive also strengthens the rights of the public to access this information and to participate in the planning procedures. In terms of Rethymno, the Floods Directive is being implemented at the spatial scale of Crete without producing any results for the city of Rethymno, since no potentially high risk zones were identified during preliminary assessment. The above fact is being justified due to the large spatial scale of directive's implementation which is the water district. Currently the results (reports and maps) of the conducted assessment are being published on a website under the Ministry of Environment and Energy[5] ("Flood Directive 2007/60/EC of the European Parliament and of the Council of 23 October 2007 on the Assessment and Management of Flood Risks,").

The **Strategic plan on the Greek National Platform for Disaster Risk Reduction** (DRR) has been set up since June 2012, as Greek obligation derived by the Hyogo Framework of Action (HFA) (GSCP, 2015), which commits all nation states to proceed to the establishment of similar platforms. The National platform is actually a network of civil protection services, authorities and organizations including private sector, research institutes and voluntary organizations. Main objective is the integration of DRR agenda in the decision making procedure at local and national level which aims to reduce risks of natural or technological disasters and to promote the principles of HFA and especially the culture of prevention (Mavrogenis S., 2016). Detailed analysis regarding DRR in Rethymno is provided in RRCA report for Rethymno (Mavrogenis S., 2016) and Deliverable 1.3 document (Fraser A.; Sorg L. et.al., 2016).

[5] Official Website where the results of Floods Directive implementation at water districts are being published: http://floods.ypeka.gr/

The Circular for planning and action of Civil Protection to tackle flood risks is updated every year (usually every autumn and provided by the General Secretariat of Civil Protection - GSCP). The circular takes into account the national law and the EU Floods directive and define: the categories of structures for flood protection that aim to reduce floods and mitigate their effects; and the necessary civil protection measures for securing preparedness for the confrontation of emergencies and the direct management of their consequences. Furthermore, it provides a National framework for flood management, relevant strategic planning and coordination of measures and activities of all involved civil protection services and departments on national, regional and local level: Regions, Regional Units, Decentralised Administrations, Municipalities, Police and Fire Services, as also the GSCP itself ("The Circular for planning and action of Civil Protection to tackle flood risks - General Secretariat of Civil Protection "). The document also engages the authorities and involved institutions to proceed to Memoranda of Activities which describe exactly the standard operational procedures, the responsibilities and the role of each department in flood management, emergencies and civil protection measures.

Besides with the above research of the legal framework in Greece, PEARL researchers had to go through a stakeholder's analysis, to get a comprehensive overview of the institutional situation and governmental practices as well as of the administrative system and procedures regarding flood risk management and protection for Rethymno. Key aims of this desk research were: the identification of the different institutions or authorities and their role in flood management; the communication among them; the coordination of activities across the different levels of governance (national, regional, local and citizens); and finally all possible barriers, lack of communication or hierarchical gaps that complicate flood risk management.

On a second level, meetings were held with the respective local and regional authorities and institutions. Main objectives of those meetings were: the comprehension of Rethymno's flood problems during the past years; the solutions/strategies/measures implemented towards flood defence; their future plans and ambitions; the interdependencies among the different authorities; the flow of information and the hierarchy in flood related issues; the data collection; knowledge and experience transfer (details on the meetings are stated on Deliverable 5.1 document (Sorg L. et al., 2016)).

The authorities' roles in decision making procedure are illustrated in an organizational chart/sociogram, as an attempt to figure out the flow of communication and decision making among the organizations and/or their services. The chart displays the key stakeholders, ways of interaction, and highlights the gaps in communication and knowledge sharing. Full description of institutions, responsibilities and the organizational chart are included in the PEARL Milestone 14 document (BlätgenT., Gourgoura P., & Lykou A., 2014).

The main point emerged from the above analysis and interaction with stakeholders during workshops, was the lack of effective communication among them, bad monitoring of the different authorities' activities and barriers derived by the several levels of hierarchy or conflicting interests. The advanced bureaucracy in Greece, the segmentation, and quite often the overlapping of responsibilities among multiple levels of governance produce communicational and monitoring gaps which result to poor flood risk governance. Gaps in communication among the many services and bureaucratic procedures were highlighted by most of the local stakeholders too (Gourgoura P. et al., 2015).

In addition to the complicated administrative governance, the current financial crisis in Greece has resulted to a downgrading of flood risk management and civil protection policies. As a result of the three Memoranda (2010, 2012 and 2015) and the accompanying austerity measures, the public sector's budgets and expenses have been reduced dramatically. As a consequence is that most of the public services, especially local and regional ones are understaffed, e.g. The Civil Protection Department of the Regional Unit of Rethymno consists of one employee. Many qualified public servants have been retired while no replacements have been made. At the same time the legislative changes combined with the implementation of the memoranda fostered the facilitation of investments and not the implementation of environmental law and the promotion of resilient strategies that respect the environmental priorities (Mavrogenis S., 2016). Lack of sufficient funding and the understaffed environmental public services have downgraded even more the flood risk governance performance, as a consequence of the general environmental governance performance. The RRCA report provided for Rethymno, under WP1, also highlighted the above issues and actually proved the input provided by stakeholders' analysis and meetings (Mavrogenis S., 2016).

Furthermore the financial crisis has resulted to a continuous unstable political situation in Greece. National elections in January and September 2015, have caused a low activity record of key Directorates and Ministries responsible for flood management. Due to repeated changes in Ministries' structure and departments, the responsible people were either not officially in charge to take action or not willing for quite some time. This problematic situation in Central Government and Ministries has as consequence, poor governance (Gourgoura P. et al., 2015).

Finally, it has been identified that most of the activities and implemented strategies are of post disaster management and there is a lack of strategic planning for prevention and mitigation of potential risks (Fraser A.; Sorg L. et.al., 2016). The absence of awareness raising activities, efficient early warning systems and adequate information of the public was also highlighted. Many flood risks in Rethymno are the result of individual activities and intervene in the flood risk evolution (Gourgoura P., Lykou A., & Koutiva I., 2016). As realised through the discussions and the activities during several technical meetings and two LAA workshops with stakeholders, Rethymno doesn't really need more structural measures but awareness raising. Sensitising citizens and building on more responsible civil behaviour are of primary importance and should be first implemented. Most of the actions that need to be done to enhance the flood protection of the city, are in terms of awareness raising of the several citizens' groups (residents, business, engineers/contractors) (Gourgoura P. et al., 2015). Nevertheless, having collected such information in terms of existing flood defences, the location of all collected engineering works that has been implemented or are/were still under construction has been presented on a map (Figure 119) and summarized at Table 31.

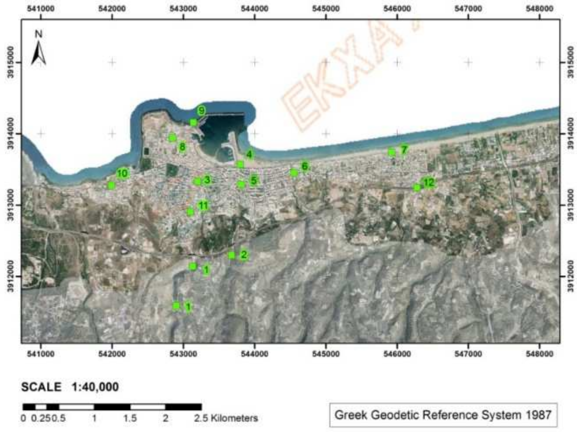


Figure 119: Rethymno's flood defence infrastructure as described and identified by stakeholders

Table 31: Brief description of Rethymno's flood defence infrastructure as identified by stakeholders

ID	NAME	DESCRIPTION	EFFICIENCY
1	Kamaraki 2	Flood control dam	yes
1	Kamaraki 1	Flood control dam	yes
2	Sinatsaki	Flood control dam	yes
3	Diversion of Kamaraki	Partial, possible overflow to the sea	yes
4	New outlet of Sinatsaki	Construction of new box type drainage	Anticipated yes, very recent to evaluate
5	Arrangement works of Sinatsaki	Structures arranging Sinatsaki stream	Unknown
6	Arrangement works of Koraka	Structures arranging Koraka stream	Unknown
7	Arrangement works of Koutsolidi	Structures arranging Koutsolidi stream	Unknown
8	Separate stormwater network of the Old Town	Network & drainage collectors	yes
9	Armour works of Port Facilities	Engineering failure of study for armour stones	No
10	Studies of drainage network at Koube area	Study to be implemented	Unknown
11	Drainage network at Mastaba area	Partially constructed, Q capacity questioned	Unknown
12	Engineering works of Amari's interchange		Unknown, Under Construction

7.1.4 Available data used for research activities

Within the case study work, information and data has been harvested by several sources. Those might be summarised as follows along with the type/topic of information obtained:

- The National Cadastre and Mapping Agency S.A.: Digital Surface and Earth Models
- The Hellenic Statistical Authority: Statistical and geospatial data obtained from the three last Census (1991, 2001, and 2011)
- Open data sources, National or International e.g. Corine database, GEODATA.gov.gr, ENYDRIS etc.: Land use, administrative boundaries, hydro-meteorological data etc.
- The Hellenic National Meteorological Service: Precipitation and wind data
- National Observatory of Athens: Precipitation data and wind data

- Site of Ministry of Environment and Energy: Preliminary assessment and material of Floods Directive implementation
- Institute of Mediterranean Forest Ecosystems and Forest Products Technology: Land and vegetation maps
- Technical Department of Rethymno's Regional Unit: Studies of port facilities as were originally conducted and implemented
- Civil Protection Department of Rethymno's Regional Unit: Precipitation data
- Organisation of the Development of Crete S.A.: Dam breach study of Potamon dam
- Technical and Planning Department of Rethymno's Municipality: Geospatial data of the urban area e.g. road network or the general urban planning and existing studies that have been conducted related to PEARL objectives e.g. coastal engineering study aiming at the construction of reef breakwaters.
- The Water Supply and Sewerage Company of Rethymno: Reports of studies from flood protection infrastructures and assumptions of their design and general guidance/information on operating systems and networks
- The Port Authority of Rethymno: Updated studies of port infrastructure regarding extensions and future plans e.g. in order to facilitate cruise ships or seaplanes
- The Fire Departments of Rethymno: Standard Operational Procedures documents
- Former Mayors: Photographic material and reports on past flood events and damages
- Freelance civil engineers in Rethymno: Stormwater studies and drawings
- LAAs workshops, technical meetings with Rethymno's authorities and online questionnaires: Primarily related to flood management procedures and risk perception and awareness
- Household door to door survey (conducted by IREUS): Citizens risk perceptions and awareness
- Literature review and scientific documents
- Newspaper, Websites and Blogs:
- Information related to flood event and damages
- Field visits: Photographic material of infrastructure, damages and flood problems

7.2 Key research activities and results

7.2.1 WP3- Holistic and Multiple Risk Assessment

As stated in the case study description of this report, Rethymno is a coastal EU city facing multiple flood risks which have great impact to city's residents, homes, business and public infrastructure. Therefore, risk assessment and evalutation of risk under multiple scenarions was one of the primary odjectives within Rethymno case study. This objective led to the development of an integrated framework which combines different models and methodologies utilised in the simulation

of flood risk and the understanding of hazards. The primary components of this framework are comprised of the followings (Figure 120):

1. Estimation of atmospheric variables and development of climate change scenarios
2. Estimation of Wave Characteristics (4-level downscaling approach)
3. Modelling of nearshore response to hurricane impacts and storms (e.g. storm surges, wave propagation, sediment transport, erosion, wave diffraction and refraction, etc.)
4. Catchment hydrological modelling (incl. hydraulic calculations of natural channels networks)
5. Urban flood modelling (incl. surface flow & stormwater network)
6. Comparing alternative solutions suggesting interventions for damage repair & protection

Figure 120: The integrated modelling framework applied in Rethymno

While trying to understand downstream stressors from the coast, the components of this framework include a sequential process working on different spatial and temporal scales, starting from the level of climatic analysis at a regional level and ending with the simulation of wave overtopping at port facilities and wave run-up at the shore. While trying to investigate the physical processes and the wave climate in Rethymno's coastal region that lead to storm events with serious impact on the hydrodynamic circulations, simulations of wave propagation for the period 1960-2100 (hind casting and forecasting) has been performed. Following the procedure described **Error! Reference source not found.**in Deliverable 3.4 of PEARL and carrying it out considering different scenarios of wave characteristics (duration, wave height and period) in order to distinguish the events that have the most serious effect on the wave over-topping at the place of the coastal structures, several storm events were identified.

For the inland area, a comibnation of 1D-2D MIKE models (MIKE 11, MIKE 21FM and MIKE Urban) has been setup and coupled through MIKE Flood **Error! Reference source not found.**for the simlautaion of flood events and their propagation in space and time. The combination of highly sofisticated models along with the high accuracy of data such as the DEM of 2 m spatial resolution, has resulted in long computational times and heavy computational loads which then led to the decision of creating two different set up of the urban part (Area 1 – West area of Rethymno, Area 2 – East Area). Focusing on Area 1, the 2D model covers 6.06 km^2 of Rethymno's coastal area comprising of both sea and inland regions, and its mesh is comprised of 774,619 elements varying in size from 0.064 m^2 to 500 m^2. Small mesh elements were used for built-up areas, roadways and flood plains, while bigger elements were used for rural and sea areas.

One of the precipitation event which has been used as catchment loads in model set ups, was the one recorded on November 10th, 1999 (127.4 mm in total, 100 mm fell in 2 hrs time period), since it had major impacts to city's functions and services. The simulation period for the aforementioned

event lasts 12 hours with a time step varying based on model setup versions. Further, while trying to be consistent with the work described in the Flood Directive, a precipitation event of 100 years return period was also simulated. Indicative results of water depth are being presented in Figure 121. Most vulnerable zone in the west part of Rethymno is Akradiou Street, and especially the area around the museum. Those areas corresponds to number (4), (5) and (6) of Figure 118. Specifically, at the area of museum (4) the maximum water depths derived from simulations is 1.57 m for 1999 event and 1.71 for 100 year precipitation event.

Apart from precipitation loads, the coupled urban models have been set up in order to simulate storm events related to the coastal pressures. Until now, two storm events have been simulated using the 2D hydrodynamic components of MIKE models. Those are the event on January 27th, 19:00, 1961 (end of simulation January 31st, 23:00, 1961) of North Direction, category 4 and the one starting on March 1st, 3:00, 2027 (ends on March 4th, 2:00, 2027) of North direction and category 5. During set up of those scenarios, profile series of water surface have been extracted from coastal results and used as boundary conditions for the urban modelling. Unfortunately while running those simulations, they gave no inundation to the inland area which is justified by the fact that the hydrodynamic component is incapable of simulating overtopping phenomena during of which volumes of water intrude the adjacent zones of port facilities and inundate part of the Old Town. Therefore, new simulations are currently being set up in order to use as point source the resulted discharges from overtopping estimation and simulate their propagation is space through the 2D hydrodynamic component of inland models.

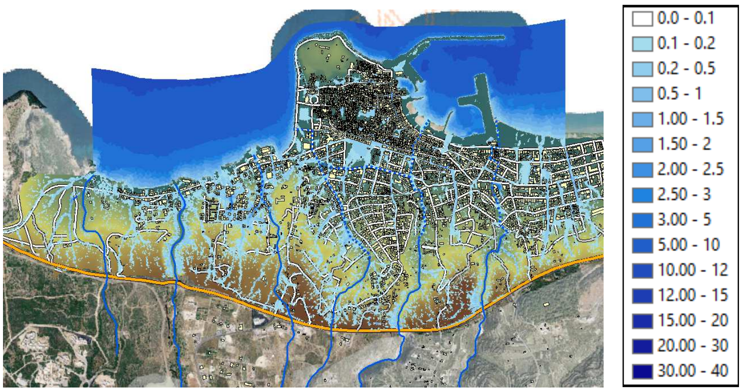


Figure 121: Results of water depth derived from the simulation of flood event recorded on November 10th 1991

Apart from the simulations that have already been completed, additional ones will be performed in order to simulate different hydro-meteorological scenarios that stakeholders would like to have available and examine through the WebLP platform of WP5. The simulations will be performed for Area 2 too. Scenarios of failure of infrastructures will also be examined e.g. dam breach of Potamon dam, as well as the impact of different urban growth scenarios. By running a CA model modified and enhanced within PEARL by NTUA, different land use will be provided affecting roughness values hence, altering possibly the flood phenomena.

Vulnerability assessment has also been performed in Rethymno, following the suggested framework which has been developed in WP1. While utilising all available geospatial and statistical data, vulnerability assessment was conducted at a block scale after its three components i.e. susceptibility, lack of coping and lack of adaptive capacity were estimated. All assumptions, indicators and their weighting used in order to produce the maps are being described in

Deliverable 3.4 of PEARL. The final vulnerability map has been produced after performing min-max normalization of resulted values so that the newly derived values of vulnerability will range from 0 to 100. In this way, the map will be immediately comprehensible for further discussions with Rethymno's stakeholders during the last LAA meeting which will take place towards the end of the project. For the representation of results, the quantile method was used for 5 classes of vulnerability (Very High, High, Medium, Low, and Very Low).

Based on the outcomes of vulnerability assessment it becomes apparent that the social vulnerability is very high at the east area of Rethymno, at the adjacent zones of Platanias River. The above results have been produced while utilizing statistical data which has to do with the categories: demography, poverty and income, housing and neighbourhood conditions, social network, access to medical service, action, information, education and research and finally gender equality.

Along with additionally scenarios, an extended vulnerability assessment approach will be possibly fulfilled at the last year of PEARL, so that the data collected from Rethymno's household survey (conducted by IREUS) to be incorporated too. After having fulfilled hazard and vulnerability assessment, risk assessment was conducted and final flood risk maps where produced for the west area of Rethymno (Figure 122).

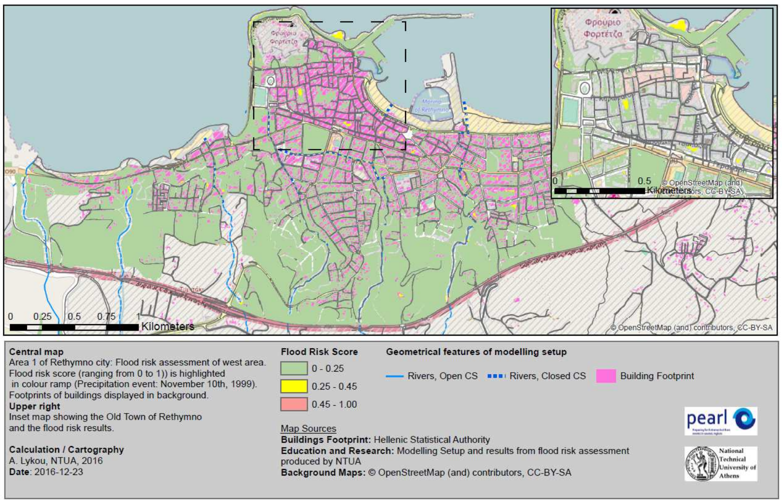


Figure 122: Flood risk map for Area 1 of Rethymno (results from simulation of recorded precipitation event on November 10th, 1999

All the above described work and results are part of Deliverable 3.4. At the upadated version of this document which is planned to be be submitted towards the end of the project, all components of flood risk assessemnt will be enriched with additional results due to the examination of additional scenarios and the final flood risk maps will be produced for the whole area of Retymno since set up of models will be expanded for the Area 2.

7.2.2 WP4- Flood forecasting and early warning systems for coastal regions

T4.2

Within the content of developing a modellig framework for flood risk assessemnt in Rethymno, a complex model chain was set up demanding great deal of computational power. Being consistent with the aim of this task, alternative procedures and guidelines were described and implemented

for the minimisation of computational loads and the maximisation of computational power within the modelling work. Havind described the susceptibility of Rethymno to multipe physical pressures along with its complex topography, a combined set-up of sophisticated models was required for the simulation of flood phenomena. Rethymno flood models employ a 3-way coupling of 1D and 2D simulations engines (DHI's MIKE models), enabling analysis of urban, coastal and riverine flooding under different precipitation scenarios (past recorded events or produced under different return periods) (Deliverable 4.2).

Followng the general guidance described in Deliverable 4.2 and DHI's suggestions, the following speed-up techniques were tested and evaluated with Rethymno urban coastal flood model. Those are the following:

1. Selection of model domain, computational grid type and elements size
2. Modification of modelling approach
3. Maximising computational power

Key lessons learned extracted during mesh generation related to component one of the above list and eventually adopted in order to enable the creation of new mesh files in shorter time were:

- Division of area under study into smaller parts and use of local maximum element area parameter depending the areas of interest and the necessary/desired resolution (type of domain and available DEM resolution)
- Generation of mesh step by step in each sub-area since it enables to easily locate problematic areas obstructing mesh generation e.g. invalid arcs
- Instead of defining only the maximum element area, it is advisable to control the resolution of mesh through geographical entities e.g. roads polylines or building polygons
- Gradually increase mesh resolution and complexity and test it through initial simulation

While applying the first and second speed up technique, the set up of operational and functional models which ensured normal run complete of simulations was possible. The use of MPI method instead of OpenMP gave a speed up factor amost equal to 1.42. The total overall gain while comparing the performance of the two computers along with GPU computing resulted in the greater speed up factor of around 6. Comparing the computation time of the two apparoches i.e. applying rain on grid on the domaim or distributing runoff to a fictive network, it was evidenced that the simulations lasted aroung 7.9 times more when 2D rain was used. Further details on all three speed up approaches, computational times and compariosn of results are being provided in the Deliveralble 4.2 (PEARL Consortium: Lead Author: DHI, 2017).

7.2.3 WP5- Decision support and policy development for strengthening resilience of coastal regions

T5.1

The objective of task 5.1 is the identification of key stakeholders involved in decision making procedure regarding flood risk management in Rethymno and the establishment of a local Learning and Action Alliance (LAA) that will be evolved along three axis (based on methodology of Van Herk S., Zevenbergen C., Rijke J., and Ashley R. (2011)): establishing facts, creating common images and setting shared ambitions. Towards this direction PEARL researchers proceeded to a

stakeholders' analysis and additional technical meetings with key services and organizations (as described already above in chapter 7.1.3 of this document).

Based on theory and methodology of LAAs (which is fully described in Milestone 14 (BlätgenT. et al., 2014) and Deliverable 5.1 documents (Sorg L. et al., 2016)) applicable for the implementation and running of one LAA there are several procedural steps to follow. Referring to Ashley R.M. and Blanksby J.R. (2009), Ashley R. M. et al. (2012), and Dudley E., Ashley R., Manojlovic N., van Herk S., and Blanksby J. (2013) present a practical guidance for the design and running of a LAA.

Taking into account the above suggested methodology, the establishment process of the Rethymno LAA has been built on the implementation of rounds of workshops. Three rounds of interactive workshops are foreseen (TASK 5.6) for the whole project duration while at this point two of them have already been implemented. Aims of those workshops (among other PEARL objectives) are to launch the concept of LAA to stakeholders, to promote the establishment and secure the functioning of the initiative. The detailed analysis of the workshops procedure and results is stated under TASK 5.6 paragraph of this chapter.

Concerning the LAA progress the reactions of the stakeholders could be rather considered positive but also hesitating. Despite the increased interest expressed by all participants and authorities' representatives, several doubts and concerns were raised at the same time. Indeed there is a general sense that a LAA in Rethymno would be an asset in terms of flood management for the city, and all participants agreed to give a chance to an innovative approach, but on the other hand many of them rely on a pessimistic view that not many things can be done. The fact that no "leaders" were identified among the participants, who will be willing to actually run the LAA turns the success of the initiative doubtful (Gourgoura P. et al., 2015).

Although positive results and comments followed the workshops a clear evaluation of the LAA itself is not feasible yet since the LAA is not yet self-running, and potential members of it have not taken any action. During the 2nd workshop specific actions were decided but so far nothing has happened. The future workshops and NTUA's activities in the case study area, as well as the completion of tools development (PEARL platform, knowledge base, and water detective application) will further support and promote the LAA initiative, as it will help locals to work on specific scenarios and accordingly act or/and collaborate. Consequently the LAA could be considered to be still in initial stage (Gourgoura P. et al., 2015).

It is crucial to highlight that regardless the progress of LAA function, key points that define the direction of future action, have already been identified and commonly agreed by the participating groups. Those are the following:

- **The necessity of a LAA** that could provide significant support to the current authorities and municipality's work towards flood management and disaster risk reduction
- **The poor monitoring** of **several civil protection services** and **communicational/hierarchical gaps**
- The fact that **most of policies** applied are **of post–disaster management** and do not promote preparedness activities, awareness raising and risk mitigation
- **The need for awareness raising actions instead of structural measures.** Major flood problems derive from citizens' ignorance and private activities which intervene in the flood

risk evolution. It was commonly agreed that activities sensitizing citizens and building of a more responsible civil behaviour are of primary importance and should be first implemented

T5.2

The usual response of urban communities to flood hazard challenges (such as those faced by the Rethymno case study) was mainly extensive flood-control infrastructures, such as levees, dams, arrangement works, designed in an ad hoc basis, trying to solve flood problems locally. Latterly however, there is a shift from “Conventional Flood Planning” to “Flood Resilience Planning”, which, we argue, makes an attempt to emphasize the importance of adaptation and mitigation processes in managing flood risk while changing the paradigm from “fighting with water” to “living with water”. Following the definition of the term “resilience”[6], as adopted within this project (Deliverable 3.1, (2016)), the assessment of resilience in Rethymno was considered a primary steps towards flood resilience planning assisting at the same time stakeholders throughout the decision making processes.

The Flood Resilience Index framework (Batica J. & Gourbesvill P., 2014) initially developed within CORFU project and enhanced/modified within PEARL (Deliverable 5.2) was used as a first step for assessing Rethymno’s flood resilience at city level. FRI framework served as a tool for the quantification of flood resilience through an overall index which was calculated based on a collection of indicators grouped under the 5 dimensions: natural, physical, economic, social and institutional. The scenarios considered for FRI evaluation was two, Scenario 1 of storm surge that took place on winter 2015 and Scenario 2 of pluvial flooding occurred on November 1999. Analysing further the assumptions made during FRI assessment is outside of the aims of this deliverable but readers might refer to Deliverable 5.2 for further information. The overall index following the above framework received an overall value of 1.28 for Scenario 1 and 1.60 for Scenario 2. In the below graphs (Figure 123) the rating which each dimension received is presented in the resulted spider diagrams.

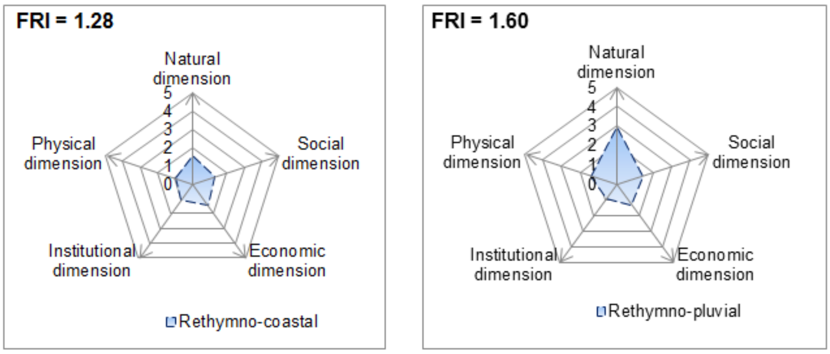
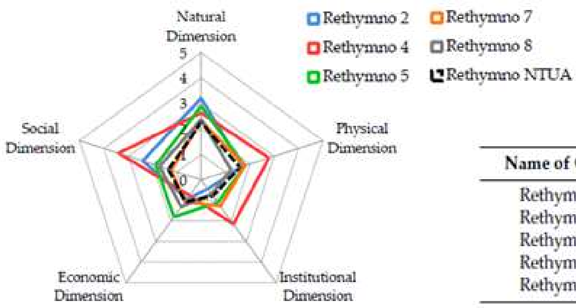


Figure 123: Radar chart presentation of FRI on city scale, results of coastal scenarios places on the left whereas results of pluvial scenarios on the right

After consultation with stakeholders in the case study area, including hands-on exercises that took place in the 2nd LAA workshop (please refer to workshops’ report), the need for adjustments of the initial FRI framework to improve intuitiveness and ease to use was identified. As a consequence, the initial total number of indicators of the FRI method (91 indicators) has been reduced to 60,

6 Resilience is defined as “the ability of risk bearers, assets or components of nature to prepare for, respond to, and recover from the impact of a flood event in a timely and efficient manner”

while a few indicators have been added to the Natural dimension. Seeking also expert judgment in weighting of indicators, an online survey was conducted with 15 experts, the results of which were analysed and produced the “default” weighting of each indicator contributing in resilience estimation. To operationalize the modified PEARL FRI methodology, the PEARL FRI Tool was developed available through the online PEARL Knowledge Base of Task 5.3. By using the tool, users are able to estimate the resilience of a city for a specific flood event (or flood type event) in five dimensions, visualize the results in a spider diagram and compare them with other cities or with other flood (type) events of the same city. Testing the developed methodology in Rethymno, local stakeholders of all engaged authorities in flood risk management actively participated in the evaluation process during the second LAA workshop. In fact, they requested to assess the level of resilience of their city by evaluating the different indicators per dimension using the online tool. The results are being presented in Figure 124 below:



Name of Group	Authorities' FRI	Expert's FRI
Rethymno 2	1.70	1.39
Rethymno 4	2.35	
Rethymno 5	1.86	
Rethymno 7	1.53	
Rethymno 8	1.44	

Figure 124: FRI results for the city of Rethymno and spider diagram of Rethymno's resilience for extreme flood events

Analysis and results have been thoroughly described in a journal article prepared by Karavokiros G. et al. (2016) and published in Water Journal by MDPI and seconds workshop report of 2nd LAA workshop in Rethymno.

Having developed such a tool with multiple interconnections e.g. between indicators and related measures, stakeholders, being aware of the poor performance of their city in a specific dimension, are able to identify measures, which could improve the resilience of the city in exactly those fields of interest. The later, has been tested as part of second exercise where LAA members were asked to identify and suggest measures that would increase resilience per dimension if they were implemented (refer to next paragraph under Task 5.3)

T5.3

Taking an important step towards the development of Knowledge Base (PEARL KB) and the first part of the task i.e. the collection and evaluation of engineering, environmental and operational strategies and solutions for adaptation and mitigation, the consortium members consulted experts in the field of water management and stakeholders form case study areas. In a first LAA workshop, organized in the city of Rethymno, project members had the opportunity to discuss with local authorities and other stakeholders' issues related to flood resilience in their region and present first aspects of the PEARL KB concept. In about the same period a review of similar projects (e.g.

PREPARED[7], NWRM[8]) gave valuable information on how these have structured information related to resilience measures. Research efforts have been allocated towards the collection of best practices and measures for adaptation and mitigations against hazards and risks. As a result of these efforts, the PEARL development team concluded to the following main concepts on which PEARL KB is focusing:

- **Resilience measures** and **strategies** capable to prepare for, respond to, or recover from the impact of a flood event in a timely and efficient manner.
- Another important data category are **Applications** of resilience measures which refers not only to real case studies, but also to modelled/simulated case studies or even to prototypes and lab physical models. PEARL KB focuses here on information that would potentially help stakeholders to assess the suitability and effectiveness of measures in their own region.
- **References** are metadata of sources that back the above information related to resilience measures and/or applications such as papers, books, URLs etc.
- **Additional data categories** related to resilience measures and case studies include illustrations, related projects, data provider etc.

For the initial data collection in the categories Resilience measures, Applications, Sources and Illustrations, an Excel template has been developed and distributed to project partners. A number of experts have contributed to the data collection, harvesting information also from related projects and sites. For Rethymno case study, all types of measures that have been implemented in Rethymno or the measures that would be suitable and are considered to be implemented, as highlighted by the local stakeholders, have been included in the PEARL KB database along with some actual applications e.g. the Flood control dam of Kamaraki stream.

Apart from the initial phase of collecting data and identifying the attributes of measures and applications which lead eventually to the design of the KB's structure, Rethymno's stakeholders provided valuable suggestions on creating a more user friendly web interface while testing the developed tools during the two LAA workshops. During the last workshop, LAA members tested all the above described procedures online. More specifically, they were requested to assess the level of Rethymno's resilience in a city scale by evaluating the different indicators per dimension using the PEARL KB FRI tool (refer to section Task 5.2 under WP5 of this document). After that, users were encouraged to navigate within the online PEARL KB and explore the available measures and case studies in order to identify and indicate measures they think would be more suitable to be implemented in Rethymno, but also to identify measures that would increase the level of resilience of each dimension and the overall resilience of the city in case they were implemented (Karavokiros G. et al., 2016).

T5.4

The objective of Task 5.4 is the collection and development of methods and tools aiming to support the selection of resilience strategies providing also the results of implementation of such methods in Rethymno case study. The deliverable submission of this Task has been officially postponed

[7] Official Website of PREPARED project: http://prepared-fp7.eu/
[8] Official Website of THE EUROPEAN NWRM PLATFORM: http://nwrm.eu/

until month 45 (in order to be consistent with the end date of the task and also include the work fulfilled between M36 and M45).

In this task, a combination of different methods and tools is being identified, proposed and developed for the creation of an integrated methodology that will assist decision making part of which will include the simulation of the decision making process itself of authorities responsible for a city's flood protection and preparation. This combined approach, which will form eventually the online PEARL Toolbox, aims at supporting authorities in the selection of resilience measures and strategies and the preparation against extreme hydro-meteorological events. The stages of the methodologies are summarised as follows:

1. All the resilience measures/strategies from the PEARL Knowledge Base are considered for implementation in a specific area
2. Resilient strategies are selected from PEARL Knowledge Base, based on the specific characteristics and hazards affecting the case area, involving stakeholders through the established, under PEARL, Learning, and Action Alliances
3. The specific attributes of the selected resilient strategies that offer a minimised cost and a maximised protection from extreme events are identified using optimisation algorithms and multi-criteria decision analysis
4. The selected resilience measure/strategies and their attributes, specific to the case area, are inserted in a new agent based model (ABM). This ABM simulates the authorities' decision making process for the selection of resilient strategies and assesses the performance of the case area under different socio-economic and flood events scenarios

Algorithms collected within this task, are divided in Optimization and MCDA algorithms, based on which (along with algorithms' attributes) the conceptual data model of the toolbox database has been built on. An algorithm may be implemented in as single or many Tools. Metadata of references to both tools and algorithms are stored in table source, providing information on their basic characteristics (author, title, year of publication, source type etc.). The PEARL Toolbox shares a common database with the PEAL Knowledge Base.

The designing process of the new Agent Based Modelling tool used as a roadmap the Institutional Analysis Framework (IAF) (Crawford S. & Ostrom E., 2005; Ostrom E., 2005, 2009) and included results from other WPs of the PEARL project (such as the Root Cause Analysis (RRCA) Framework of WP1, the creation of the Learning and Action Alliances (LAAs) of WP5, the stakeholders' workshops, and the household surveys of WP1 conducted by IREUS.). This new ABM is named PEARL ABM SAS and simulates how authorities prepare against flood risk and aims to support the exploration of alternative intervention options under different socio-economic conditions and different flood event scenarios that are comprised by series of flood occurrences of differing intensities.

The following figure (Figure 125) gives a conceptual framework of the model. The agents that represent the local authorities cooperate with the agents that represent the stakeholders in order to make decisions based on the available funds and the perceived annual flood risk, regarding the implementation of preparedness actions and new resilience measures. The outcome of PEARL ABM SAS is a qualitative measurement of the performance of the area in respect to the flood events that occurred during the simulation year.

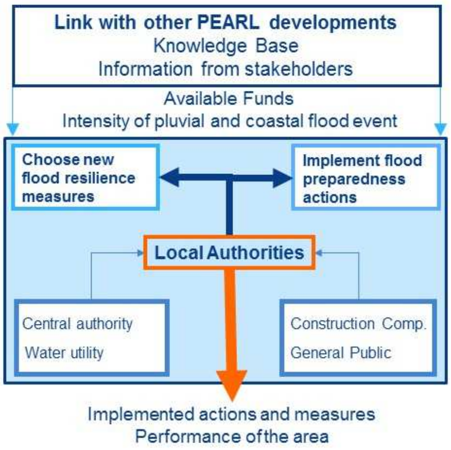


Figure 125: Conceptual framework of the PEARL ABM SAS applied in Rethymno

The main aim of the proposed methodology is to be able to transfer scientific knowledge to decision makers by creating a methodology and a tool that will assist decision makers to explore the response of the city to their decisions under different flood event scenarios and socio-economic conditions.

In the remaining months, the Toolbox will be expanded by including additional algorithms and by integrating the ABM with an online interface, and linking it to the PEARL platform and the PEARL toolbox. Additionally, the created PEARL ABM SAS will be presented in the final stakeholder workshop, where the stakeholders will be trained on how to use it and how to make use of its results. Updated version of this document will provide further information on the final toolbox along with the results after testing it with the local stakeholders and LAA members. Further analysis of all the above steps and procedures will be provided on M45 of PEARL i.e. at the end of this task as per DoW.

T5.5

Task 5.5 will produce and deliver the PEARL Web Learning and Planning Platform which is being developed by Satways on M40. This platform, known as the PEARL WebLP, is a Web accessible Rich Client application that can be considered as an Integrated GIS-based Collaboration Toolbox. Its purpose it to consolidate various Flood Risk Management applications under a single end users interface and provide them with well-defined interfaces for their interaction with core platform services like 2D/3D mapping, messaging and collaboration tools for planning and interactive learning (Karavokiros G. et al., 2016).

The Pearl WebLP, as described within Dow, is planned to serve as interface between PEARL and the members of LAA, an aim that was fulfilled for Rethymno case study. Having followed the manual provided by Satways, NTUA has proceed with the uploading of all geo-spatial data used within the modelling work of Rethymno case study (as static layers), as well the initial results of simulations (please refer to WP3 chapter in this document and/or Deliverable 3.4). Even though data, such as road and river network or river basins are available as static layers i.e. the user is able to turn them on/off through a tree structure, the results have been uploaded and are available to the users through a scenario manager. By creating a plugin in order to create the scenario manager, the user is able to select different parameters and scenarios e.g. precipitation event, urban growth scenario, dam break and navigate through the results i.e. flood maps (Figure 126). Being consistent with the aim of task 5.5 the end users i.e. Rethymno's stakeholders are able to

visualise the effect of alternative choices or under different scenarios, the risk situation and soon its propagation through time. Through the scenario manager module the platform allows for a customised experience in which different combination of choices by the stakeholders extract different modelling results from the platform's database. Going one step further and apart from the visualisation of pre-run scenarios, the WebLP has also been integrated with other PEARL tools and models. The PEARL KB FRI tool is fully accessible and operational within the PEARL WebLP, a), as well the database of the Water Detective application where all crowd sourced information has been concentrated. Soon the ABM PEARL SAS will be available too, running new simulations and operating remotely as a service. The PEARL WebLP has been demonstrated to local stakeholders on the last LAA meeting in Rethymno, giving a glimpse to its functionalities, the available data and results and most importantly to its possible use from the authorities engaged in flood risk management procedures e.g. the Fire Department.

Figure 126: Flood risk results on the 3D map component of Rethymno case study

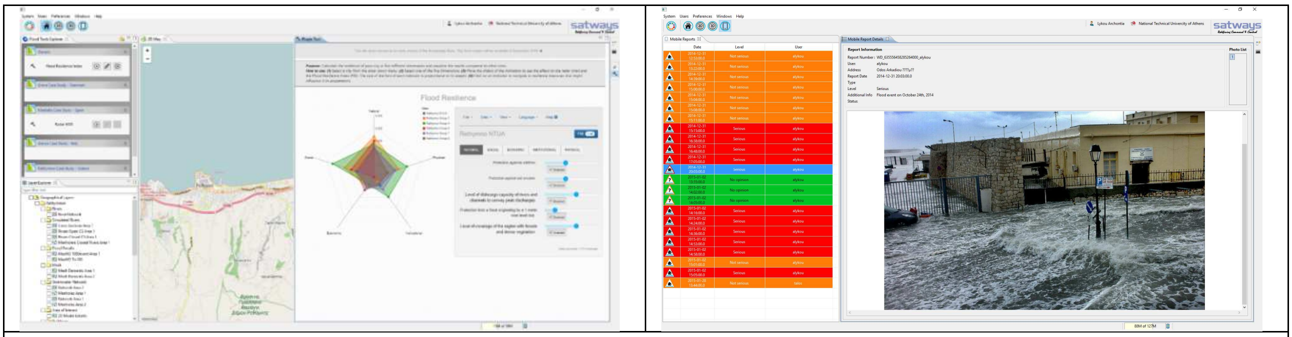


Figure 127: FRI Assessment of Rethymno case study accessible through the PEARL WebLP's interface (left), Reports, created through the Water Detective crowdsourcing application while used in Rethymno, are available through the PEARL WebLP (right)

T5.6

The key objective of this task is the delivering of specific and actionable Roadmap for Rethymno with the consensus of local society. The deliverable is foreseen for month 48 (end of the project). The process described in task 5.1 concerning the LAA establishment and the interactive workshops designed and implemented under this task, are supporting the format and actual design of Rethymno's roadmap. Concerning the workshops, as already mentioned two of three projected events have already implemented.

The **first workshop took place on 1st & 2nd of October 2015** and was assisted by the Municipality of Rethymno. The event was scheduled and managed to serve multiple purposes defined within PEARL. Primary goal was to launch the LAA concept for Rethymno case study i.e. to interact with the key stakeholders identified, to analyse the decision processes, their risk perception and information flows and to identify leverage points and appropriate scales/contexts, in which PEARL's support would result in the most pronounced impact. Full analysis, methodology of interactive activities and key results are provided in the event's report (Gourgoura P. et al., 2015).

The **second workshop took place on 7th & 8th of June 2016.** Primary objectives for this event were the further promotion of the establishment and functioning of Rethymno's LAA and the exposure of stakeholders to tools, deliverables and early prototypes that are being developed within the PEARL project (Gourgoura P. et al., 2016).

The activities scheduled within this workshop assisted to the continuation of interaction and knowledge exchange between the representatives of Rethymno's authorities and PEARL outcomes after the technical meetings and the 1st workshop.

Further information necessary for several WPs of PEARL was also collected (e.g. risk assessment and ABM development of WP3 and FRI framework implementation of WP5, etc.). But most importantly, stakeholders were given the chance to indicate and form the future scenarios that they are interested to have examined within the modelling work of PEARL and also to interact and use the developed tools while providing further suggestions that will enhance their efficiency (Gourgoura P. et al., 2016).

Moreover, results from the Risk perception household survey conducted under WP1 by IREUS, were presented to stakeholders. The presentation of the survey fostered a very interesting dialogue with the local authorities and provided significant input for the future roadmap and the adequate planning for Rethymno city. Valuable input was utilized as feedback for the PEARL Risk and Root Cause Assessment (Deliverable 1.3 of WP1).

The third workshop is anticipated to be held on autumn 2017 and will aim to the training of locals on the PEARL tools, the design of the city's Roadmap and standardization of LAA, and the presentation of PEARL main outcomes.

7.3 Additional research activities and results

7.3.1 WP1- Understanding formation of vulnerabilities and risk in coastal regions

For the Rethymno CS area, two methodologies, developed within WP1, were already applied. These are the Risk and Root Cause Assessment (RRCA) and the assessment of a household survey.

The methods used in PEARL to undertake Root Cause Analysis were reviewed extensively in Deliverable 1.2 (Fraser A. et.al., 2016), which provided a sourcebook for researchers and policy-makers interested in adopting the approach. A key principle of the PEARL Root Cause Analysis is the inclusion of multiple stakeholders from different disciplinary perspectives. In Rethymno, findings from face-to-face interviews with individual experts and stakeholders were corroborated with findings from a stakeholder workshop. For Rethymno, the interviewees included experts from water resources and civil protection agencies, the former mayor and regional authorities, NGO representatives, port authority, hotel and restaurant owners and local households. The interview

questions and Root Cause Analysis reports were structured around the Root Cause Analysis framework, and focused as far as possible on understanding the causes of specific disaster events. The drafting of the Root Cause Analysis report was undertaken in close conjunction with the local partner NTUA, and the findings fed into, and corroborated against, the first stakeholder workshop undertaken in Rethymno. Root Cause Analysis of annual flooding events in Rethymno, Crete, highlighted how flooding related to storm waves and flash flooding, was also linked to the challenges of maintaining existing risk mitigation infrastructure and moving to a more holistic risk governance approach, including greater public awareness-raising. The analysis highlighted how these challenges reflected a long-standing history of weak governance capacity at the local level, political organisation that precluded wide stakeholder engagement and institutional fragmentation of disaster risk management at higher levels of governance. As well as the interactions and feedbacks between these processes, the historic analysis also revealed the discontinuities and non-linear nature of such processes: an earlier period of infrastructure investment by the EU in risk mitigation measures was superseded by a more recent period characterised by the impacts of austerity. However, austerity measures are also rupturing pre-existing political relations, opening up new possibilities in the future for public engagement in disaster risk management in the town.

As the method focused on interviews with relevant experts rather than affected households and individuals, root causes and drivers related to perceptions, values and beliefs were not systematically explored. However, the analysis highlighted that often conflicts of perception formed part of the governance root cause category, while socio-economic and related demographic change influenced perceptions, values and beliefs. Root Cause Analysis was also conducted in conjunction with a household-level vulnerability assessment - for a discussion of the use of the two methods together see Deliverable 1.3 (Fraser A.; Sorg L. et.al., 2016).

The aim of the household survey was to assess how individuals respond before/during/after a flood, and thereby gain an understanding of various risk management strategies. The survey covered questions on the availability of information (e.g. early warning, evacuation routes), social networks and support from local authorities, as well as individual preparedness. Key findings and detailed analysis of household survey are in the relevant report provided by IREUS.

The results of the household survey were presented to stakeholders, followed by discussions in the course of the 2nd stakeholder workshop in Rethymno (see report by Gourgoura P. et al. 2016).

7.3.2 WP2- Understanding formation of hazards under extreme events

Even though NTUA is not officially participating in WP2, data has been provided to the team of Cambridge. An attempt to run different hydro-meteorological scenarios that will be provided by the collaborative work of MPG and CAM will be made.

7.3.3 WP4- Flood forecasting and early warning systems for coastal regions

The PEARL Water Detective application along with the developed portal which has been created for managing the collected applications has been tested in Rethymno by NTUA and has provided valuable feedback to the developers. Further, all above developments have been demonstrated to the LAA members of Rethymno during the 1st and 2nd LAA workshop.

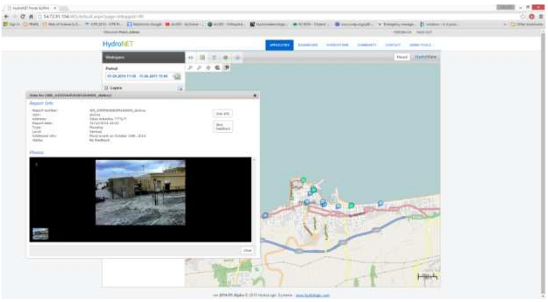


Figure 128: Reports, created through the Water Detective crowdsourcing application while used in Rethymno, area

7.4 Summary and lessons learned

Rethymno is a coastal area of Crete, Greece, facing multiple hazards leading to coastal, pluvial and fluvial flooding at several parts of the city. Based on recorded flood events, Rethymno was more susceptible to pluvial/fluvial flooding until the year 2000, whereas recently the flood problems seem to be concentrated around the port facilities and the coastal zone mainly connected with violent wave overtopping and storm surge phenomena. The “transition” from inland to coastal flooding is considered to be also the outcome of several flood defence structure created after the 1999 flood. Areas that seem to be in great risk, based on authorities’ testimonies and research, are located at the Old Town of Rethymno and the adjacent zones of Platanias River close to its outlet (towards the sea).

In terms of institutional and governance practice, even though there are several policies described within legal, international and national documents, they haven’t actually assisted in the improvement of flood risk management at a local level due their spatial scale of implementation, the lack of multi-stakeholder approach and the fact that they are giving emphasis on post disaster management and reconstruction measures, instead of prevention and mitigation of risks. At a local level, problems that seem to have bad impact in flood management processes are the lack of effective communication among authorities, bad monitoring of the different authorities’ activities and barriers derived by the several levels of hierarchy, the advanced bureaucracy and the overlapping of responsibilities. The financial crisis has also leaded to the lack of sufficient funding and the understaffed environmental public services, both of which have downgraded even more the flood risk governance performance.

For the city of Rethymno, several structural measures have been created and assisted in the flood protection of the city, but the absence of awareness raising activities, the lack of early warning systems and the inadequate information of the public are the domains towards which authorities should take some actions.

Taking all above into considerations while having as a final aim to develop adaptive risk management strategies for Rethymno community and the shift towards flood resilience planning, several tools and frameworks have been developed in order to enhance decision making procedures, assist stakeholders in flood risk management and eventually enable them to develop actionable roadmaps. The PEARL approach applied in Rethymno might be summarised as follows (Figure 129):

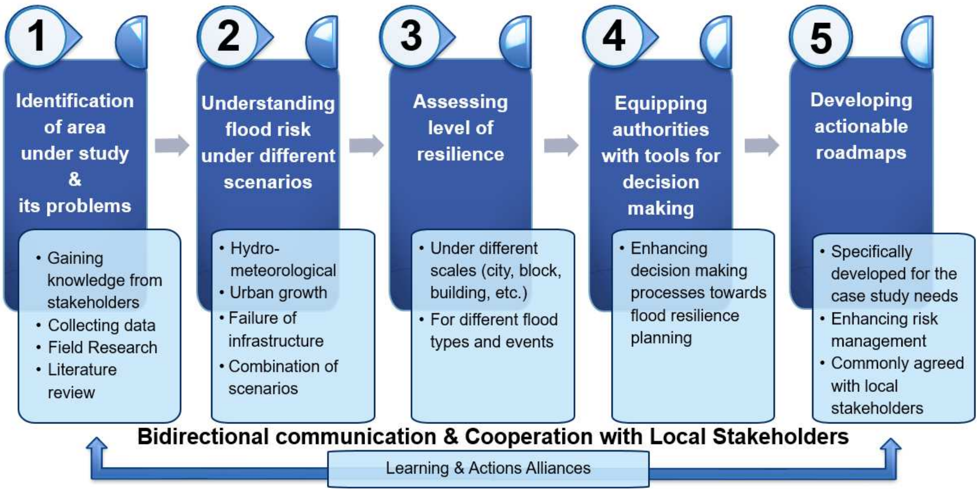


Figure 129: The PEARL approach applied in Rethymno

The **identification of area under study** aimed at collecting data and knowledge on flood problems, their cause and impacts, the existing or future flood infrastructures and their efficiency and finally the comprehension of local flood management procedures.

The developed **integrated modelling framework** enabled the simulation of physical phenomena along with the impact that might have the technical (e.g. flood infrastructures) and social (e.g. urban growth) root causes in the evolution of flood risk. Through the application of the modelling framework several scenarios have been and will be examined.

Having gained such knowledge on the hazards, the **vulnerability assessment** which was applied in Rethymno incorporated all social aspects that are being described within the PEARL vulnerability framework and have a great effect in the formation of vulnerabilities. Combination of hazards and vulnerabilities produces the final flood risks for Rethymno case study.

Since the shift towards flood resilience planning is a major objective within the PEARL project, the **level of Rethymno's resilience** was qualitatively assessed, by applying the FRI framework and identifying the dimension of an urban system that are more susceptible to floods. Further, the FRI framework was modified and was "transformed" to an operational tool easy and accessible for everyone to use.

The institutional and governance "reality" in Rethymno, as was assessed through the stakeholders' analysis and the implementation of RRCA framework, revealed the need of enhancing decision making processes by equipping authorities with necessary tools and integrated frameworks and solutions. Those widely applicable tools, which have been tested in Rethymno, are:

- The **use of water detective application** which enabled the collection of crowdsourcing information related to flood problems which can be later rerouted to responsible authorities for further actions or provision of alerts
- The **exploitation of the WebLP platform** through which the data, crowdsourcing reports and results of risk under different scenarios (hydro-meteorological, failure of infrastructure and urban growth) were uploaded and are available for visualization assisting in the understanding of flood risk and most importantly giving access to other developed tools from one web interface such as the PEARL KB FRI tool

- The **PEARL Knowledge Base** gave access to an integrated environment to Rethymno's authorities through which they assessed the level of city's resilience by using the developed KB FRI tool, explored and identified related measures that would improve the status of indicators for resilience increase if they were implemented and at the same time being suitable for Rethymno, while having access to flood resilience solutions that meet city's criteria and needs and applications of measures and strategies all around the world and their publications.
- The currently being developed **PEARL Toolbox** has been populated with an initial repository of algorithm and tools (optimisation and multi-criteria decision analysis algorithms) which have been identified through a systematic procedure and are available for end-users to explore. Most importantly, the toolbox gives access to **PEARL ABM SAS tool** which has been developed and tested in Rethymno in order to simulate authorities response and decision processes by taking into consideration aspects such as available funds, cooperation and synergies between authorities and identified measures and actions applied or suitable for Rethymno. The final outcome is the list of measures and actions that are being implemented through a ten year period and a qualitative assessment of city's performance in respect to the flood events.

Bidirectional communication and close cooperation with local stakeholders has been ensured by the very first month the project and established through several technical meetings and the implementation of the Learning and Action Alliances framework. The LAA members are being informed and have the chance to test every outcome of PEARL.

Having access to such tools, authorities/LAA members might use them within raising awareness activities and take a step further in engaging citizens to flood risk management.

Unifying all above research activities, frameworks, tools and outcomes, Rethymno's actionable roadmap will be developed which will be specifically developed based on Rethymno's needs, commonly agreed with local stakeholders, which will seek citizens supports and engagement, will be evolved through the LAA actions and aligned with the EU Flood Directive.

8 Case Study – Taiwan

8.1 Introduction to the case study area

8.1.1 General description of the case study area

Taiwan, located at the central west of Pacific Ocean, has coastline of 1600 km and 23 million populations. The location is within one of the typhoon-prone area in the world. There are 3.5 typhoons approaching Taiwan in an annual average and the number of typhoons per year is increasing to 5.5 in the recent decade. Typhoons bring strong wind, extreme waves, high water level (storm surge) and heavy rain. These phenomena increase risks for the coastal area. In addition to extreme precipitation during typhoons, the river characteristics and topography of Taiwan are important factors that lead to flooding. The rivers in Taiwan are short and have steep slopes that exceed 1/100 in upstream reaches and 1/200~1/500 in downstream reaches. Concentrated rainfall in short and steep river basins generates rapid flow increases and flow peaks.

Tainan coast is the study area in PEARL project. The coastline of Tainan City is around 63.7 km. Located at south-western of Taiwan, Tainan City is bordered by the Taiwan Strait to the west (Figure 130). It is the oldest city with more than 80% of the population lives near the coast. In 2016, Tainan City had a population of 1.9 million in its 37 districts. The total area of Tainan is 2200 km^2, with an average population density of 860 residents/km^2. However, the population density in the Tainan urban area is 4500 residents/km^2. There are six rivers that run through Tainan: the Bajhang River, Jishui River, Jiangjun River, Tsengwen River, Yanshui River and Erren River (from north to south). Midwestern Tainan is an alluvial plain of the Yanshui River and Tsengwen River, with a few hills and mountains distributed in the east. The only river that runs through the urban area of Tainan is the Yanshui River, with a length of 41.3 km and a watershed area of 340 km^2. The selection of Tainan City as the study area is not only because of its significant urban development but also because rainfall is the dominant factor that influences flooding.

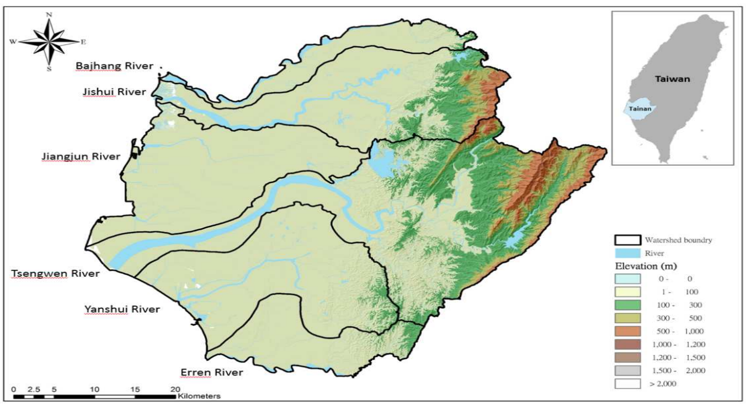


Figure 130: Location, river distribution and topography of Tainan City, Taiwan

8.1.2 Hazard and risk situation in the case study area

The average annual precipitation in Taiwan is 2500 mm, reaching 3000 to 5000 mm in mountainous regions. Most of the precipitation is concentrated in the typhoon and monsoon

season during the summer. According to records, the maximum hourly precipitation reached 300 mm, and the maximum one-day precipitation reached 1748 mm, which is 93.4% of the world record. Extreme wave which has wave height of 23.9 m was also measured during typhoon Krosa (2001) and a storm surge caused by typhoon Chebi (2001) reached 0.94 m. Due to the combined effect of extreme precipitation, river characteristics and topography of Taiwan, coastal flooding becomes one of the main nature hazards of Taiwan. The Water Resources Agency (WRA) of Taiwan reported that approximately 3000 buildings are damaged by floods annually, with an associated loss of approximately 400 million USD, which is approximately 4.6 times more than the loss caused by fire damage in Taiwan.

Tainan city has frequently flooded in the past. The floods that occurred in Tainan City were generally induced by multiple factors, including rainfall which exceeds the drainage system capacity, a poor condition of the drainage system, flood defense failure, rising sea level due to high tides and/or storm surges, and urbanization. According to historical records, several typhoons, such as Morakot in 2009 and Kongrey in 2013, have hit Taiwan. These typhoons were accompanied by abundant rainfall that caused serious damage, especially in Tainan. Figure 131 illustrates historical flood events in Tainan City that were caused by typhoons and rainstorms in past 10 years. A flood happened every one or two years. In the furture, more severe hazards might occur due to global warming. More than 300 projects have been implemented in Tainan City to prevent flooding over the past 10 years, but these projects have not solved the problem.

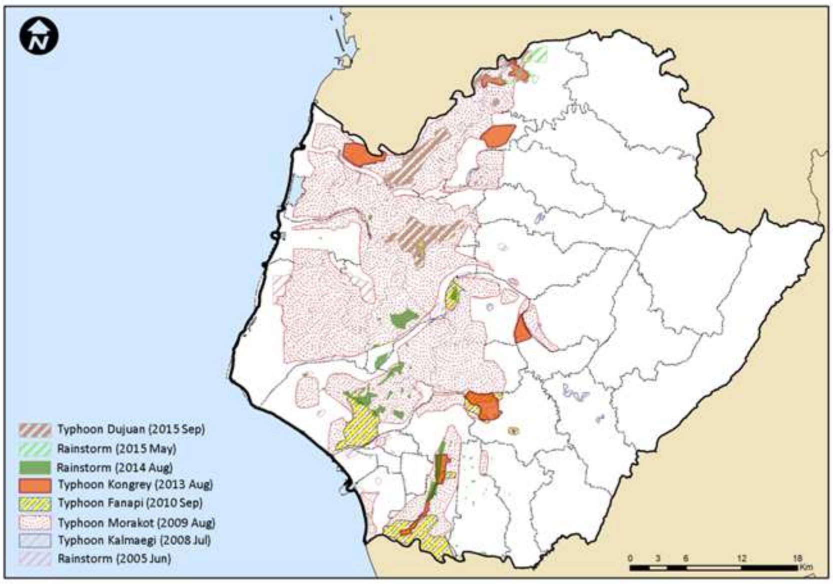


Figure 131: Historical inundation events of Tainan City, Taiwan

8.1.3 Current institutional and governance practice

Flood protection strategies in Tainan include structure adaption and non-structure adaption. The structure adaptation methods are limited for extreme event. This adaptation aims to ensure and strengthen existing facilities to prevent extreme events and reduce flood potential. The methods used are (1) rebuild and strengthen river banks, (2) build sluice, (3) rebuild bridges and extend narrow river sections, and (4) build detention basins and large water gates. On the other hand, non-structure adaptation methods are coordinated to reduce disaster impact, such as (1) promoting flood prevention community and disaster prevention education advocacy, (2) strengthen

the flood warning system, (3) developing flood inundation maps and flood risk maps, and (4) preparation of emergency reaction and evacuation in disasters.

Current flood mitigation plans in Tainan city includes three parts. The first part is determination of disaster magnitude which is according to the design of hydraulic structures and analysis of risks of flood inundation as well as simulation of different scenarios. The second step is to assess the risks and lost. Finally, a database of disasters and a monitoring and warning system are built. The integration of disaster reduction data has been done and keep updating by National science and technology center for disaster reduction (NCDR) in the central government. Measurement and forcast data are provided by more than 20 local government, including Tainan city. Meteorological forcast and measurements, including typhoon records, are provided by Central Weather Bureau (CWB). Water resources agency (WRA), on the other hand, gives warning of flood as well as simulations and forcast of inundation hazards. Those data are used for strategy decision and the allotment of resource.

8.1.4 Available data used for research activities

Large amount data were collected and used for constructing a Flood Inundation Map (FIM) for Tainan city in order to assess the risk. They includes geographical and hydrological data as well as historical records, operating rules of sluices and reservoirs and reports of regulation projects, as shown in Table 32.

Table 32: List of data collected in this poject for development of a floos inundation map for Tainan city in Taiwan

Geography	Hydrology	Others
• DEM • Aerial image • River/drainage cross section • Reservoir • Hydraulic structures • Sewer system • Coastal dyke • Sea bathymetry • Land use condition	• Rainfall • Discharge • Water level • Tide level • Wave	• Historical flooded extent and depth • Operating rules • Regulation reports

The digital elevation model (DEM) is generated by LIDAR with spatial resolutions 40 x 40 m for hillside fields and 5 x 5 m for low-lying areas. River cross-sectional shape includes all six rivers in Tainan with interval of 300 m in non-urban areas and of 20 m in urban areas. Data of hydraulic structures and instruments including 4335 rainwater drains (open channel) and 4335 underground rainwater sewer system were collected. These data include shapes and elevations of the systems as well as locations and lengths. Other structures or hydraulic instruments including 1206 sluice gates, 955 bridges, 81 river dykes, 13 reservoirs, 38 ponds or detention basins, 380 pumping stations are also collected (see Figure 132).

Moreover, satellite and aerial images are also used to divide or adjust the sub-watersheds, which were defined according to rainwater drainage or sewer systems. Land use conditions were collected to identify the land roughness and derive the flow behaviour. More than 45% of the land in Tainan City is used for agriculture and only 35% of Tainan City comprises villages or urban

areas. Rainfall records from 37 rainfall stations that have recorded hourly rainfall for more than 20 years were used. The river level and discharge data are mainly used for calibration of the 1D hydrodynamic model. Tidal data are used for a storm surge analysis and as the downstream boundary of the river in the 1D hydrodynamic simulation. Wave data (height, period, and direction) and 200 m resolution bathymetry data are used for the run-up analysis together, especially during the typhoon period. Finally, data from historical flood events, including flood depths and flood extents, over the past 10 years were collected for model calibration and validation purposes.

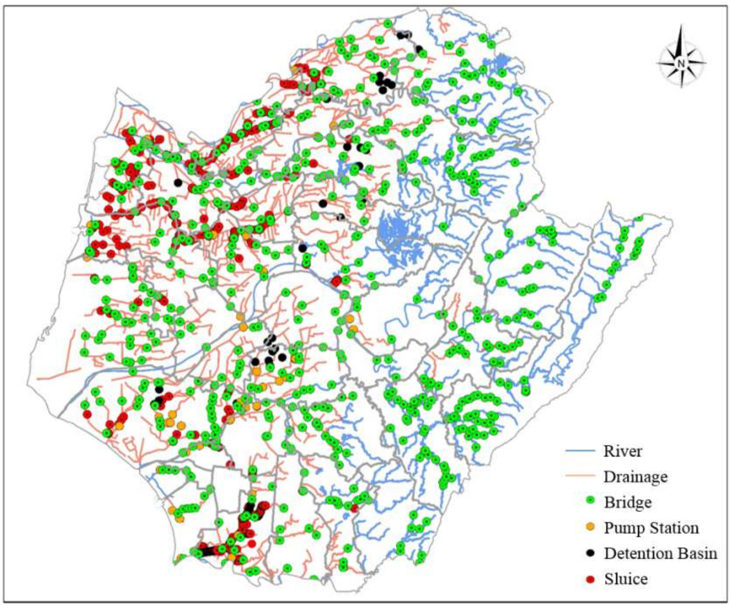


Figure 132: Network of river, drainage and hydraulic structures in Tainan City, Taiwan

8.2 Key research activities and results

8.2.1 WP2- Understanding formation of hazards under extreme events

In order to reach the Task 2.5 “Development of extreme event scenarios”, wave, storm surge, rainfall and sea level rise are analysed for extremely conditions for Tainan area.

Wave and storm surge

In this work, the less frequent events (return periods of more than hundred years) are seen as extreme events and can be applied as reference for risk assessments. Extremely ocean wave usually happened during typhoons for Tainan coast. In this study, long-term historical typhoon wave data were simulated because the length of field measurements on waves were not long enough. Parameters for more than 100 typhoons from 1980 to 2013 (totally 33 years) were collected. The data include typhoon central pressure, wind speed (field), moving speed and the path. Typhoon wind fields that generated by atmospheric numberical model were provided by Central Weather Bureau. The typhoon induced wave heights were then simulated by using MIKE21 SW module. It was found that Person Type III distribution is the best fitting model for typhoon generated wave heights. The various return periods on significant wave height were estimated and listed in Table 2.

A storm surge is usually characterized as an abnormal rise in water level generated by a storm, over and above the predicted astronomical tide. In this study, the High Water of Ordinary Spring

Tide (HWOST) is used as the base tide height. The maximum storm surges derived from 105 typhoons from 1980 to 2013 are obtained by numerical simulation. The heights of storm surge at the Tainan coast, that were estimated for return periods of 5, 10, 25, 50, 100, 200 and 500 years, were also shown in Table 2.

Table 33: Results of wave heights, storm surges and rainfalls for various return periods for Tainan City, Taiwan

	Duration (h)	**Return Period (Years)**						
		5	**10**	**25**	**50**	**100**	**200**	**500**
Significant wave height (m)		7.84	9.10	10.69	11.87	13.02	14.64	18.54
Storm surge (m)		1.50	1.57	1.67	1.74	1.80	1.87	1.96
Rainfall (mm)	6	179	207	240	262	283	302	326
	12	237	273	314	343	370	396	428
	24	289	347	419	473	526	579	650
	48	329	395	479	541	602	664	745

Rainfall

River runoff is the driver of flood simulations, and it is assumed to be mainly generated by precipitation. The occurrence and quantity of runoff are dependent on the characteristics of the rainfall event. Annual maximum rainfall depths for durations of 6, 12, 24 and 48 h were obtained using historic hourly data from 37 rainfall stations in Tainan with records of longer than 20 years. The rainfall depths for recurrence intervals of 5, 10, 25, 50, 100, 200 and 500 years are derived for the corresponding durations. The analysis results for the Tainan rainfall station were shown in Table 2. The results of the frequency analysis were used to develop the relationship between rainfall intensity (or depth), duration, and frequency (or return period) at all sites and to create IDF (Intensity–Duration–Frequency) curves which used to estimate rainfall intensity according to assumed duration and return period. Horner's equation is used to fit the IDF curves in this study.

Sea level rise

Sea level rise is not globally uniform. 58 tidal stations at East Asia coasts from Permanent Service for Mean Sea Level (PSMSL) were analysed. Those data have duration longer than 15 years to reduce error resulting from low frequency signals including decadal signal. The result shows 49 out of 58 stations have the rising trend. An average trend of sea level at Eastern Asia is 2.7 mm/yr, which is 1.6 times higher than the global average. However this trend is highly non-homogeneous.

Figure 133 shows the contour of the rate of sea level rise at the whole East Asia area. At China Bohai Sea, the sea level has almost no variation (only around 0.1-0.4 mm/yr) within last few decades. However it is still rising. On the other hand, it is found that there is a high rising rate at the mouth of Yangtze River. The value is 6.2 mm/yr. This means the sea level will rise more than 62 cm before the end of this century. This amount should be more serious since the intension of global warming is yet to be taken into account. Moreover, there are large rising trends at the band of Festoon Islands that can be seen in Figure 4 with shadow area. Within the Festoon Island band, the rising rates are in the range of 3 to 6 mm/yr which is two to four times of the global average rising rate. This region locates on the connection of Philippine Plate and Eurasian Plate. Subduction of the Philippine Sea Plate under remnants of the Eurasian Plate, plus break-away parts of the Philippine Sea Plate formed the Philippine Mobile Belt and Taiwan, and induced

volcanic and earthquake activities. Therefore vertical land movement is energetic and the vertical land movement should be taking into account.

A further analysis of tidal stations around Taiwan shows that the mean trend is 2.4 mm/yr. However, the mean trends of north, east, west Taiwan are 2.4, -0.85 and 4.7mm/yr, respectively. This again indicates the non-homogeneous of sea level rise trends in terms of spatial distribution.

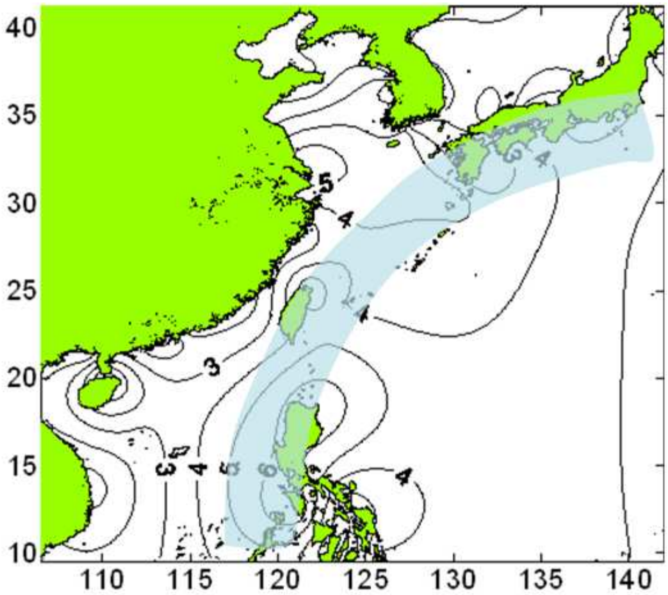


Figure 133: Isogram of the sea level rise rate at East Asia area

In order to reach the Task 2.6 “Modelling extreme events in coincidence”, the joint probability of wave height and sea level of which is the dominate impact to the coast area of Tainan is studied.

The impact that caused by typhoon on coastal area is a combined effect of different sources, such as huge wave and high water level. Generally, studies of the impacts were done on individual source and linear summarized. Waves is the main and direct source on coast. Tide level includes storm surge, wind setup and wave runup is also an important factor. These phenomena are both enhenced during typhoon period. Besides, they also influence each other. Therefore, a study of typhoon impact on coast area based on the joint effect of wave height and tide level is necessary.

In this study, four stations were chosen to represent the coast around Taiwan. These stations are Hualien (east), Longdong (north), Hsinchu (west), and Erluanbi (south). The longest data is 13 years. To eliminate the shortage of limited data sets, the Compound Extreme Value Distribution (CEVD) was used in this study. By considering the number of typhoons and the joint distribution of short-term extremes, CEVD gives a simple way to modify the statistic results to close to the reality. Assuming the number of typhoon follows Possion distribution, the joint distribution can be written as (Eq. 9):

$$F_0(x,y) = \mathrm{e}^{-\lambda} + \sum_{k=1}^{\infty}\int_{-\infty}^{y}\int_{-\infty}^{x}\frac{\mathrm{e}^{-\lambda}\lambda^k}{k!}k[G_X(u)]^{k-1}g(u,v)\mathrm{d}u\mathrm{d}v = \mathrm{e}^{-\lambda}\left(1+\lambda\int_{-\infty}^{y}\int_{-\infty}^{x}\mathrm{e}^{\lambda G_X(u)}g(u,v)\mathrm{d}u\mathrm{d}v\right)$$	*Eq. 9*

where $F_0(x, y)$ is the Poisson bivariate CEVD, λ is the average number of events, $G_x(u)$ is the distribution of wave height and $g(u, v)$ is the joint probability density function of wave height and tide level.

To apply the CEVD, it is necessary to know the distribution function of indivisual source. Four common distribution functions were chosen to fit the data: generalized Pareto distribution (GPD), generalized extreme value distribution (GEV), three parameters gamma distribution (GM3), and three parameters lognormal distribution (LN3). This study used Kolmogorov-Smirnov test to examine the goodness of fit. Since the distribution functions of wave height and tide level are not independent, multivariate copula function was used in this study. The data were fitted with four commonly used copula functions which are Gaussian copula, Gumbel copula, Clayton copula, and Frank copula. For velidate the goodness of fit, Akaike Information Criterion (AIC) was used. The lower value of AIC means better goodness of fit.

Table 34 lists the results of distributions of each factor at four stations. The results can be substituted into equation (8.2.1.1) to obtain CEVD of each station. The copula probability density function of Longdong station was illustrated in Figure 5. A further application to typhoon return period is also proposed using the results in Table 3. A comparison were illustrated in Figure 6. In contract to traditional frequency analysis method, which condisers wave height and tide level distribution are independent, the results of CEVD are more reliable.

Table 34: Stations and best-fit results

Station	Data duration	Best-fit tide level distribution	Best-fit wave height distribution	Best-fit copula function
Hualien	2004-2014	GEV	GEV	Frank copula
Longdong	2000-2014	GPD	LN3	Clayton copula
Hsinchu	2001-2014	GEV	GPD	Frank copula
Erluanbi	2001-2014	GPD	GEV	Clayton copula

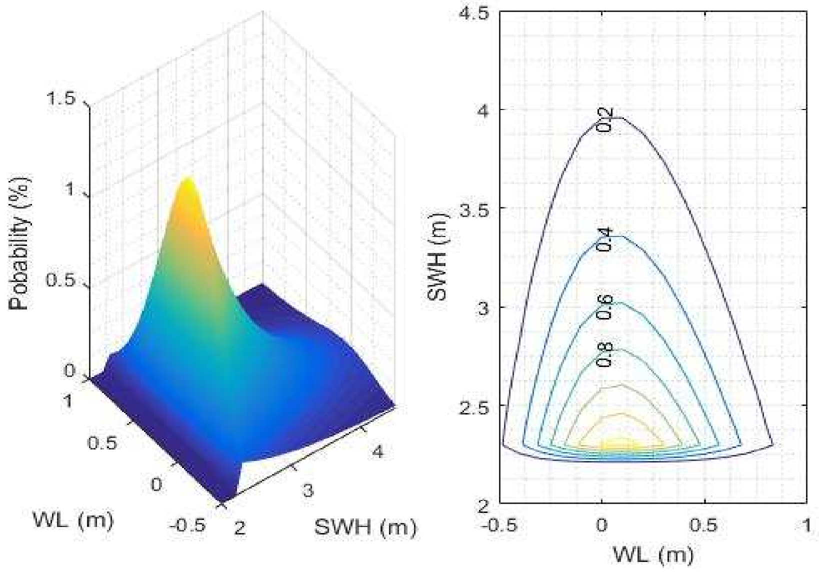


Figure 134: Joint probability density function (Clayton Copula) for tide level (WL) and wave height (SWH) at Longdong station (left) and three-dimensional plot with colours (right)

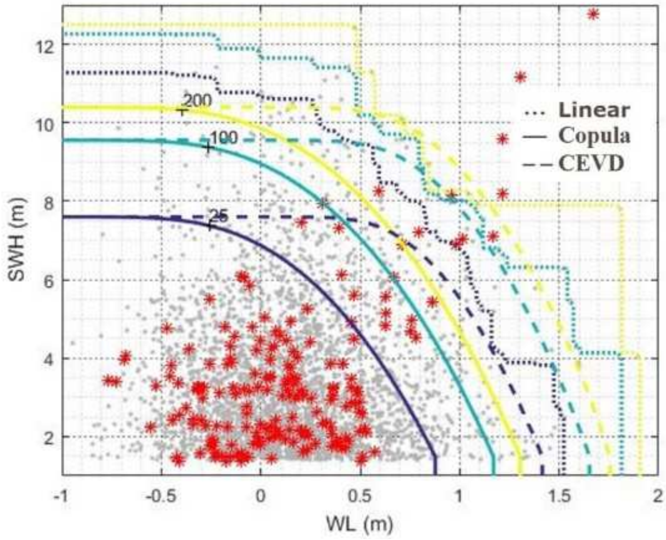


Figure 135: Typhoo return period at Longdong station. Red asterisks are measured data, grey dots are data generated by Monte Carlo simulation. Dotted line represents traditional linear method, solid line are Copulas and dashed lines are CEVD. Purple, green and yellwo colours represent return periods of 25 yrs, 100 yrs and 200 yrs

8.2.2 WP3- Holistic and Multiple Risk Assessment

Development on Flood Inundation Maps for Tainan city

Flood Inundation Map (FIM) is designed to represent the possible flood conditions under various rainfall scenarios. The information of potential flooded areas is necessary to assess the risk. Two types of rainfall scenarios were assumed for the development of FIM for Tainan city: one is the topography-based cumulative rainfall (CR) and the other is the periodic rainfall (PR). Topography-based cumulative rainfall assigns rainfall amounts for various rainfall durations, but the amounts depend on topography. From historical data analysis, it is known that the rainfall amount in highland areas is 2.1 times higher than in the low-lying areas in Tainan city. The type of periodic rainfall is based on rainfalls of several return periods for various durations. Thirty-four scenarios consisting of quantitative and periodic rainfalls were assumed. To consider the effect of the sea, another eight scenarios with simultaneous rainfall and storm surge events were assumed for various return periods and 24-h durations. In total, 42 scenarios were used to produce the FIMs in the present work.

Figure 136 shows the FIMs with 100-year rainfall and durations of 6 and 24 h. These rainfall scenarios with different return periods are similar to those of cumulative rainfall, but they are presented differently to satisfy different requirements. Flooding began to occur in the coastal area (elevation < 1 m) for low-intensity rainfall events. The flooding is due to low-lying land in the coastal area. When the rainfall intensity increases, the flood extent expands due to the influence of low-lying areas. However, when the rainfall intensity increases, the flood extent reaches elevation > 10 m in some areas because the river discharge capability decreases due to tidal chokage. Figure 137 shows the results of various scenarios. The flood extents of a 100-year rainfall event for durations of 6, 12 and 24 h (scenario codes PR-6-100, PR-12-100 and PR-24-100) are overlapped, as is the influence of the storm surge (PR-24-100S). The most extreme scenario (100-year rainfall for 24 h) triggered severe floods, especially in the southern Tainan region (right-panel of Figure

136); however, the storm surge considerably affected low-lying areas in the western part of Tainan City.

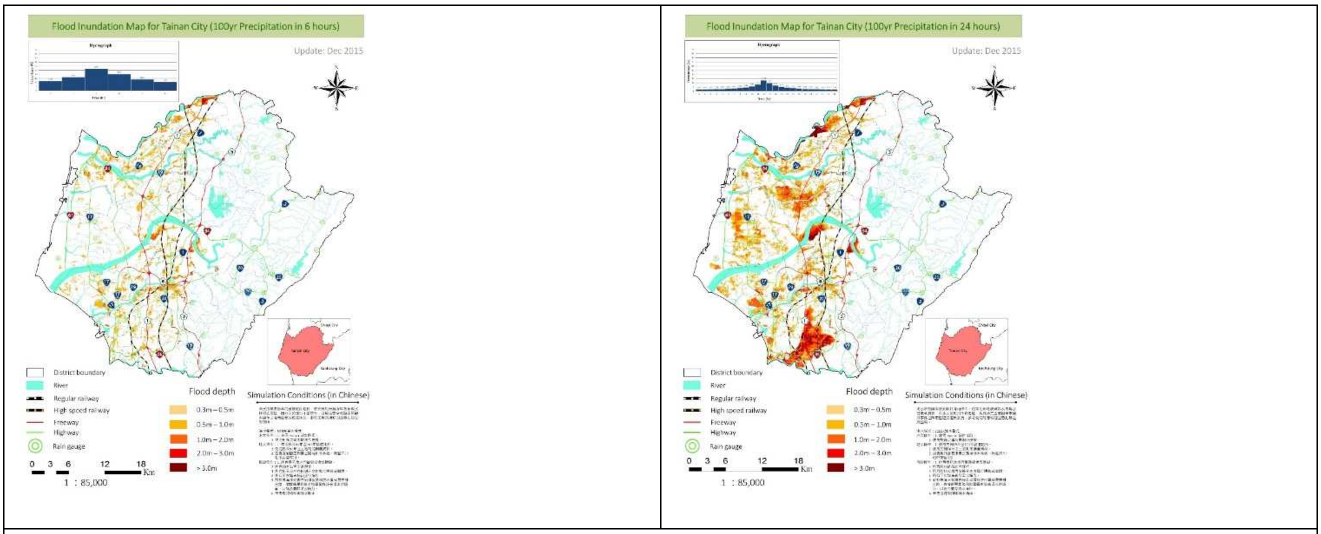


Figure 136: Productions of flood inundation map for Tainan City under conditions: 100-yrs rainfall for 6 h (left) and 100-yrs rainfall for 24 h (right)

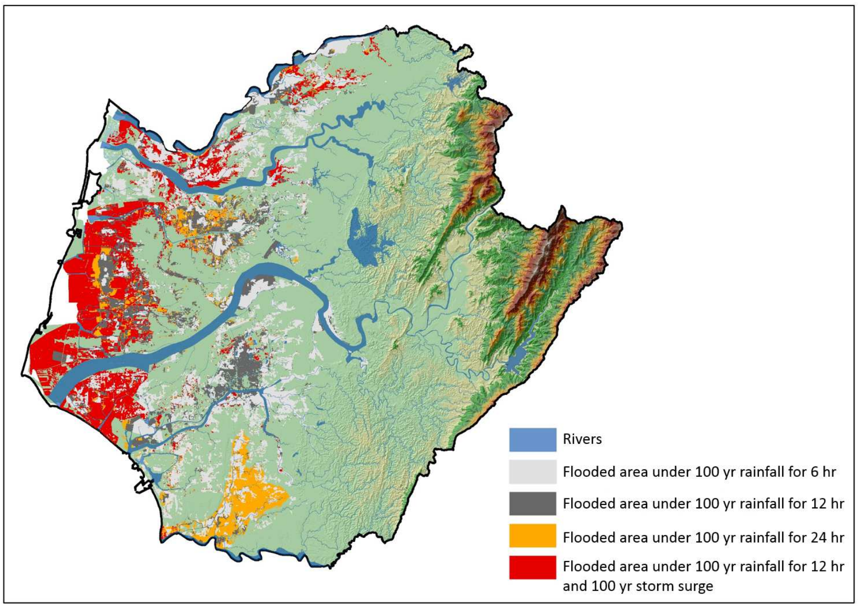


Figure 137: Overlap of the flooded area under various scenarios

Analysis for vulnerability assessment

This study adopted the indicators of coastal vulnerability that were established by United National Environment Programme (UNEP, 2005). These coastal vulnerability index (CVI) is a function of five indicators (Eq. 10). These indicators are population density in coastal area (PD), probability of natural disaster incidents (ND), forest cover (FC), geographic exposure (GE), and human development index (HDI).

$$CVI = f[(\mathrm{PD}) + (\mathrm{ND}) + (1 - \mathrm{FC}) + (\mathrm{GE}) - (\mathrm{HDI})]$$	*Eq. 10*

The indicators are standardised by Eq. 11 before being substituted into Eq. 10

$$\mathrm{index} = (\mathrm{X} - \mathrm{X_{min}})/(\mathrm{X_{max}} - \mathrm{X_{min}})$$	*Eq. 11*

Here, X indicates the data value for X indicator and the subscript of min and max represent minimum and maximum of that indicator, respectively. The calculated CVI is standardised and classified into three classes. When CVI is higher than 0.1 and lower than 0.5, the vulnerability is moderate. On the other hand, if CVI is above 0.5 or below 0.1, the study area has high or low vulnerability.

According to classification of UNEP, the CVI at Taiwan is 0.517 which is one of the most vulnerable countries in the world. Therefore, a local coastal vulnerability assessment was proposed. The local coastal vulnerability is a combined effect of three evaluated factors. In total, there are ten parameters were used in this assessment (Table 4). According to the proposed CVI, the vulnerability is classfied into five scales, which are extreme high ($\mathrm{CVI} > 36$), high ($20 < \mathrm{CVI} \leq 36$), moderate ($12 < \mathrm{CVI} \leq 20$), low ($7 \leq \mathrm{CVI} \leq 12$) and extreme low ($\mathrm{CVI} < 7$).

The coastal vulnerability map of Taiwan using the proposed factors is plotted as Figure 9. In general, the western coast is more vulnerable than the eastern coast. Extreme high vulnerable suburbs are mainly located at middle- and south-western coast. This is due to the higher vulnerability of environmental factor (e.q. sandy coastline) and of social-ecomomical (e.g. higher development). It can also be found in the map that the coastline of Tainan is classified to has moderate vulnerability.

Table 35: Evaluated factors for vulnerability analysis

Evaluated factor	Vulnerability evaluation parameter
Physical Factor	1. population density 2. fundamental protection facilities
Environmental Factor	1. coastal morphology 2. mean wave height (m) 3. mean tidal range (m) 4. coastal erosion 5. coastal geology sensitive area 6. rate of land subsidence (cm/yr)
Social-Economical	1. Human Development Index 2. Fundamental facilities : harbor, aquaculture, lifelines areas

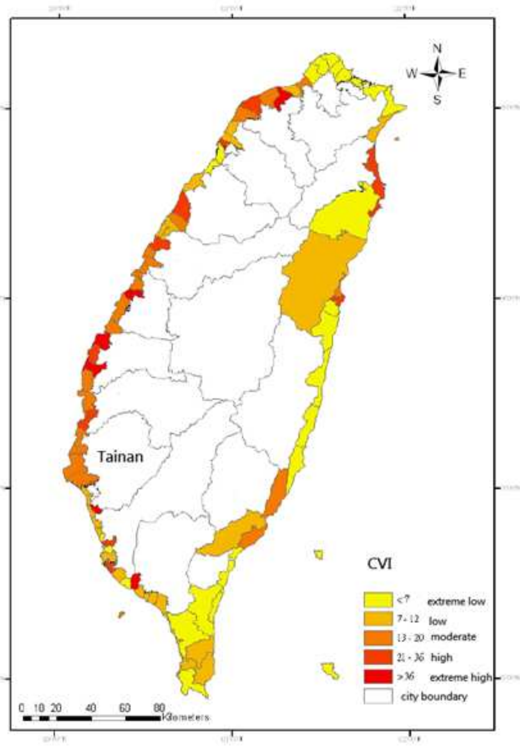


Figure 138: Coastal vulnerability map

Risk assessment

According to International Strategy for Disaster Reduction (ISDR), the definition of risk can be written as Risk = Hazard * Vulnerability. Impact on coastal area of sea-level rising due to climate change at the end of the 21st century was assessed. Different sea-level rising scenarios were adopted and the possible submerged areas can be seen in Figure 10. From the figure, it can be seen that large portion of Tainan City could be submerged in the scenarios in both scenarios, especially southern Tainan (bottom panels of Figure 10). The higher the sea level rise, the larger the area could be submerged.

Based on the coastal vulnerability map that obtained from previous section (Figure 9), the risk map of Taiwan coastline was established and shown in Figure 11 (scenario of 1.4 m sea-level rising). Similar to vulnerability map, the western coast has higher risk than the eastern one. Southwestern coastline of Taiwan has the highest risks which might be caused by sea-level rising and Tainan City was classified with moderate risk. From the risk map of sea level rising, we can know that higher attention and protection are needed for area with higher risks, i.e. southwestern coastline of Taiwan.

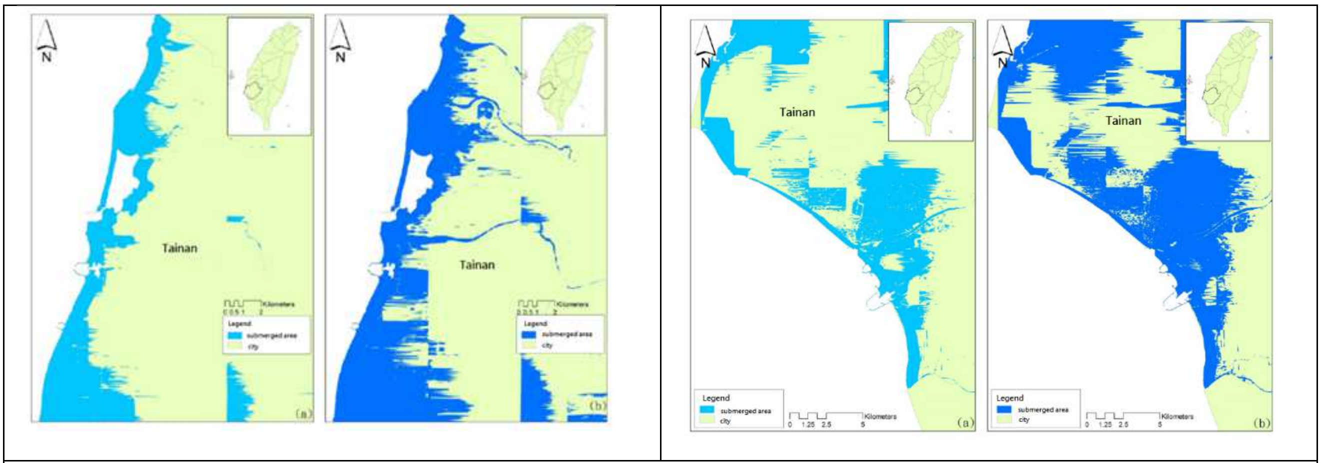


Figure 139: Maps of submerged areas due to sea-level rising: a) rise 0,5m, b) rise 1,4m, northern Tainan (left), southern Tainan (right)

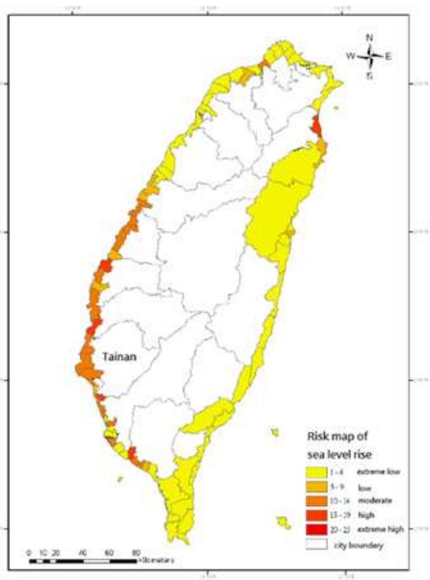


Figure 140: Risk map of sea level rise of 1,4 m

8.3 Additional research activities and results

8.3.1 WP7

As a third party of the research group, National Taiwan Ocean University (NTOU) is highly interested in the transformation of European concepts on coastal risk assessment to Taiwan as well as contribution to PEARL groups with Taiwanese experiences. Two workshops have been held in Taiwan to achieve the goal. The first workshop was held in November 25 to 28 of 2015 in National Cheng Kung University in Tainan city of Taiwan. This workshop was opened to all persons who are interested in PEARL in Taiwan. More than 80 audiences from universities, research institutions, consultant companies, and also from central and local governments participated this workshop (Figure 141). Five European experts including PEARL project coordinator Prof. Zoran Vojinovic were invited to attend the workshop and presented their results

and experiences. On the other hand, 5 local presentations shew the problems and current solutions that Taiwan is facing. After in-door presentations, a field trip was arranged to visit the Taiwan case study area.

The second Taiwan workshop was held in November 6 to 10 in 2016. This workshop was jointly organized with the International Conference on Hydroscience and Engineering (ICHE) as a mini-symposium. More than 160 participants attended ICHE. PEARL coordinator Prof. Zoran Vojinovic attended the worksop again and was invited to give a keynote speech for all ICHE participants (Figure 142).

These two workshops not only promote the PEARL concepts and results for Taiwan locally but also to international community via the international conference. Meanwhile, PEARL partners Prof. Zoran Vojinovic, Prof. Peter Fröhle and Prof. Christos Makropoulos attended a meeting with colleagues in Water Resources Agency (WRA) which is the responsible authority for water problem in Taiwan during their visit for the second workshop. Theywill be invited as International Advisors of WRA to give suggestions for flood risk mitigation for not only Tainan city (this case study area) but also any cities in Taiwan.

Figure 141: Audience attended to PEARL Taiwan Workshop 2015 held in NCKU, Tainan

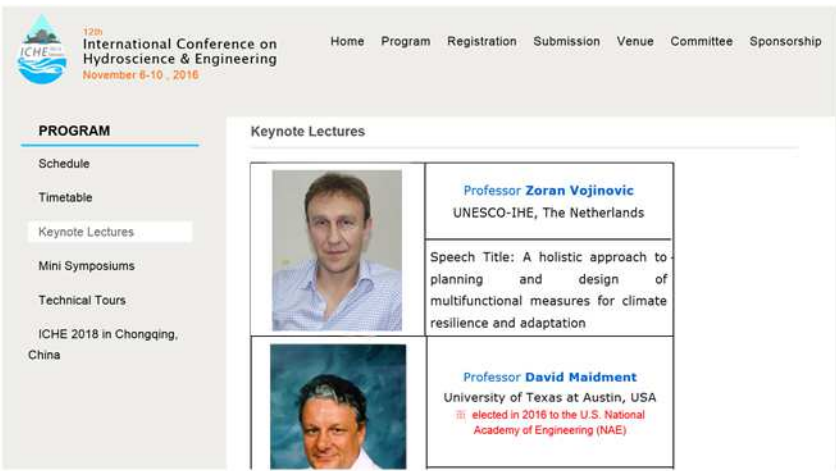


Figure 142: PEARL coordinator Prof. Zoran Vojinovic was invited to give the keynote lectures at the International Conference on Hydroscience and Engineering (ICHE) which was held in November 2016 at NCKU in Tainan City, Taiwan

8.4 Summary and lessons learned

Taiwan is located at western Pacific Ocean. Due to the typhoon impact, coastal flooding is one of the main hazards in Taiwan. Typhoons bring heavy rains in a short time as well as extreme wave heights and storm surges from the seaside. When one of the threats occurs individually but extremely or more then two threats occur in coincidence, flood occurs especially in the coastal area. Water Resources Agency (WRA) of Taiwan (which is the responsible authority of water problem in Taiwan) investigated that the flood induced loss every year in Taiwan is much higher than earthquake or tsunami generated.

Due to different types of threats as well as different geographic and social conditions, the strategies of the coastal flood mitigation are not fully the same with European countries have. Therefore NTOU/NCKU shares the cases and experiences we had in Taiwan with PEARL partners and learn European experiences by PEARL platform.

In Taiwan, the research focus for coastal flooding is on the development and improvement on the technologies for flood potential simulation and the warning system. According to frequent flooding, numerous field data and records were corrected which is a very good area for model calibration. However, we learn from European cases, much focus on social-economic issues, including public engagement, education and risk assessment which will be the direction for Taiwanese cases.

9 Case Study – St. Lucia, The Caribbean

9.1 Introduction to the case study area

9.1.1 General description of the case study area

The case of St. Lucia covers the capital (Castries) of a small island (St. Lucia) in the Caribbean region with an area of approximately 0.45km^2 shown in Figure 143 and Figure 144. Although loss of life due to flooding in Castries is rare, it does however result in property damage and loss of productivity which has a huge impact on the economic development of St. Lucia. Minor floods usually occur after short duration high intensity rainfalls, with more severe flooding occurring as a result of storm events.

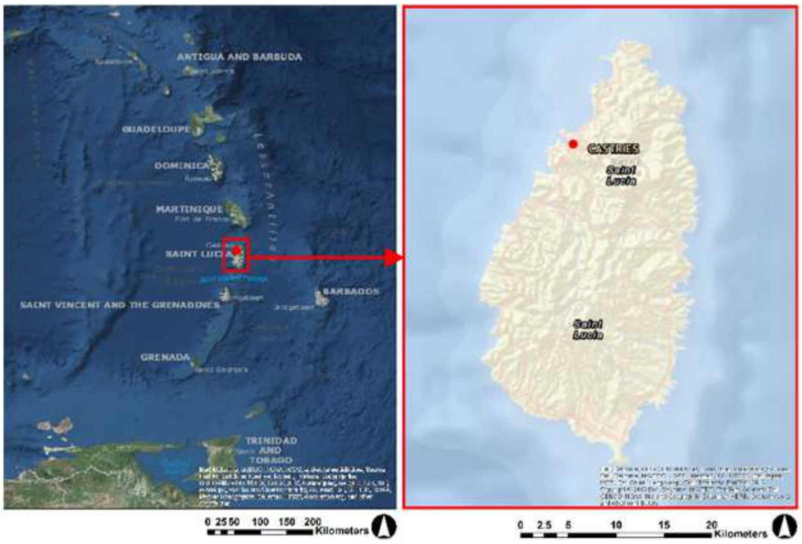


Figure 143: Location of the Castries case study area in Saint Lucia in the Caribbean

Figure 144: Castries city centre (red outline) in Saint Lucia

The area is at risk from pluvial flooding, especially during short duration high intensity rainfall, as well as fluvial flooding from the river located south of the city. A real-time pluvial flood warning system for Castries has been developed. Coastal flooding in the area is apparently rare but may occur during storm events. Therefore, given its coastal location in a hurricane-prone region, the pluvial flood forecast model was extended to also consider flooding from the sea, and used in this new Castries urban coastal flood warning system developed under the PEARL project.

Drainage features

The study area is located to the north of the estuary of the main river which has been directed through a concrete channel in some areas. There are a number of small ravines which also drain into the city. The city contains a system of storm drains which discharges via two outfalls into the harbour during favourable conditions and otherwise pumped when free drainage conditions are less favourable (e.g. during a storm surges). Coastal wave action can limit the effectiveness of the drains and the river from discharging flow into the harbour. This may lead to standing water in the drains that run within the city as well as the main river and in more severe cases the backwater effects may cause surcharging and may cause the river to overflow its banks, thus resulting in fluvial flooding. Because of its location and the features that surround it, the area is prone to: (i) fluvial flooding from the river and the small ravines which drain into the city; (ii) Coastal flooding due to storm surges; and (iii) pluvial flooding. However, coastal flooding in the study area is rare although it may occur during storm events. Since the outfalls are just above mean sea level a more likely scenario is flooding due to a strong back water influence due to tidal or storm surge effects. In an earlier effort to control fluvial flooding as a result of the ravines a detention basin was constructed 10 years back (see Figure 145).

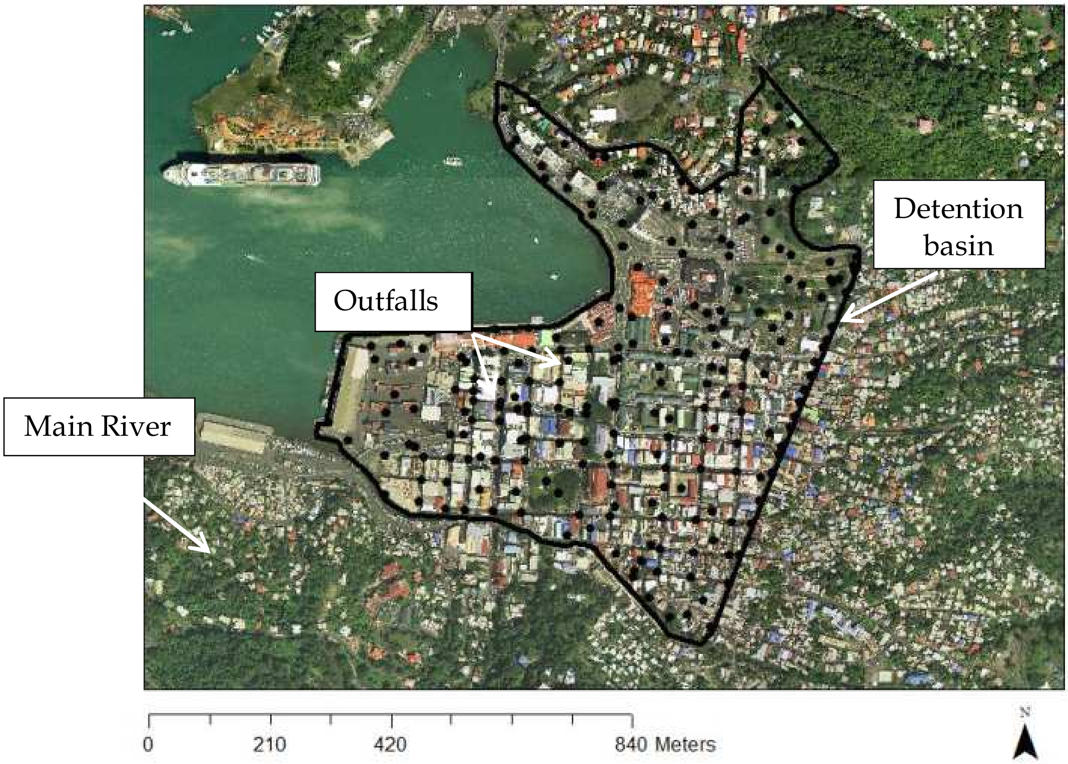


Figure 145: Study area and its drainage features. The solid black lines indicates the boundary at the applied 2D model and the black dots the spot heights used to generate the terrain model

Rainfall regime

The Caribbean region is conditioned to be wet between May and November and its climate is characterised in most parts by its bimodal precipitation regime, with an initial maximum in May, a relative minimum around July-August, and a second maximum (longer and greater wet season in terms of monthly precipitation totals) in September-October. The region is also affected by tropical storms and hurricanes which is a primary rainfall source contributing to the second rainfall peak in the annual cycle. The relative minimum experienced in the middle of the wet season is termed "midsummer drought" (MSD), which represents a diminution in rainfall. However, precipitation in the region is highly variable in both space and time, thus the bimodal structure and in particular the midsummer drought is not consistent across the islands. The MSD for Barbados is shifted one month and occurs from August to September. Although the literature does not contain data specific for St. Lucia, 10 years of daily rain gauge data (2001-2010) was used to investigate the mean monthly rainfall pattern. The results highlight (Figure 146) that the rainfall seasonality is similar to other islands in the Eastern Caribbean and in particular the MSD coincides with that of Barbados, which is geographically closest to St. Lucia (see Figure 143).

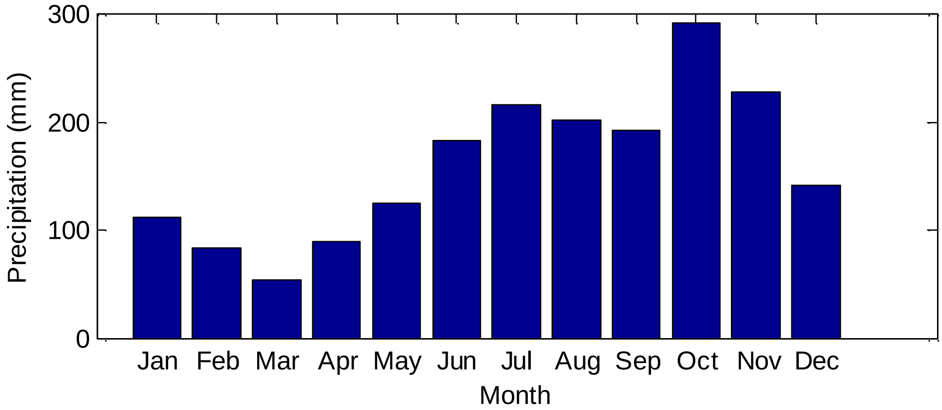


Figure 146: Mean monthly rainfall for the period 2001-2010 depicting the bimodal structure with MSD occurring around August-September

9.1.2 Hazard and risk situation in the case study area

St. Lucia is often hit by hurricanes, e.g. the hurricane Tomas, which resulted in a 24-hour rainfall of 533.3mm on 31st October 2010, but data available for flood model verification are limited. Similar to earlier pluvial flood modelling efforts, available data for model calibration comprised of images for 2 flood events in Castries published online. Examples are shown in Figure 147 for flooding on 1 May 2013. Comparison of observed and maximum simulated depths in Table 36 show flooding is calculated at the expected locations but that calculations overestimate depths compared to (estimated) observed values. However, although the exact times are uncertain, the images were most likely from after the event when floods have subsided, and not at the height of the flooding. Thus, more precise data are needed for verification, but nevertheless the current model gives a good indication of the location and magnitude of expected flooding for a real-time flood forecasting system.

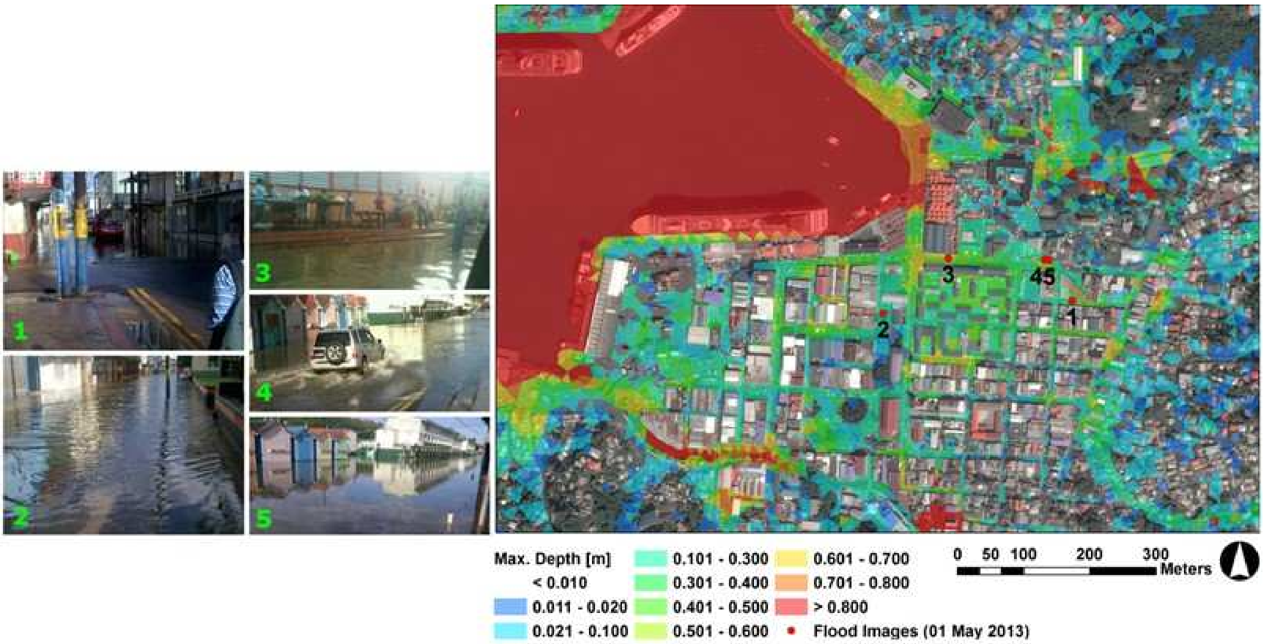


Figure 147: Images of flooding from during or after the 1 May 2013 flood event in Castries, Saint Lucia published online are shown on the left (Source: Rene et al., 2015). Maximum water depth results using the new Castries coastal flood model for the 1 May 2013 event are plotted on the right.

Table 36: Model verification based on estimated flood depths from images

	1 May 2013 Event				
	Image 1	**Image 2**	**Image 3**	**Image 4**	**Image 5**
Observed estimated depth [m] (Source: Rene et al., 2015)	0.1	0.2	0.1	0.1	0.2
Simulated max depth [m] (Source: Rene et al., 2015)	0.4	0.2	0.3	0.3	0.2
Simulated max depth [m] (Current coastal flood model)	0.38	0.27	0.5	0.32	0.21

9.1.3 Current institutional and governance practice

The administrative and legal framework in Casteries, St. Lucia follows the national Guidelines. Detailed studies of the administrative and legal framework, incl. stakeholder analyses have been outside the scope of the St. Lucia case study.

9.1.4 Available data used for research activities

Data Acquisition from NOAA and StormGeo

The flood forecast model is driven by forecasted sea level and NWP rainfall data routinely obtained from NOAA (NOAA National Ocean Service, 2013) and StormGeo (StormGeo, n.d.). During data acquisition, sea level data are retrieved from a NOAA website (see Figure 148), and rainfall forecasts from DHI's Water Forecast system database holding StormGeo data. Data from the NOAA website are read and data mined to derive sea levels from Mean Lower Low Water (MLLW) tide level values (MLLW is 0.173 m below Mean Sea Level (MSL) in Saint Lucia). At the same time, NWP rainfall forecasts from StormGeo for the next 24 hours are obtained from the Water

Forecast database located at DHI. Both time series are collected and stored through MIKE Workbench, and are then processed to ensure that the data time series cover the flood model simulation period. Finally, the time series are set as boundary conditions to the flood model, which is routinely run by the system.

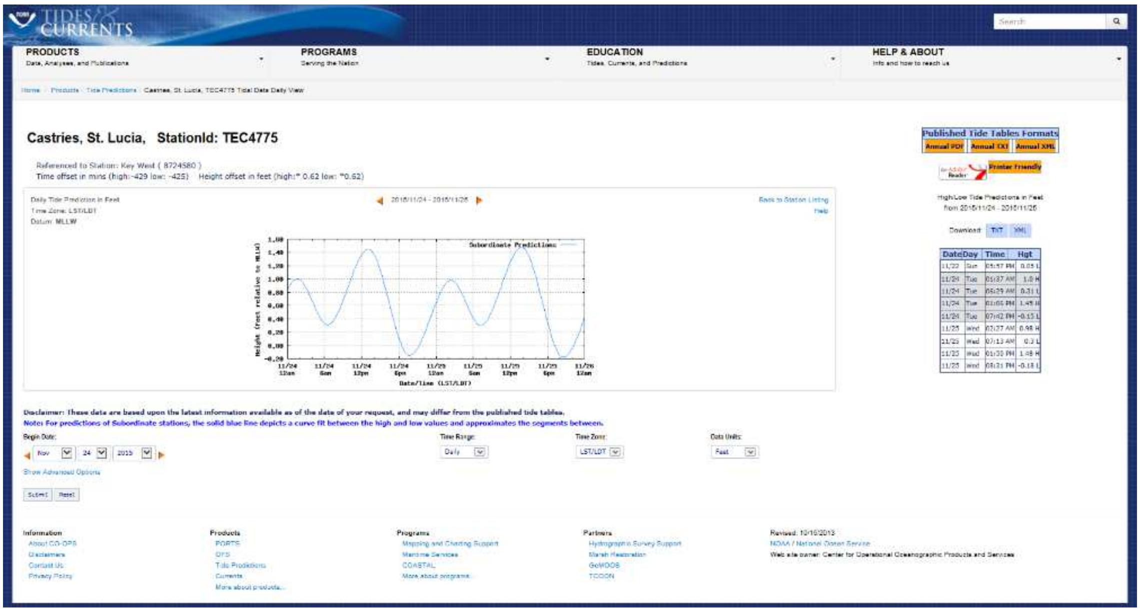


Figure 148: The NOAA website from where sea level data are obtained (https://tidesandcurrents.noaa.gov/noaatidepredictions/NOAATidesFacade.jsp?Stationid=TEC4775). (Source: NOAA National Ocean Service, 2013)

9.2 Key research activities and results

9.2.1 WP4- Flood forecasting and early warning systems for coastal regions

T4.1

The new Castries Flood Warning System was built following the earlier pluvial flood warning system developed by Rene et al. (2015). However, in this new system, a more efficient flexible mesh approach is used for the 2D flood model instead of Cartesian grid discretization (see Figure 149). Coastal flooding (i.e. flooding from the sea) has also been included in the simulated processed in addition to pluvial flooding, and the model domain has been extended to include not only the city centre but also upstream sub-catchments and the land and sea areas around the port.

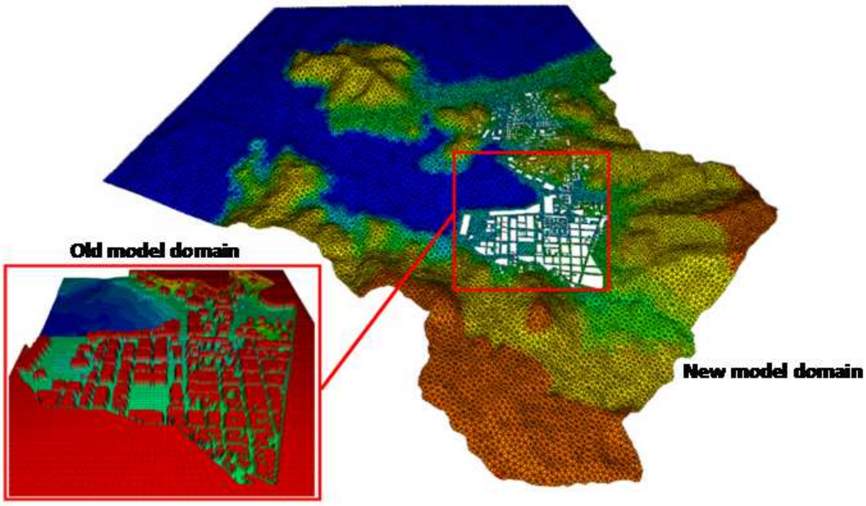


Figure 149: Figures showing the 2D model domains and computation grids for the earlier pluvial flood warning system (lower left) and the new coastal flood warning system (right) for Castries, Saint Lucia. The red outlines indicate the location of the old model domain in the new expanded model area.

Framework and methodology

The Saint Lucia Flood Warning system employs a 2D hydrodynamic model to forecast coastal flooding in Castries. The flood model is driven by rainfall and sea water level forecasts, and the forecasted results as well as various information about the system are published (in real-time) on a website (www.stlucia.dhigroup.com). The various components of the system are illustrated in Figure 150 and further described in succeeding sections.

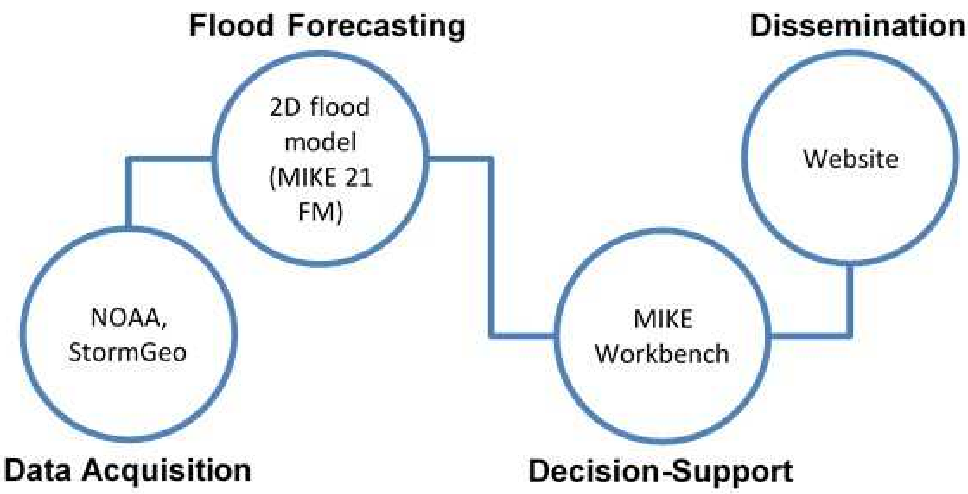


Figure 150: Diagram showing the main components of the Saint Lucia Flood Warning System.

Flood Forecasting with MIKE 21 FM

A 2D flexible mesh model is used for coastal flood forecasting in the Castries Flood Warning System. The model was built using MIKE 21 Flow Model FM, a modelling software that calculates two dimensional flows based on the 2D incompressible Reynolds-averaged Navier-Stokes

equations. It employs a flexible mesh approach that uses a cell-centred finite volume method for spatial discretization in the calculations (DHI, 2013).

The 2D model covers around 8.5 km2 of inland and sea areas around the port in Castries (Figure 151). The element mesh comprises of around 32 000 triangular elements ranging in size from around 0.5 to 1 200 m2. With the assumption that buildings in the area are largely impervious to surface flows, the presence of these structures is considered by removing them from the calculation mesh (see Figure 151 and Figure 152) Figure 152. This means that calculations are not performed over these areas, and flows are simulated to occur around/between these structures reflecting their influence on surface flows. Small mesh elements are used to describe most of the inland areas (Figure 152), since small elements are needed to properly resolve (flow-influencing) structures on the complex urban terrain, such as streets, alleyways between buildings, and building corners. Relatively larger mesh elements are used to represent sea and rural inland areas, which helps optimize the number of computational elements, and hence computation time, for the model.

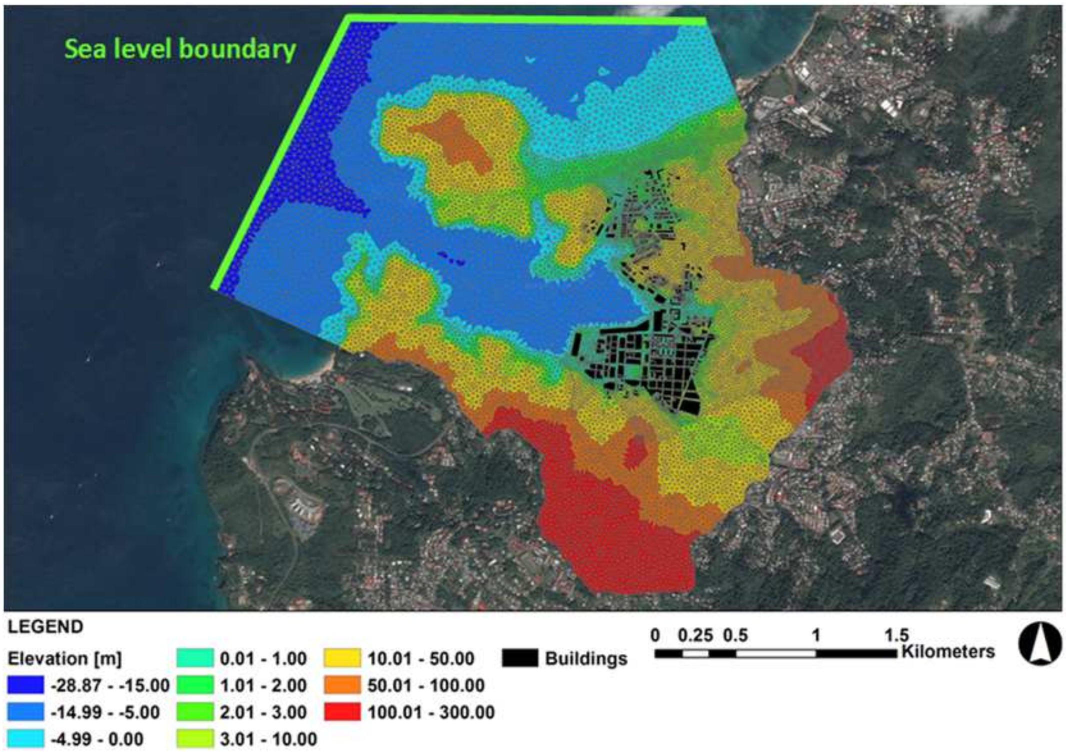


Figure 151: A plot showing the 2D coastal flood forecast model for Castries. The 2D model for the inland and sea areas around the harbour (coloured areas) employs a mesh of different-sized triangular elements. The presence of buildings is considered in the mesh (black shapes), and the sea boundaries of the 2D model are indicated in the figure (green lines).

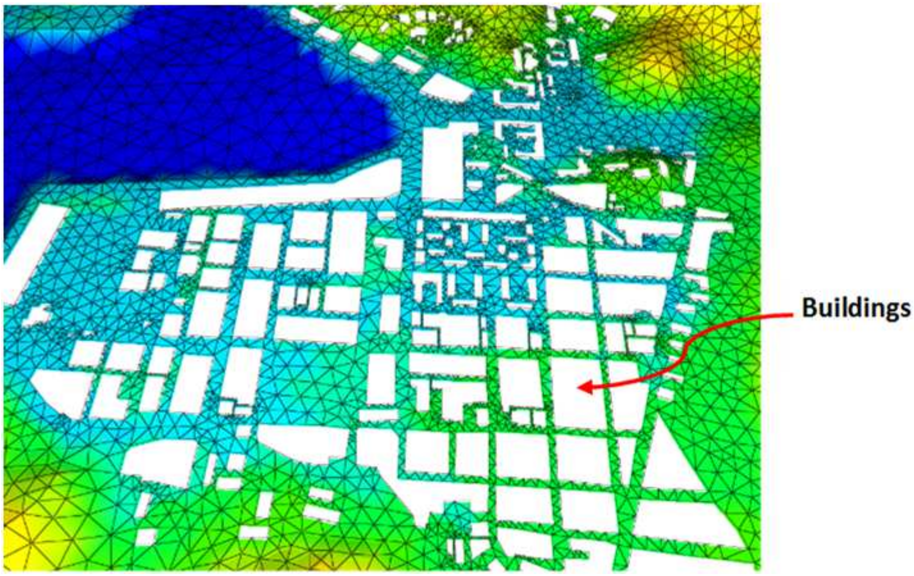


Figure 152: A closer view of the 2D model element mesh representing the terrain at the centre of Castries. Buildings are removed from the mesh (shown as white spaces) as a way to consider the influence of structures on surface flows.

Forecasted rainfall from StormGeo is used as spatially-distributed precipitation input to the 2D flood model. The surface runoff process is approximated using the rain-on-grid approach in the 2D model. Also, for the Castries flood model, rainfall over buildings is assumed collected by the urban sewer system and not applied to the 2D grid. The technique could also be further refined by pre-processing the rainfall time series input considering (i.e. subtracting) the design capacity of the urban drainage system. Forecasted sea levels from NOAA are also applied to the 2D model as water level conditions at the open sea boundaries towards the Caribbean Sea.

In the system, 24-hour flood forecasts are made every 4 hours at 22:00, 02:00, 06:00, 10:00, 14:00, 18:00 CET. The Saint Lucia flood forecast model takes around 20 min computation time to simulate a period of 24 hours. Results are shown on the website as static maximum water depths and time-varying water depth animations.

Decision-Support using MIKE Workbench

Important locations in the study area were identified, and noted in a spreadsheet in MIKE Workbench (see Figure 153). After each flood simulation, results at these important points are extracted, stored, and analysed to derive maximum values upon which flood warning information is issued. Coloured place markers are used to represent these points in flood map on the website (Figure 154), and the colours are changed according to whether flooding is forecasted to occur at a point or not. Calculated water depth time series at the pre-identified critical points could also be viewed on the website.

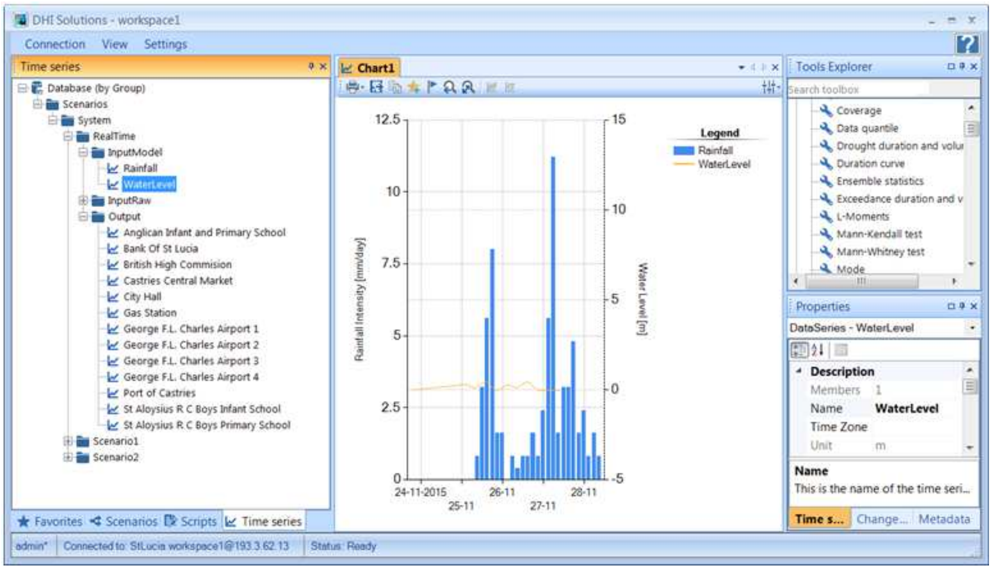


Figure 153: The MIKE Workbench interface showing the various input and output data being handled by the Saint Lucia Flood Warning System.

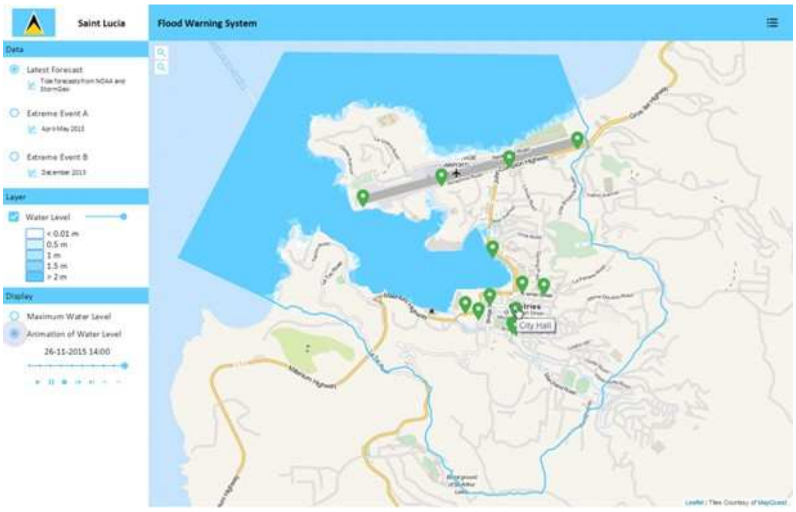


Figure 154: The flood map on the website shows place markers for pre-identified important places (e.g. the City Hall) in Castries. The markers are colour-coded according to computed maximum flood depths for the next 24 hours from green (0-20 cm), to yellow (20-40 cm), and to red (above 40 cm).

A summary of the various data that may be viewed on the website include:

- GIS data layer showing model extents
- Spreadsheet with a list of critical locations and maximum calculated flood values for the next 24 hours
- 2D water depth animation and static maximum water depth map
- Time series for water depth at critical locations
- Time series for boundary conditions used in the flood modelling

Dissemination through 'http://stlucia.dhigroup.com/'

Information on the Saint Lucia Flood Warning System and real-time flood forecast results are published on the website 'http://stlucia.dhigroup.com/'. The site was built using Polymer (Polymer, 2015) linking to the DHI Web API (Application Programming Interface), which supports data access

in MIKE Workbench. The website shows information on real-time forecasts as well as results from historical event simulations (Figure 155). By default, the maximum simulated water depth is displayed on the map, but the user can also display an animation showing the propagation of flooding. Pre-identified important locations are shown on the map with markers coloured according to calculated maximum flooding as green (0-20 cm), yellow (20-40 cm), or red (above 40 cm). The user can click on the place markers to view calculated water depth time series at each location, and boundary conditions used for the flood simulation may be viewed through the time series icon under the 'Data' menu (see Figure 155).

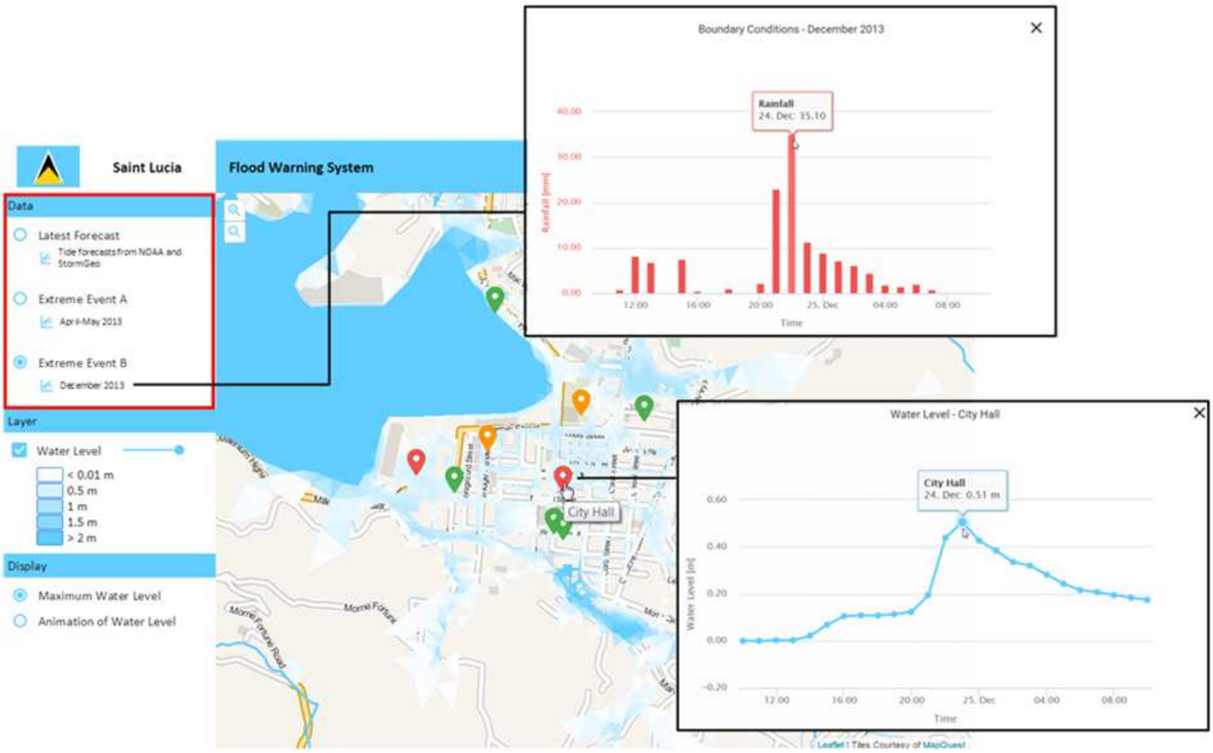


Figure 155: Latest flood forecasts as well as results from 2 historical event simulations could be viewed on the website (menu outlines in red). The boundary conditions data may be viewed through the menu on the left, and water depth time series results may be viewed by clicking on place markers on the map. The plot shows calculated flood depths for a rainfall event (i.e. Extreme Event B) in December 2013.

Performance and evaluation

The updated Saint Lucia Flood Warning System is relatively new, and was put into operation in November 2015 (see http://stlucia.dhigroup.com/ and Figure 155). To date, new 24-hour coastal flood forecasts are being issued regularly (i.e. every 4 hours) since the system was launched.

The system will continue to be monitored and improved within the course of the PEARL Project.

9.3 Summary and lessons learned

The main lessons learnt from the online coastal flood warning system developed for Castries, Saint Lucia are that the research has showed that is to possible to develop and run a flood forecast system for the combination of flood risks from storm surges and pluvial flooding. Further, the St.

Lucia case was run remotely on computers located in DHI, Denmark. I.e. the research has further demonstrated that it is feasible to host flood warning systems as locations far away from the actual places at risk. This finding means that computers and model do not have to the present locally, where there might be power failures and maybe a lack og human capacity to run and maintain a flood warning system. Although this case study is a small tropical island, the approach is adaptable to other locations. The generalizability of this approach is subject to certain limitations and is not limited to the size of the area, nature, severity and extent of flooding which would dictate the type of mitigation action required.

So far, issues and points for improvement have been identified since its launch. These, include:

- **Collection of measured sea level data at Castries Harbour.** To be used for sea level and flood model verification.
- **Collection of operation (quantitative) performance statistics in MIKE Workbench**. Job statistics comprising of 'Duration' data could be recorded in MIKE Workbench. It is a time series of calculation times (in hours) for all forecast simulations, and thus provides not only information on how much time a forecast simulation took, but also whether the system isrunning at a point in time, as 'zero hours' simulation time is unlikely and probably indicates that the system is down.
- **Improving data presentation on the website**. The rainfall forecast boundary time series is not shown properly, and information on the current forecast period is not readily shown.
- **Improving sea level forecast boundary data.** Additional sources of forecasted sea level data used as boundary conditions for the coastal flood forecast model will be identified.

During the last year of PEARL, we will work on the issues above.

10 Case Study – St. Maarten, The Caribbean

10.1 Introduction to the case study area

10.1.1 General description of the case study area

Sint Maarten is a constituent country of the Kingdom of the Netherlands as of 10/10/10. It encompasses the southern third of the Caribbean island of Saint Martin, while the northern two-thirds of the island constitute the French overseas collectivity of Saint-Martin. Its capital is Philipsburg. Its population is 40917 on 34 km^2. [9] Sint Maarten is located at the northern end of the Leeward Islands at 18.4^{0}N and 63.4^{0}W with a coastline of 364 km, see Figure 10-1. The island is of volcanic origin with low and hilly terrains. Elevation ranges from near sea level along Caribbean Sea to 386 m above mean sea level of Mt Flagstaff at the northern hilly part along the borderline. Arable land accounts 10% of the land use in the island.[10]

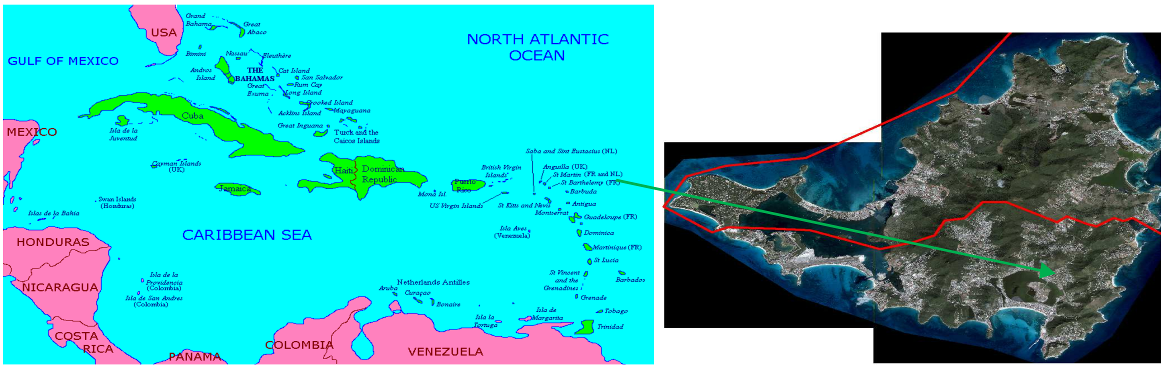


Figure 9-156 Location of St Maarten

The general climate of the island usually varies from a relatively dry season (January-April) to a rainy season (August-December), with moderate winds from the east to northeast. Showers normally occur during the late afternoon, as local effects of heating, humidity, etc. combine. Additionally, temperatures usually remain around 27^{0}C with the warmest month being August. The tropical nature of the island extends into seawater temperatures of around 27.2^{0}C, while skies typically range between mostly clear to partly cloudy.[11]

10.1.2 Hazard and risk situation in the case study area

Being located in the North Atlantic Ocean, Sint Maarten has been subject to hurricanes for many years. The Atlantic Tropical Cyclone Season runs from June 1st up to November 30th. Almost every year at least one tropical cyclone occurs within a range of 100 miles and on the average once every 4-5 years hurricane conditions are experienced in the island. The most recent

[9] Hurricanes and Tropical Storms in the Netherlands Antilles and Aruba –report from Meteorological Department Curacao - http://www.meteo.cw/Data_www/Climate/documents/HurricanesandTropicalStorms.pdf (Accessed Nov 1, 2014)
[10] CIA World Fact Book - https://www.cia.gov/library/publications/the-world-factbook/geos/sk.html (Accessed Nov 1, 2014)
[11] http://www.meteosxm.com/climate/ (Accessed Nov 1, 2014)

hurricanes to cause considerable damage to the island were the hurricanes Omar (2008), José (1999), Lenny (1999), Georges (1998), Luis (1995), Marilyn (1995), Hugo (1989), Donna (1960) and Dog (1950). The damage estimated with hurricane Dog was about US$ 70.000, without loss of lives. Hurricane Donna left a quarter of the island homeless and killed seven people. However, the damage caused by Hurricane Luis was extensive. The total damage due to Hurricane Luis was estimated to be approximately 1 billion US dollars (direct and indirect). Over 80% of all construction (residential, businesses, churches, hotels and schools) sustained serious damage or had been completely destroyed. Nearly all power and telephone lines were damaged and out of operation which left the island for several days without communication with the rest of the world. The hurricane also killed seven people (drowning). The tourism based economy took years to recover after Hurricane Luis. This shows that the potential impact due to hurricanes has increased considerably over the recent years due to economic and population growth on the island. [12]

Apart from the above mentioned hydro-meteorological hazards, the stormwater catchments and streams on Sint Maarten have several unique characteristics that contribute to the severity of flood-related impacts, Figure 10-2 shows photographs during and after a flooding event due to heavy precipitation. Urban environments are usually situated on low-lying areas, with little consideration for stormwater drainage, and as such are subject to flash flooding (i.e. inland flooding) from surrounding hills or extreme rainfall events due to hurricanes. The stormwater channels or streams are often short, entering the ocean as low or mid-order streams. They are typically inadequate to convey excess rainfall runoff due to the limited capacity, obstructions and the morphological rising of the stream bed. Those areas close to the sea (such as Philipsburg) are very vulnerable to inundation due to high water levels resulting from storm surge. Typically, the localised flooding due to inadequate stormwater drainage system happens almost every time it rains. In residential areas, the streets are usually narrow due to inadequate development control mechanisms and as such they represent a limiting factor for further enlargement of stormwater channels.

Figure 9-157 Flooding after heavy precipitation

Based on the past events, it is apparent that the disaster prevention, preparedness and mitigations on the island have not been sufficiently developed to be able to cope with the disasters. Therefore, for Sint Maarten authorities, the ability to address the diverse problems of flooding and wind impacts due to hurricanes, and to minimise the risk of flood-related disasters represents a major challenge.

10.1.3 Current institutional and governance practice

[12] Hurricanes and Tropical Storms in the Netherlands Antilles and Aruba; and Fire Department Sint Maarten - http://www.brandweersxm.net/org/disaster-management/disaster/ (Accessed Nov 1, 2014)

St Maarten's status as a small island and historic marginalisation within the Dutch Federation influences its economy, politics and culture. From the 1960s, the island experienced a key turning point with the development of the airport and port, and the return of islanders with money to invest following the oil booms in Aruba and Curacao, which facilitated tourist development and which led to demographic growth and in-migration. Economically, St Maarten is a highly open economy dependent on tourism and related sectors, and the US economy in particular, although financial services, cruise passenger spending in duty-free outlets and property development also contribute. While relative to other Caribbean islands St Maarten has a high income per capita its income is also highly unequally distributed. Like other case study locations in PEARL such as Rethymno in Crete, St Maarten has faced acute public sector resource constraints. This is partly as a result of the impacts of the global economic downturn from 2008, although St Maarten weathered the downturn better than other Caribbean nations, but partly owing to its small island status and the impact of devolution in 2010 which resulted in St Maarten becoming an autonomous country within the Kingdom of the Netherlands (rather than governed as part of the Netherlands Antilles). The island is societally small-scale, but the structure of the economy has sustained high levels of migration from other Caribbean nations, including a relatively large group of mostly unskilled (and also illegal) immigrants. This population group is highly mobile: within a period of 3-5 years an estimated one-third of the population moves on to North America or Europe (Transparency International 2015). Political and judicial responsibility Saint Maarten function as a country, following a referendum and devolution of power within the Netherlands Federation in 2010. (Fraser, 2016).

Photographs (Figure 10-3) showing urban development in St Maarten since 1950, source: VROMI (Ministry of Public Housing, Spatial Planning, Environment and Infrastructure)

Figure 9-158 Phillipsburg 1950 and 2015

The Government of Sint Maarten is currently developing a national development plan. As part of this national development plan, the spatial development plan is designed to prevent undesirable developments by zoning land for the desired use. The plan will also introduce building codes and inspections which may reduce the exposure and vulnerability of residential and businesses of natural hazards.

Stakeholders analysis

During the application of the RRCA in St Maarten a formal stakeholder analysis was not performed. However, the analysis of the interviews that were carried out with key stake holders

provided a good inside about the main stakeholders and the role they play for risk and disaster management. Based on the collected information the following summarises the stakeholder analysis. Fraser, 2016.

The emergency management system (a policy plan with 10 focus areas, each specifying relevant actors, targets, e.g. the number of fire stations and actions to be taken in an emergency) was developed for all the Antillean islands after Hurricane Luis and has provided a stable structure for disaster management, with much continuity in key personnel (the Ordinance and Plan were approved in 2000). A National Disaster Co-ordinator was appointed and the Fire Department given a key role in disaster management. Developed as a response to events in a "trial and error" fashion, the organisational system for preparedness and response, including annual awareness-raising campaigns, is well-established among government institutions and has been supported by successive Lieutenant Governors and Prime Ministers (after 2010). It contrasts previous eras in which "different agencies all said different things". A key underlying difference between this aspect of risk management and the failure to address the land use and building control issues that drive up risks was explained by one respondent as: "Forecasting and warning is safe and people are willing to support it" (Interview Fire Dept.), and by another: "When it comes to hurricanes there is no political play, the concern is for communication" (Interview DCOMM). This is underpinned by an emergency shelter system and advisories for evacuation, although there is no mandatory evacuation. The effects of Luis are reflected not only in the practises of government ministries, but across many entities: one respondent from the port authority reported that hurricane preparedness was "now much more of a routine in response to events" (Interview Port Authority).

A key source of institutional resilience on the island also lies in the capacities of the non-governmental sector and historic ways of working between government and non-government actors. Due to the historic lack of public resources (as a small island), when the emergency management structure was designed for the island from 1995, it was recognised that the private sector also needed to be involved. Non-government actors are therefore included in the Emergency Support Function task forces alongside government bodies.

To give an example of ways of working, in terms of shelter management, the government guarantees the security of emergency shelters, the Red Cross opens them and does the initial registration and medical checks and then the Community Development Department takes over (but shelters and staff training are not paid for by the government). The level of formalisation in these arrangements varies: VROMI, for instance, has a standing agreement with an NGO called the Nature Foundation for environmental protection and management (a form of agreement relatively common in the Dutch Caribbean), but other NGOs don't necessarily have mandates with government. There is overlap in key personnel that facilitates the arrangements: the Head of Disaster Management is also the President of the Red Cross. Some may get basic funding, but others not. The lack of formal agreements was not reported to be a problem, with a strong sense of "The role comes with the responsibility, and comes with the territory" Interview Ministry Public Health), although a formal agreement with the Red Cross and with shelter owners was being developed by the Ministry of Social Development to manage key aspects of liability. However, although no major problems were reported, it may be hard for NGOs such as the Red Cross to plug the capacity gap, given that they rely on volunteers who are doing other jobs. Even the Nature Foundation, which receives a subsidy from government, reported that it could only be reactive in its functions.

The business sector has also been a key source of capacity and resilience, both autonomously and in conjunction with government. An example of collaboration was the clean-up of sunken boats and debris in the Simpson's Bay Lagoon after 2014 Hurricane Gonzalo, organised by VROMI in conjunction with local businesses, for whom the debris threatened the upcoming tourist season

and safety of maritime operations.

Many businesses also have their own preparedness and response plans, including making their properties secure, but may also be mandated nationally or internationally to do so (e.g. the port is required to have a plan nationally, the airport due to international aviation standards, the insurance company Nagico has its own internal response plan, response preparedness committee and a continuous watch on warnings, in part because of a national requirement on financial institutions). Insurance companies and banks also contribute to citizens' promotions and preparedness activities for hurricanes – e.g. putting out an emergency list as part of their product marketing and offering discounts for putting up hurricane shutters (which in turn reduces their risks)

Governance and institutional arrangement for emergencies

Based on information collected by WMO, 2016 and the interview to Paul Martens, head of the fire brigade in St Maarten. The institutional arrangement for emergency management (including hurricanes and flooding) is presented in Figure 10-4. In case of a severe weather threat (especially tropical cyclones) in the Netherlands Antilles and Aruba, the MDNAA (Meteorological Service of the Netherlands Antilles and Aruba) shall inform the highest local and federal authorities, local emergency management authorities and the local populations. The role of the MDNAA is further to inform and advice local emergency management authorities on what steps to take to handle the expected inclement weather or other potentially damaging geophysical phenomena.

According to law, the MDNAA is responsible for the issuance of official warning messages for tropical cyclones and other severe weather or other geophysical phenomena (PB 2003 No. 59, Art. 6 Cl. 2) in the Netherlands Antilles and Aruba. These warning messages can only be retransmitted without being altered by third parties and the MDNAA should be mentioned as the source.

The MDNAA has an advisory role to the local disaster management organizations in all islands of the Netherlands Antilles and Aruba (Source: WMO, accessed December 2016)

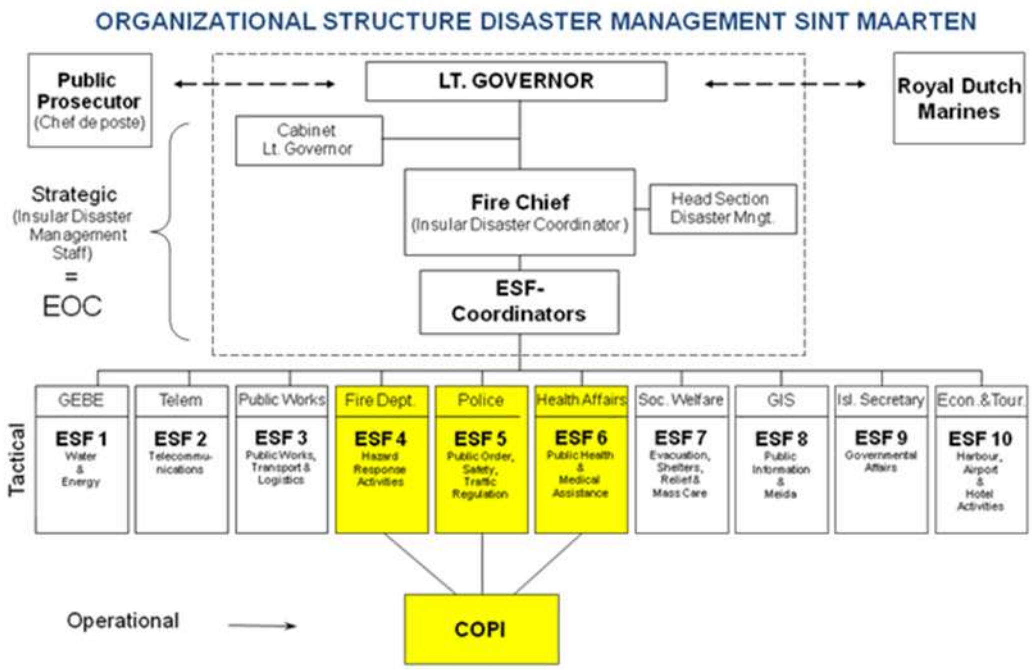


Figure 9-159 Disaster management in St Maarten (Source: WMO, 2016 and Martens P, 2016)

The MDNAA will function as a liaison to the disaster management staffs in all islands. All islands in the Netherlands Antilles have a comparative organizational disaster management structure.

Current Flood protection measures

In relation to the use of hazard and risk maps and their use to communicate with the stakeholders and community, the local fire departments inform the public in special folders or in the phone directory about hazard risks related to tropical cyclones.

There is no other information for the public about other hazards related to other meteorological or other extreme geophysical phenomena, it is mainly focus on hurricanes. For the emergency response and planning the following sources of information are available:

- Local knowledge is being used as basic hazard-risk information.
- The only hazard risk map that St. Maarten has is for flooding of the Cul de Sac area (prepared by UNESCO-IHE). Some modelling has been done as well for this area. There is a joint plan being prepared for the Dutch Quarter and French Quarter areas on that island.
- There are no known hazard risk maps for the other islands of the Netherlands Antilles nor for Aruba

The contrast between Hurricane preparedness and response and other disaster types, including flash flooding. According to one interviewee: “we are experts at hurricanes, everyone can tell you how to prepare…but we think that because we are aware of hurricanes we are aware of everything else” (Interview SHTA). A key challenge is the contrast between the usual warning onset period for hurricanes of 2-3 days and that of a flash flood of 20-30 minutes. Some moves to greater overall flood preparedness have been made: a flooding disaster response plan has been drafted and advisories are issued. One respondent reported that since the 2005 flash floods, in which a women died after getting out of her car, there is greater awareness of staying off the road and a preparedness ‘kit’ is sold for cars (as well as homes, which has long been part of hurricane preparedness measures). Even for hurricane events, however, there was uncertainty at how St Maarten would cope today with events of the magnitude of Hurricane Luis (i.e. above a category 3-4 hurricane). As one respondent commented: “It is basically clean up as fast as possible, get to higher ground and see what is left” (Interview Port Authority). There is also a lack of preparation for possible tsunami events.

The withdrawal of Dutch development aid with devolution, reduced EU funding through the European Development Fund (as St Maarten is now only an Associate Member of the EU) and constraints on international borrowing with a debt relief settlement agreed with the Dutch from 2010 (although they may borrow from the Dutch as a last resort). The financial pressures of being a small state, without economies of scale and with high debt ratios that can make it difficult to borrow internationally, is cited as a more pressing constraint on government than the impacts of the global economic downturn. As a result major planned infrastructure works had been delayed to keep the deficit down.

Development aid financed many infrastructure and social development projects that were not seen locally as an investment priority, such as roads and water and sewage infrastructure, in areas that were not a political priority, but also projects were pre-financed, whereas now liquidity constraints means delays (although one respondent also reported that the island lacked the capacity to manage previous inflows of foreign aid). Each ministry has its own risk-related budget (there is no National Disaster Fund at present).

The Ministry of Public Health officials reported that dedicated funds would be necessary if they were to have dedicated staff for preparedness, more appropriate equipment and better planning

and structures in place. A former government official reported that expertise in planning projects and getting money from external sources such as the EU was currently lacking. “Now we have to be self-reliant and it is a huge challenge” (Interview VROMI). Ultimately, in a major disaster, respondents said they expected to be reliant quickly on the Dutch and on international humanitarian assistance (with a contingent of Dutch marines already present in St Maarten during the hurricane season who assist with reconnaissance and clean-up). In 2014, the Finance Minister warned that the island might be able to finance one catastrophe, but not successive disasters (Today St Maarten 2014).

One of the key elements of the disaster management is the existence of early warning systems and communication channels and protocols. According with the information provided by the interviews there are some issues in these areas:

Forecasting:

- Lack of small weather stations as well as functioning radar. The lack of functioning small weather stations in part relates to weaknesses in government co-ordination, e.g. between VROMI and the Met Office.
- Ongoing capacity building at the Met Office following the devolution of functions to the island from 2010. The development of the Met Office has been supported by international expertise. The current operating capacity of the Met Office is estimated at around 60% of planned operations (Interview Met Office).

Warning and awareness:

- Official communications are least likely to reach illegal / immigrant groups due to language barriers and mistrust in government. Other challenges to communication included: the transience of communities, the lack of capacity to translate communications into other relevant languages in an emergency that people forget the information, that needs are different in the high and low seasons.
- Communications infrastructure relies on radio, with sirens discontinued due to technical issues, but more radio and TV presence and cell phone broadcasts still needed. With more and more private channels, the challenges of co-operating with the private sector increase, and the public are not aware what is government information, e.g. people call the national hurricane centre when they should call local met services.
- There is training by the Fire Dept., e.g. at the airport, although some agencies are not yet fully on board (such as the police). Likewise, exercises take place in schools but less so in businesses and government agencies.

10.1.4 Available data used for research activities

- Contour maps/Terrain data
- Aerial photos
- Cadastre maps
- Development maps
- Layout of the existing channels
- Channel profiles
- 1D-2D models
- Rainfall
- Historical verification

10.2 Key research activities and results

10.2.1 WP1

King's College London carried out the Risk Root Cause Analysis for St Maarten. The findings from St Maarten have been used to structure and inform Work Package 1 inputs to the development of root cause analysis-informed agent-based models (ABM) in Work Package 3. This is a brief summary of the main findings.

Although there was no formal stakeholder process convened through PEARL on St Maarten, the research findings can be validated by stakeholders, and then disseminated informally among stakeholders through ongoing contacts held by KCL and UNESCO-IHE as PEARL partners.

The application of the Risk Root Cause Analysis Method in St Maarten

The Risk Root Cause Analysis for St Maarten followed the methodological approach laid out in PEARL Deliverable 1.1. The research is based on individual, expert interviews with stakeholders, where the aim was to capture as diverse a set of views about disaster causation as possible through interviews with multiple stakeholder types. 22 interviews were conducted between July and November 2015, the majority face-to-face interviews but also telephone interviews with those whom it was not possible to meet during fieldwork on the island. The researcher 'snowballed' out from interviews with initial contacts provided by other PEARL researchers to generate a wider field of interviewees.

The interviews were in-depth, typically lasting 1-2 hours each. The interviews centred on actor behaviour pre-, during and post- flooding events as well as eliciting stakeholder opinions about the broader causes of specific disaster events on the island. The interview structure adapted the broad PEARL Risk and Root Cause Analysis Framework – which displays root causes acting on risk across the inter-acting physical, governance, socio-economic and perceptions, values and beliefs domains – for the context - for example, seeking to understand the impact of changes in governance on the island in 2010 on risk management.

A limitation of the study lies in the sectors and stakeholders who were unrepresented in the study sample – for St Maarten this was representatives of the tourist and hotel trade, critical infrastructure facilities, donors, property developers as well as community leaders and affected residents.

The Root Cause Analysis highlights, although it does not make explicit, many of the inter-connections across the physical, socio-economic and governance domains and pathways that give rise to risk. This has been reported in deliverable 1.3. The information from the Root Cause Analysis has been used as an input in the description of the Agent-Based Modelling work in a format that highlighted the actors, actor-relationships and underlying institutions conforming the current flood 'system'. In conjunction, the outcome of the interviews also provides a timeline of policy measures and the underlying motivation for relevant policies, as reported in interviews, a summary description is presented in the Table 10-1 here below.

Table 9-37 Timeline of events and policy measures. (source: Fraser, 2016)

Known trigger / motivation	Policy action
Hurricane Frederic in 1979 exposes weaknesses of pump and waterworks	Several measures taken such as lowering of ford to allow water to flow into Salt Pond
Controversy about certain building developments highlighted in the media	Beach Policy 1994, first attempt to regulate development Hillside Policy 1998

Known trigger / motivation	Policy action
First planning permit request made it clear that guidelines were needed – guidelines were supposed to bridge phase until Global Land Use Plan could be developed Socio-Economic conference of 1995 also emphasized that natural resources were being destroyed	*(these are guidelines, not laws)*
1990s Hurricane events	Leads to better building and infrastructure construction by public and private sector (e.g. almost all cables now run underground); strengthened building codes and enforcement; disaster management and co-ordination structures, plans and training exercises put in place; curfew system put in place; improvement of Government communications and annual hurricane awareness campaign introduced The destruction of Great Bay in 1995 and the washing away of the beach in 1999 led to the building of the Philipsburg boardwalk from 2003, which was built to protect against storm surge. It was financed by the government and the Harbour (it also included an aesthetic aspect to attract tourists to Philipsburg).
1990s Dutch Ordinance legally obliges zoning and later Dutch development funding	Triggers attempted zoning policies, but none approved into law
2005 Floods	UNESCO flood mapping studies (recently put into GIS so flood risk areas can be defined and evacuation procedures improved) Prompted measures, but 'faded away'
2010 flooding	New pump installed in 2011 / 2012, although recommended in 2003
2014 Hurricane Gonzalo	Renewed political calls for drainage improvement lead to drafting of Stormwater strategy (but not approved)(prior to this budget claims for the work never executed) Change of policy to open shelter in the event of any forecast hurricane, rather than event of a Category 3 magnitude hurricane Also change in response by non-government actors: Port will now move to full preparedness for any named storm, rather than wait on warnings Reported that there was political will after Gonzalo to make real changes Extension of trenches and expansion of flood gate following IHE-UNESCO requirements for South Pond and Fresh Pond
Ongoing revision of Disaster Ordinance and Plans, including Emergency Support Functions as institutional structure increasingly out-moded and need to improve working of some Emergency Support Function groups	Ongoing revision of Disaster Ordinance and Plans, including Emergency Support Functions
Address to Parliament by known local	2015 prolongation of the Hillside Policy by the legislature

Known trigger / motivation	Policy action
NGO activist, as legislature wanted to approve new developments up the hillsides	

The complementarity of the agent-based modelling work to the RRCA approach is that it provides a futures-oriented perspective and simulation of multiple scenarios, where the Root Cause Analysis and Vulnerability Assessments are mostly oriented to a historic and contemporary perspective for a particular set of conditions. In turn, the work of WP1 has been used to identify key stakeholders as well as key behaviours (rules and norms) for the ABMs and contributed to a stronger understanding of institutions and institutional dynamics in the MAIA model which underpins the institutional ABM work, beyond reference to social systems

10.2.2 WP3

Information from the Root Cause Analysis method was used for the development of agent-based models (ABM) which are part of the the PEARL Holistic Risk Assessment Framework. For work package 3 there are two ABMs in PEARL developed at UNESCO-IHE. The first one focuses on the interaction of floods, humans and their built environment as drivers of hazard, vulnerability and exposure. The drivers are the institutions which in model terms are expressed in terms of institutional statements. For example, land use planning can be a driver of exposure and institutional statement derived from this driver could be “Land owners must not construct new buildings (or houses) if their land is located 25m from the waterfront.” The ABM in this study addresses long-term institutions related to prevention and mitigation and recovery phases of the disaster management cycle. The second ABM focuses on the short-term, operational and management related to the preparation and response phases of the disaster risk management cycle. These are connected to flood early warning and evacuation processes. A summary of the on going research results for the evacuation ABM is provided in the WP4 session.

The findings of the RRCA were used to formalise the concepts based on the MAIA framework. Institutional statements are extracted and coded from RRCA outputs based on the methods described in (Basurto et al., 2009; Watkins and Westphal, 2015).Concept formalization is an iterative process which continues until the problems formulated and systems identified are well captured in MAIA structures (Ghorbani, 2013). The following tables show examples of the different structures of MAIA and the formalization.

Table A. Social structure

Name	Property	Personal value	Information	Possible role
Households	- Wealth - Level of risk to take - Risk awareness - Insurance - Building plan	- Safety	- Zoning policy - Beach policy - Hillside policy - Building ordinance - Insurance policy	- Land owners
Businesses	- Asset - Profit - Level of risk to take - Risk awareness - Insurance - Building plan	- Profit maximization - Safety	- Zoning policy - Beach policy - Hillside policy - Building ordinance - Insurance policy	
VROMI	- Budget	- Safety		- Permit

	- Enforcement - Fine	- Inspection - New Project

Table B. Institutional structure

Name	Attributes (roles)	Deontic type	aIm	Condition	Or else	Type
Building code	Land owners	must	elevate new house/building by 0.2 m	any location and any time	fined	Rule
Beach policy	Land owners	must not	build houses/building	within 25 m from the coast line	fined	Rule
Flood risk management	New Project department	may	Construct or maintain FRM measures	If flood leads to casualty		Norm
Flood risk management	Businesses		fund FRM measures	if measures protect asset		Shared strategy

Table C. *Physical structure*

Name	Property	Type	Behaviour	Affordance
Building (residential or business or public)	- Location - Elevation - Building function - Floor height - Flooded - Damage	- Private	- Flooded - Damaged	- Constructed - Maintained
Drainage channels (pipes)	- Location - Cross-section - Physical condition - Design discharge	- Public	- Damaged	- Constructed - Maintained
Hazard triggering factors (precipitation, storm surge)	- Return period	- Public		- modelled
Flood map	- Depth - Extent	- Public		
FRM measure	- Type	- Private/Public	- Damaged	- Constructed - Maintained

Development of the Institutional ABM

The development of ABM for the Sint Maarten FRM case study started before the RRCA field work and interviews took place. The initial model was developed using the NetLogo simulation environment (Wilensky 1999). Model inputs are obtained from desk studies and previous UNESCO-IHE studies on the island. In this model setup, there were two types of agents: businesses and ordinary residents. Businesses construct commercial buildings (e.g., hotels) and residents build residential houses. The institutions incorporated in that preliminary model were based solely on the Hillside policy. Businesses build in mild slopes and low lying areas, especially along the coast (to attract more tourists) whereas residents have more flexibility to build their houses on the island. However, since the land use zoning in the island defined higher elevations for nature, it is not allowed to build in elevations higher than 200m. In the model, the buildings, whether commercial or residential, represent the owners. Early simulation result presented in Figure 10-5 shows that commercial buildings (yellow coloured) aggregate more along the coast. On the other hand, residential housings (brown ones) concentrate on the hilly areas. The modelling exercise shows the potential of ABMs in showing emergent phenomenon, which in this case is location of different types of buildings, from simple institutions.

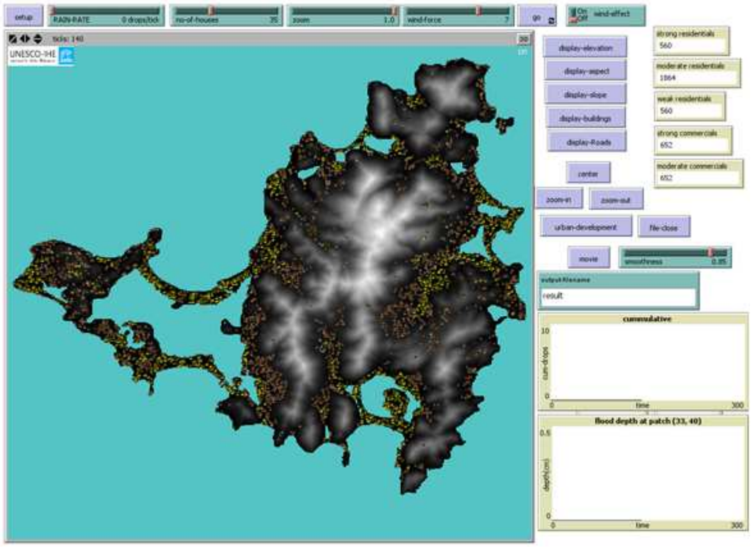


Figure 9-160 Building Pattern Result in the NetLogo visualization environment

After the RRCA was performed, more agents and institutions were identified and hence the ABM was expanded. To simulate the co-evolution of the human-flood systems and the FRM dynamics better, the modellers identified the need to couple the ABM with a flood model. In addition to a more realistic representation of the flood system, coupling a flood model with the ABM provides a platform to test the different FRM policy implementations (e.g., enlarging channel cross-sections and constructing new detention basins). However, NetLogo was found to be limited in the coupling process, especially running the flood model executables and manipulating input-output files. Therefore, the modellers changed the modelling platform to Repast Simphony (North et al., 2013), a Java based ABM environment.

The coupled institutional ABM – flood model being developed in PEARL focuses on long-term institutions related to prevention and mitigation and recovery phases of the disaster management cycle. The following preliminary result (Figure 10-6) shows an increase in the number of flooded houses (i.e., ticks 2, 7, 10, 13 and 17) for the same return period of rainfall (i.e., 5 year). The reasons for this can be increase in flood extent and new buildings constructed in flood plains. In the first case, increase in percentage of impervious surfaces because of construction of new buildings resulted in more runoff being generated from the same rainfall intensity. That, in turn, would create much flood covering larger extent. In the second case, most of the new buildings might not obey zoning regulations and not elevate their house.

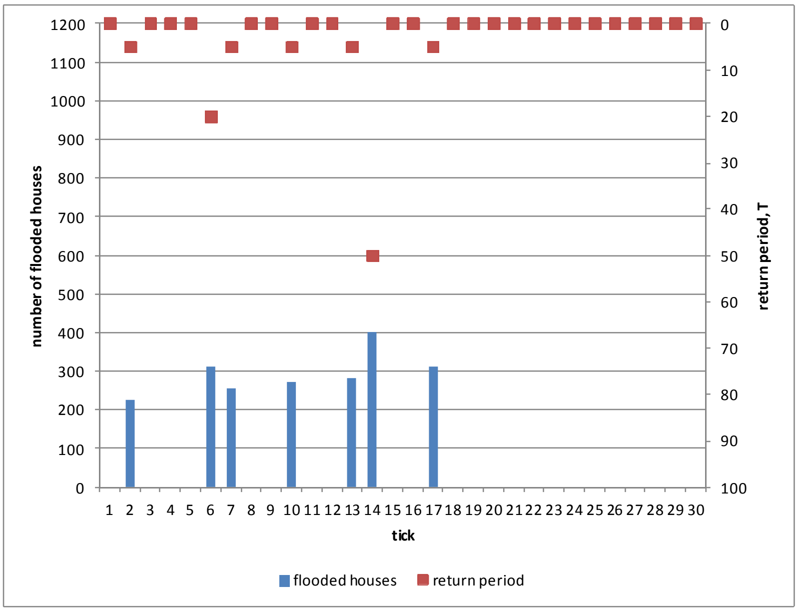


Figure 9-161. Results of a simulation for 30 years of the coupled model ABM and flood risk assessment

Remarks

This research developed and proposed a modelling framework to better represent and simulate the coupled human-flood system. The elements discussed in the human subsystem are agents and institutions that shape agents' decisions, actions and interactions. This subsystem is modelled using ABMs as they provide a functionality to represent heterogeneous agents and their institutions. The dynamic link between the two subsystems happens through the urban environment. The coupled ABM-flood modelling method permits to incorporate and model the physical changes made by "humans" on the urban environment every time step and assess how that change the flood risk in time. The methodology aims to capture the complex interaction of humans and their urban environment with flood, to simulate feedbacks and co-evolution of the coupled subsystems.

The application of the model in St Maarten, modelling human-flood interaction using coupled ABM-flood models helps to understand the system. In addition, it can be used to investigate possible future directions in flood risk management. The coupled model can also help us to study how levels of exposure (i.e., number of assets-at-risk), flood hazard (i.e., flood magnitude and extent) and vulnerability (i.e., propensity to be affected) change with change in human behavior (i.e., policies and their implementations). The outcomes that we expect from the modellings include the level of risk, in terms of assessed impact, as a way to measure the effectiveness of formal and informal institutions, and types of measures favored, or not, in an urban area based on the social, economic, political, and governance factors.

Strength and limitations of the framework

The strengths as a modelling framework include its functionality to test different policy options. This is better than a simple scenario analysis of structural and non-structural measures as it is also possible to test agents' behaviors (reaction) with different constraints and other informal institutions at the same time. The coupled ABM-flood model shows flood risk as a function of time by incorporating implementations that change flood hazard, exposure and vulnerability. This gives a

comprehensive view of flood risk than computing risk from flood event based on a single historical (unchanged) urban environment condition.
One of the limitations of the framework is that modelling two subsystems which are made of other complex subsystems requires lots of data. Adding more subsystems also requires to have a balance between better representations of a system and developing a complicated model, which results are difficult to track and interpret. Another limitation, related to modelling, is that flood model input-output files change depending on the type of software used. This can be a big issue especially when commercial software packages using binary formats are used.

Flood impacts on road transportation using microscopic traffic modelling technique

This research proposes a methodology for a dynamic integration of a flood model (MIKE FLOOD) and a microscopic traffic simulation model (SUMO). The flood model-ling results indicate which roads are inundated for a period of time. The traffic on these links will be halted or delayed according to the flood characteristics – extent, propagation and depth. As a consequence, some of the trips need to be cancelled; some need to be rerouted to unfavourable routes; and some are indirectly affected. A comparison between the baseline and a flood scenario yields the impacts of that flood on traffic, estimated in terms of lost business hours, additional fuel consumption, and additional CO2 emissions.

The overall methodology is shown in Figure 10-7. The impact of extreme hydro-meteorological events on transportation is twofold – coming from rainfall events and flooding of the road network. First, the extreme weather conditions lead to reduced maximum speed limits (Keay and Simmonds, 2005). As different streets in the network have different speed limits, the atmospheric conditions will define a proportionate speed reduction in each link. The decrease of speed limit will be driven by the intensity and the duration of the rainfall event and it will reduce road capacity before the flood has even occurred. Thus the flood impacts will start evolving in a transportation system, which already has reduced capacity due to heavy rainfall intensities.

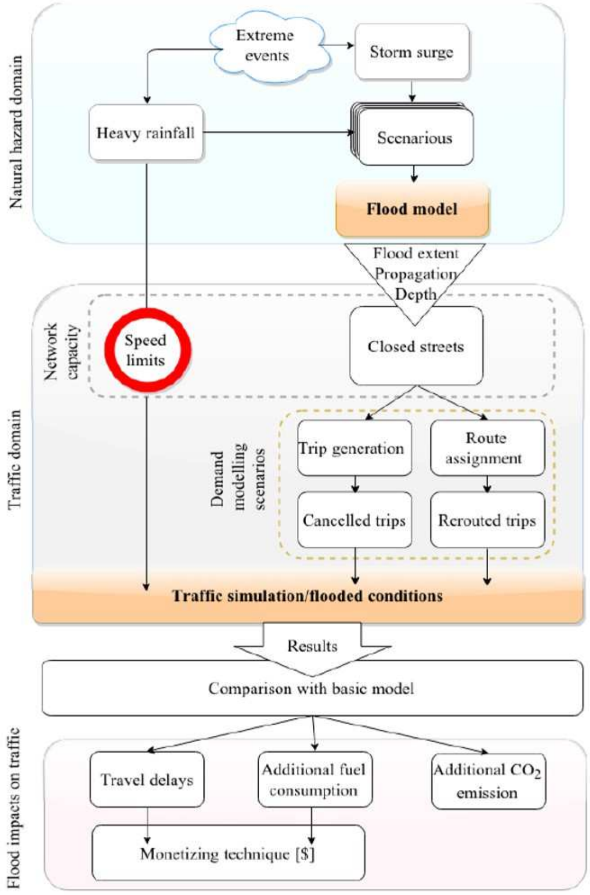


Figure 9-162. Methodology

Different combinations of intensities of rainfall and storm surges are simulated to produce the time varying flood characteristics. The consequent flood intensities in terms of flood extent, depth and propagation determine whether a street in the road network is going to be closed for traffic. This closure will affect the overall road capacities, the trip definition and the route assignment components of the traffic model

Hydraulic Model

The hydraulic modelling has been carried out on a catchment level for the most hazardous catchments in the island of St Maarten. The flood hazard characteristics (depth and velocity) were computed using DHI software MIKE FLOOD (DHI, 2007). This software ensures full dynamic coupling between MIKE 11 (1D river model) and MIKE 21 (2D model, computing the flood plain and the coastal flooding). The results from the coastal flooding model were used as boundary conditions in the MIKE FLOOD simulation. Thus surface runoff and coastal conditions were integrated at each time step. The flooding conditions were simulated for different return periods of storm events, assuming independence of the rainfall and storm surge occurrence. The results of the hydraulic model provided maps for relevant flood depth over time, depending on the flood propagation at a particular site.

Pre-processing of street maps

The road map for St Maarten was pre-processed taking the open street map layers with road

information. This was performed first by segregating major streets into edges in a GIS environment and by giving unique indices of the individual edges. The resultant shapefile was saved as an OSM and then translated to a network file, readable by SUMO. Figure 10-8 shows an overlay of the flood map and the flood water depth. The potential roads to be closed are shown in red and mainly depend on the water depth.

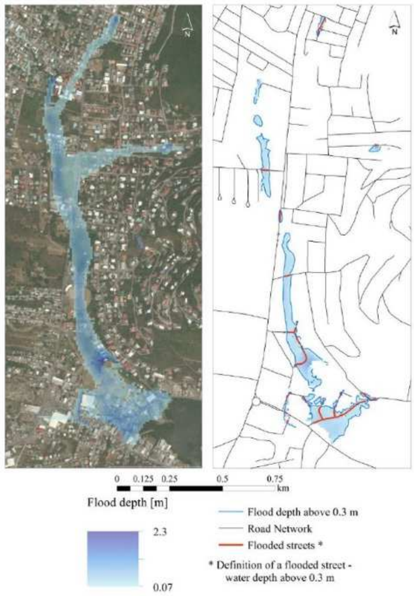


Figure 9-163. Flood map for 100 year return period and affected roads

Guidelines for a street closure can be found in studies related to car stability in flood water. Stationary vehicle stability in flood waters has been an object of experimental (Teo et al., 2012) and analytical studies (Keller and Mitsch, 1992). Shand et al. (2011) carried out a literature review for the purpose of establishing guidelines for vehicle safety on the road.

Traffic simulation with SUMO

The SUMO software (Behrisch et al., 2011) has been used to create a basic model, so that the proposed methodology can be tested. The traffic model was limited by the reduced availability of transportation measurement data, but it is believed there are sufficient data to further test the methodology. The model uses the traffic network of the whole island of St Maarten, which is rather large for conventional microsimulation network (total area 87 km2 and nearly 80 000 inhabitants). For example, when 30 cm of flood depth was used as a criterion for street closure, 268 streets in the whole network were identified to be closed and the traffic through them should be rerouted. From a traffic modelling point of view, the road network was going to suffer from 268 accidents, whose temporal characteristics depended on the propagation of the flood. In SUMO terms, each of these accidents had to be represented independently and this posed a problem when multiple scenarios were going to be modelled and discussed. Therefore, to simplify the problem, the test simulations focused on the cul de sac area. The following setting was used to setup the sumo model and some screenshots of the results are showed in figure 10-9.

- Simulated 5000 vehicles for 3 hours (10 800 seconds)
- A vehicle is inserted each second for the first 5000 seconds of the simulation
- Once the vehicle reaches its destination, it disappears from the network
- The street closures are from 300-5000 s simulation time

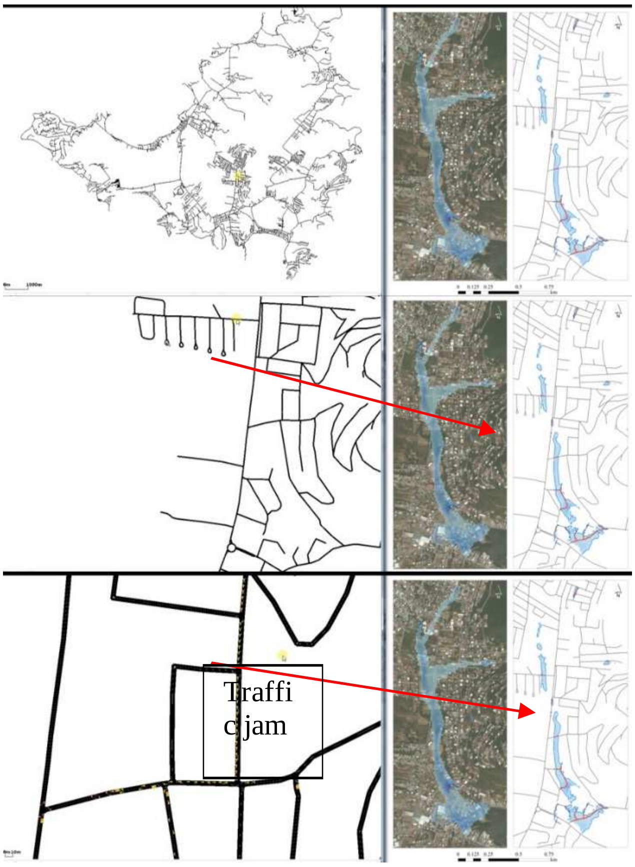


Figure 9-164 Results Sumo model generating traffic jam due to floods

Due to the lack of traffic data, modelling different vehicle classes and purposes of trips are reliant purely on assumptions. However, different vehicle classes can give valuable input, when traffic delays or cancellation of trips are monetized. This is currently represented by the activity based traffic demand model, which generates trips according to synthetic data about population and locations of big employers, schools and shops. However the preliminary results are showing a drop in the amount of running vehicles, which are the ones generating a traffic jams. Figure 10-10 shows the profile of running vehicles over simulation time.

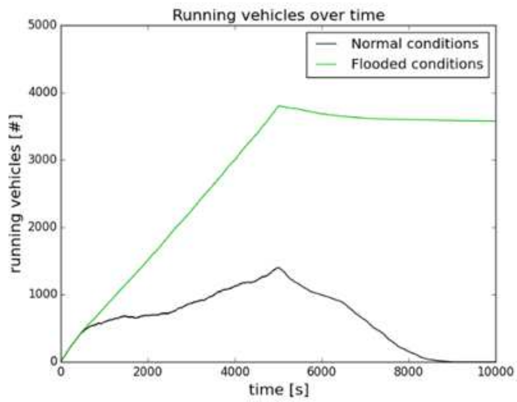


Figure 9-165 running vehicles over time

The results can be summarized as follows:

In terms of travel time

- 720 hours of additional travel time (78% increase from the normal scenario)
- 1951 vehicles have increase in travel time (57 % of the overall vehicles)
- 444 vehicles experienced delays mode than 30 min

In terms of travel distance

- 1369 vehicles rerouted (41 %)

In terms of vehicles being indirectly affected

- (%vehicles with longer travel time) – (% vehicles travelled longer distance) =

57%-41%=16% indirectly affected by slower traffic

Similarly, modelling emergency vehicles such as ambulances or fire brigade vehicles is very important in times of disaster management. For example the hospital in Philipsburg in St. Maarten can be reached only by one road which is prone to flooding. However, the evaluation of flood impacts like these is a great challenge, because losses are intangible and are no longer related to the particularities of the traffic conditions.

Remarks

This research presents a novel methodology for assessing flood impacts on traffic. Micro-simulation traffic models are starting to be used to approach that problem, even though only a microsimulation model can capture the dynamics of both the natural and social-technological sphere. The impacts of adverse weather conditions on traffic have been studied in detail, but have never been previously integrated with flood events. This methodology combines the joint impacts of both adverse weather conditions and accumulated floods to road transportation.

Traffic measurements are needed to verify and calibrate the parameters used in the SUMO model to ensure the modelling results can represent the traffic conditions properly. Cost assessment model of travel delays also needs to be adjusted to regional specifications of salaries in Saint Martin.

10.2.3 WP4

The use of Agent Based Models for climate change adaptation and development of large-scale evacuation strategies for flood risk mitigation

This research explores the use of Agent Based models to test different evacuation and communication strategies as a measure for climate change mitigation in cities under threats from floods and flood related disasters. The ABM model was used to evaluate different evacuation strategies in order to minimize risk and to prove the feasibility of new warning dissemination tools. In this context, the following steps were followed: i) creation of a framework to classify human behaviour under extreme hydro-meteorological events. ii) evaluation of ABM to simulate different scenarios for city evacuation under extreme hydro-meteorological events. iii) integration of ABM and GIS for risk assessment management. iv) testing of new technologies for warning dissemination to reduce risk and exposure.

Modelling Human Behaviour

Some general rules that must be considered when building an Agent Based Model (ABM) to be used as an evacuation and testing environment are: First, the ABM should be able to have a

proper representation of human's cognition ability. Second, the ABM model must properly capture the daily and complex human interaction and movement across the city and a third on to be able to change the behaviour accordingly with the human perception and warning information of a certain threat or flood risk. To comply with the general aspects, the following steps used were followed to set up the Model:

Agent Description: As first step it was define the agents that will be considered within the model. Two different type of agents where characterized in this ABM. The first type of agents are individuals, with every agent representing a human being in the model. The second type of agents were organizations, within this category are included those in charge of the city evacuation such as civil defence, police, firefighters, etc.; Also the warning forecast and communication agencies were modelled as organizational agents (i.e. weather forecast institutions). See Figure 9-1660-11.

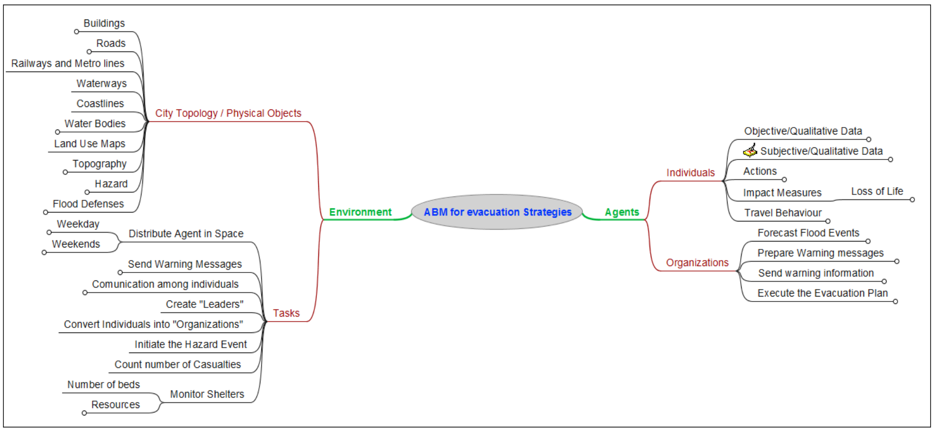


Figure 9-166. Agent and Environment Description.

Agent's Classification: The next step was to classify or to group the different type of agents, this was done in order to be able to specify different behaviours during the different phases of a flood disaster. In this research three major phases are considered: Before, the warning phase itself and during the disaster is unfolding[13]. Table 9-380-2 presents the main parameters that were used in the classification of the individual agents, here subjective and objective characteristics were taken into account.

Table 9-38. Individual Agents Classification Parameters.

Type of Parameter	Parameter
Objective Parameters	Age
	Gender
	Employment Status
	Financial Resources
	Mobility
	Language Abilities

Type of Parameter	Parameter
Subjective Parameters	Awareness
	Education Level
	Flood risk perception
	Willingness to Follow orders
	Altruism/Willingness to help others
	Resilience / Adaptability
	Access to Information

In a similar manner a possible set of actions was defined for each individual agent to once the

13 Note that the recovery or after disaster phase was not included in this ABM.

warning is sent to the community and/or the agents are aware of the danger associated with the flood (see Table **9-39**10-3 Figure 9-167).

Table 9-39. Individual Agents Classification Parameters.

Action	Observation
Evacuation	Planned and Organized, Follow instructions.
Fight	Prepare in situ
Flight	Random Evacuation (not follow orders)
Sideration[14]	Inability to respond
Search Relatives	Wife, children, parents, etc.
Return home or work place	Feel safe in these places and stay there.
Assist Others	The agent becomes an organization actor.
Antisocial Behaviour	Panic, looting, etc.

The organizational agents were grouped based on their role during the disaster phases described above as follows: 1. Organizations in charge of the forecast of the flood. 2. Organizations in charge of warning information and 3. Organizations in charge of the evacuation itself.

Environment Characterization: For this research the environment classification refers to those elements that form the physical space in a city (i.e. buildings, roads, water bodies, etc.). Additionally, the way agents will interact with the environment and how agents interact among them was also configured in the environment module. See Figure 9-1660-11.

Model Formalization and parameterization: By combining narrative rules and some flow charts it was defined for the ABM model WHO does WHAT and WHEN. For each agent (WHO), the actions to perform (WHAT) at which specific timeframe (WHEN). See Figure 9-167 for a description of the daily behavior or routine for the individual agents before a flood is forecasted (before phase). From this figure, every agent must first "Wake up" and start its normal daily routine. Using data collected from previous reports in the case study as well as some fieldwork in cooperation with the local authorities and some project partners, probability functions were built into the ABM for each type of individual agent to perform the most likely activity as can be seen in the mentioned figure. It is worth to mention that the probability will vary according with the day (week or weekend) and also the time was taken into account as an effort to simulate or represent as "real" as possible the location of agents in space when the flood event is unfolding.

Similar formalization was used with other components of the ABM such as the metrics to account for the loss of life, the daily activities of organizational agents, and for the cognitive behavior (see numeral 5 here below).

[14] The sideration term within this research is defined as the inability to respond from the psychological perspective

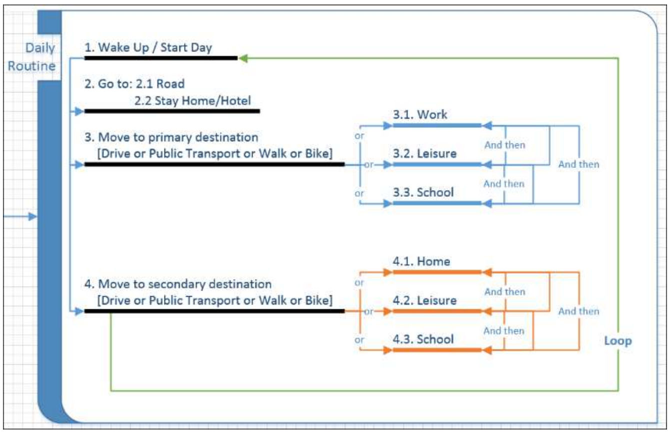


Figure 9-167. Model Formalization – Daily Routine for Individual Agents

Cognitive Behavioural Model: This module of the ABM allow the individual agents to react in a "human" like manner to the warning information. For this research the PECS[15] reference model was selected because it allows the possibility to specify the influence of physical, emotional, cognitive and social factors and their interactions during emergency situations. PECS intends to support the design process of agent-based simulations in which individual human behaviour and decision making process, the interactions between individuals as well as the interactions of individuals with the environment are in the centre of interest. The internal structure of PECS is presented in Figure 9-168. The central part of the PECS structure is used to describe the state of the agent regarding the physical, the emotions, cognition and social status of each agent. Finally, the bottom part is intended to provide the response or behaviour of the agent given the perception and state of the agent at certain time of the simulation.

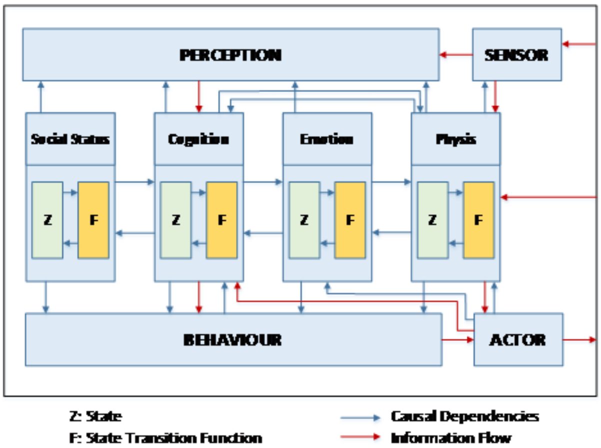


Figure 9-168. Internal structure of PECS reference model (Urban and Bernd, 2001).

By using the PECS reference model, it was possible to assign to each individual agent in the ABM model a different response to the flood evacuation scenarios performed in this research. The response for each agent was built based on the different combination of parameters listed in Table 9-38 and the possible set of action based on those reported in Table 9-39.

15 PECS is a multi-purpose reference model for the simulation of human behavior in a social environment (Urban and Bernd, 2001).

Software and Requirements: The implementation of the ABM was done in Repast Symphony[16] as a Java base, free and open source modelling system for creating, running, displaying and collecting data from Agent Based Simulations. This software is currently considered for many ABM modellers as the most powerful and popular free and open source environment to implement ABMs due to its robustness and the huge support from the online community and repast forums, another big advantage is that its implementation is fully object oriented that allows the construction of any ABM model to be much easier and allows to implement any ABM in blocks and make a modular, adaptable and reusable model. The version used was Repast Symphony 2.3.1 running under Windows 7 Professional, 64-bit operating System on a laptop with an Intel Core i7 processor and CPU @ 2.4GHz with 16 GB of RAM memory.

Results and Discussion

The ABM was tested in Dutch part of Sint Maarten Island. For this proof of concept ABM a total of 6046 agents were initialized using the residential buildings layer. The model was set up to run for an entire week from Monday to Monday and as a start of the simulation it was selected 04:00 hrs. At the beginning of the simulation every agent select a destination and start its movement towards it, which is chosen based on the individual's classification (Table 1) and according to the day and the time of the day for each agent, going from home to work, leisure, school and so on (see Figure 9-167). Into the ABM a hurricane17 based flood was introduced to test the evacuation capabilities of the agents as full 2D hydrodynamic model. Additionally, in order to explore and evaluate how the provision of warning information can affect the evacuation response and behaviours under extreme hydro-meteorological as a result of climate change, 4 different runs or scenarios were set up in the ABM:

- **Baseline scenario:** The agents evacuate according with the initial set of rules of the ABM, no new information is given to the agents in how to evacuate and the evacuation will be performed based on the "existing" knowledge of the agent.
- **Scenario 1:** A message with the warning and evacuation was sent at the same time to all the population in the island.
- **Scenario 2:** A message with the warning and evacuation was send gradually to all the population in the island, known as stage evacuation.
- **Scenario 3:** A message with the warning and evacuation was sent only to those inhabitants that reside and/or work in the areas to be expected be affected by the hazard event.

Figure 10-14 (a) presents the initial model running and (b) shows the flood coming into the island and agents already in the evacuation process. And Figure 9-170 presents the metrics or performance of each scenario.

[16] Repast: **R**ecursive **P**orous **A**gent **S**imulation **T**oolkit

[17] Hurricane Omar in 2008 was used for this test.

(a) (b)

Figure 9-27. Screenshots ABM Sint Maarten.

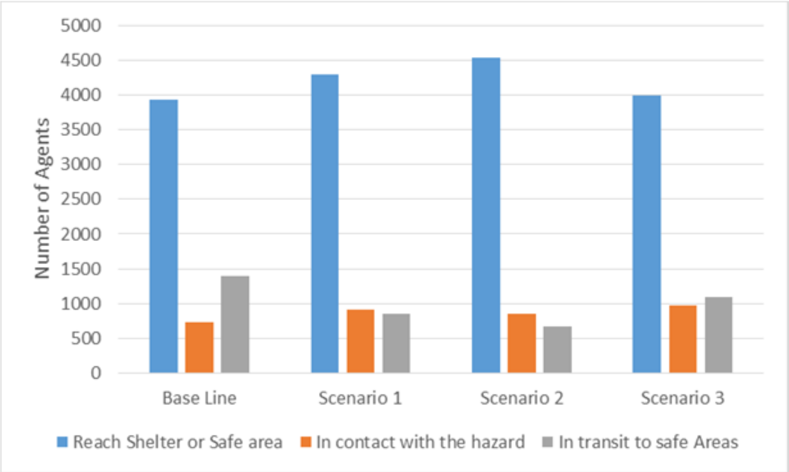


Figure 9-170. ABM Preliminary Results.

Remarks

This experiments explores and demonstrated the feasibility of using ABM to test large scale city evacuations under an extreme flood threat such as a hurricane and also to test different evacuation strategies and has the potential of becoming a powerful tool for operational risk management purposes such as: Determination of evacuation patterns, identification of critical infrastructure, can be used to identify the need to improve existing emergency locations (i.e. number of beds, food storage, etc). This ABM has the potential to test different communication strategies before and during the flooding event is unfolding, to test the effects of warning lead time, the effects of formal and informal communication in the overall performance of an evacuation, etc.

The preliminary results of this research are part of an ongoing effort to enhance the preparedness of European cities at coast location. The next steps in the research is to develop further the ABM including more detail and complex cognition model in order to adjust the behaviour in a more realistic way. The ABM model will be also expanded to include all the inhabitants of the island and more dissemination warnings will be tested in order to gain more insights on evacuation processes to help planner, decision makers and authorities to improve the emergency plans for real cities and to have a final effect on saving lives due to floods in Coastal cities.

10.2.4 WP5

Assessment of drainage strategies for stormwater management in Sint Maarten

Work package 5 aims to identify resilient strategies (i.e., protection, short- and-long term adaptation and mitigation strategies) and develop a knowledge base of existing and novel strategies and measures and the associated tools for their evaluation and assessment. It focuses on decision support for policy development and work on science-policy interfacing with an emphasis on risk governance. In connection with WP5 one sub-catchment in Sint Maarten was used to test the use of hydro-dynamic models in connections with multiple objective optimization tools. The approahc can guide the assessment and selection of measures to improve the performance of the drainage systems to avoid flooding, but also achieve different potential benefits. Here below is a summary of the work being conducted.

Case study area

The study area comprises the watershed Cul De Sac, located in the Dutch side of the Sint Maarten island territory. Overland flows converge towards the low-lying areas and the stormwater runoff is discharged at many locations. The land use in the study area is predominantly residential with some scattered commercial areas. The stormwater watersheds and streams on Sint Maarten have some characteristics that contribute to the severity of flood related impacts. Urban areas are typically situated on low-lying part, with little consideration for stormwater drainage, and as such are subject to flash flooding from surrounding hills or extreme rainfall events such as thunderstorms. The drainage system is composed mainly by open channels. In a previous study performed by UNDP (2012), detention ponding located upstream the affected areas was defined, among the structural measures, as a way to reduce flood problems in the island.
This study compare and combine traditional grey solutions with sustainable and decentralised measures, also called green infrastructure (GI) or source control measures. The inclusion of these measures is based on their potentiality to achieve multiple benefits related with other ecosystem services and urban well-being, rather than just the management of stormwater (Vojinovic, 2015).

Hydrodynamic model settings

For setting the hydrodynamic model, the area was divided in twelve watersheds. Each watershed was divided in two areas considering the differences in slopes. The slope differentiation is used to decide where to apply which measures, as defined in the study done by UNDP (2012), the idea is to use detention ponds to control the runoff coming from steep terrain areas.

The hydrological parameters needed to build the model in SWMM were estimated analysing aerial images and using information from a previous model (UNDP 2012). The hydrodynamic model was built in SWMM, using a 1D-1D approach to represent the streets as parallel conduits, which are connected to the channels system through weirs. Design storms for 5 and 10 years return period were included into the model. The infiltration model used was the curve number method, and the flow routing model was the dynamic wave.

Local physic characteristics such as soil type, drainage area, groundwater depth, and slope were considered for choosing among GI (Alves et al, 2016). Three GI practices were selected as possible measures for this case: green roofs, pervious pavements, and rainwater harvesting. Extensive green roofs and rainwater barrels with 600 litters of volume were chosen. GI are considered as properties of a given sub-watershed in SWMM. In this study, GI are modelled

creating new sub-watersheds into the model, which are completely covered by a single measure (Rossman, 2010). Thus, the model counts with 72 sub-watersheds, 97 nodes, 66 links, 12 storage nodes and 21 links representing streets

Multi-objective optimisation process

Two objectives were considered for the optimization process: flood minimisation and costs minimization. The minimisation of floods is defined as the minimisation of maximum flows in the links representing streets, therefore the first objective function is as shown in equation 1.

$$FloodMin = Minimise\left[\sum_{i=1}^{21} MaxQ_{Li}\right] \quad (1)$$

where Q is flow and L_i are the links representing streets in the model.

The second objective is the minimization of total cost, this cost includes investment cost and maintenance cost during the life cycle of measures. The corresponding objective function is presented in equation 2.

$$CostMin = Minimise\left[UC_{PP} * \sum_{i=1}^{14} A_{PPi} + UC_{GR} * \sum_{i=1}^{14} A_{GRi} + UC_{RB} * \sum_{i=1}^{14} A_{RBi} + UC_{St} * \sum_{i=1}^{6} A_{Sti}\right] \quad (2)$$

where UC_{PP}, UC_{GR}, UC_{RB} and UC_{St} represent costs by unit of area for pervious pavements, green roofs, rainwater barrels and storages, respectively; while A_{PPi}, A_{GRi}, A_{RBi} and A_{Sti} are the areas of each measure in the case of sub-watershed i.

Regarding unitary costs, for green roofs the cost varies between 40 and 170 Eu/m^2. Concerning rainwater barrels, the total estimated installation cost is 303 Eu/m^3, the annual maintenance cost is estimated as 2% of the initial cost. Pervious pavements have high variability in costs, but in general are between 10 and 20% more expensive than standard pavements. Finally, an average construction cost for open detentions is 150 Eu/m^3, while maintenance cost is estimated in 3-5% of construction cost. Dry ponds are long live facilities, typically more than 20 years (see for example; USEPA 2013).

Decision variables and constraints were defined for the optimization process. The decision variable used were the areas of sub-watersheds completely covered by GI in the model, and the areas of detention ponds. Because of there are 12 watersheds and 4 possible measures to apply in each one, the total number of variables in the optimisation process was 48. The constraints or limits established for these variables were defined studying local conditions of the urban space. In the case of pervious pavements, the maximum application was defined as 50% of the surface of roads in zones of flat slope, covering an average of 10% of total area. Green roofs and rainwater harvesting were divided among almost 100% of existent roofs, this covers around 15% of total area. One detention pond was considered for each upper or steep sub-watershed, several free spaces where to allocate these structures were identified; the maximum possible area of pond was defined considering the available surface in each case.

Table 9-40. Optimisation parameters used

Parameters	Value
Population size	120
Number of generations	80
Number of objetive functions	2
Number of variables	48
Probability of crossover	0.9
Probability of mutation	0.021

Two different strategies are evaluated in this work: only detention ponds and detention ponds plus source control practices. Each of these strategies was optimised using the objectives and variables previously described. Optimisation parameters used in this case study are shown in Table 10-4.

Results

The first strategy considered in this work includes only centralised measures, in this case one detention pond is applied to manage the runoff produced in the steep part of each sub-watershed. The second option includes these measures combined with GI, or source control practices, located in the flat zone of each sub-catchment. The practices considered are green roofs, pervious pavements and rainwater barrels. Each strategy was evaluated for two different scenarios: 5 and 10 years of return period storms.

Figure 10-16 shows the Pareto fronts obtained for each strategy considering the two storm scenarios. It can be observed that the combination of measures achieves good flow reduction for 10 years return period by increasing considerably the investment, while for the case of detention ponds the maximum investment is similar for both scenarios. The combination of measures reaches lower flood flows but also that it is working in higher investment cost ranges. Thus, both options (combination of measures and only detention ponds) are working in different regions of the plot. Applying only detention ponds lower flood reduction is obtained but the investment is in general also lower, while combining measures better performances are obtained in flood reduction but significant higher investments must be assumed.

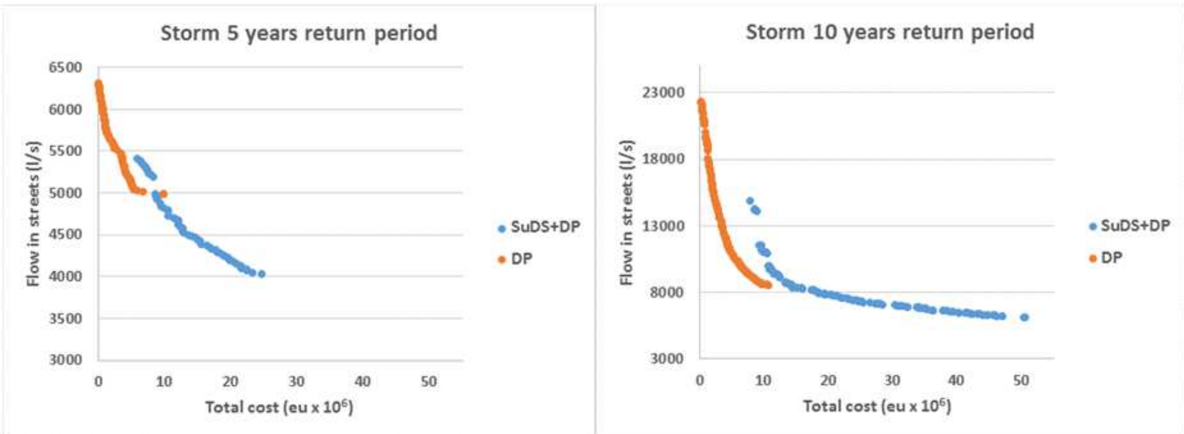


Figure 9-29 Pareto fronts obtained for each scenario, 5 years and 10 years return period, applying each strategy: only detention ponds (DP), and GI combined with DP.

To compare better these two strategies, results from average optimal solutions are presented in Table 10-5. The table shows the reduction of number of streets flooded, the reduction of maximum total flow in streets, the reduction of maximum total water depth in streets, and the portion of total maximum cost that needs to be invested in each case.

Table 9-41 Results applying average optimal solutions.

	5 years return period		10 years return period	
	SuDS+DP	DP	SuDS+DP	DP
Reduction of streets flooded	29%	29%	36%	18%
Reduction of total max. flow in streets	42%	29%	69%	43%
Reduction of max. water depth in streets	30%	15%	61%	27%
Portion of total cost invested	12%	2%	23%	3%

1.

10.3 Additional research activities and results

10.3.1 WP3

Institutional Network Analysis to study the institutional dimensions of flood risk

This research has been supervised by TU Delft in the form of a Master of Science thesis of Maja Bosh (2017). This work was co-supervised by Amineh Ghorbani, Igor Nikolic from TU Delft and Yared Abebe from UNESCO-IHE.The research focuses on the institutional dimension of flood risk management (FRM). The main research question is formulated as "what is the effect of interdependencies and connectivity between institutions on FRM, for the case of St Maarten".

To study interdependencies and connectivity between institutions, we developed a new methodology: Institutional Network Analysis (INA). This methodology was created, based on four criteria:

1. Meaningful translation of institutions into networks; finding a way of representing the institutional reality as nodes and links that adds to our understanding of the human-water coupled flood system;
2. Show materialization of institutions; institutions are mental constructs – in order to understand their effect on FRM, the link between actor, action, decision making and institutions should be addressed;
3. Trade-off between complexity and insightfulness; we want to capture institutional complexity, but we want the results to be explainable to non-scholars as well;
4. Translatable to Agent-Based Modelling; to include institutional change over time, we want our 'snapshot' of the institutional network to be translatable into a dynamic model.

The action arenas and corresponding institutional statements are used as input to draw Institutional Network Diagrams (INDs), which are a graphical representation of the institutions guiding decision makers within action arenas, based on the four FRM stages. These network representations of action arenas can be analysed on three levels: addressing institutional hierarchy, calculating network metrics and defining links between INDs.

Recommendations stemming from these insights include the development of an infrastructure to share knowledge, enabling community action, and reviewing the efficiency and fairness of governmental processes within FRM. The INA shows the importance of better knowledge transfer and addressing the unequal distribution of power, based on the position of decision makers within the institutional network. Addressing the recommendations stemming from this research indicate that a change of culture is necessary to improve FRM on St Maarten. However, the existing power structures on the island are based on strong personal relations and corruption is a pressing problem (Transparency International, 2015). This analysis may however provide useful argumentations for stakeholders that are concerned about their safety from floods.

INA may add to better FRM on four levels. First of all, on a data level INA uses the FRM cycle to structure data collection. This framework proved to be useful to develop an understanding of the case study. Secondly, the INDs force the researcher to address gaps in the collected information. Third of all, they are more readable for non-scholars than large ADICO tables. By connecting the INDs, an overview of all action arenas within FRM is obtained. The network metrics provide a non-subjective way of addressing the institutional dimension and can be used to increase awareness

and understanding of the problem amongst policy and decision makers.

Most importantly, INA (especially the institutional network diagram) enhances the MAIA framework by providing a 'flow chart' like functionality to the operational structure. However, INA also provides detailed inputs to the collective (also called social) and constitutional (also called institutional) structures. Conceiving of institutional dynamics as a network within a complex adaptive system, the analysis first identified the agents and then the institutional statements (or rules, norms and shared strategies; see more about institutional statements in Crawford and Ostrom 2005) that guide responses to flood risk. Material from the Root Cause Analysis (both raw data and the relevant bibliographic library as well as the final Root Cause Analysis report for St Maarten) was shared with the ABM researcher at TU-Delft, who processed the data according to particular attributes identified from Social Network Theory, an Influence Diagram and the syntax of the MAIA Framework. Then, a series of institutional statements that could inform the model development was drawn up. For example, VROMI (the agent), must (the deontic condition), organise the clean-up (the aim), if necessary after a storm event (the condition) - followed by any applicable sanction. Networks also illustrate the main institutions involved in different areas of the flood response system, e.g. short-term response and clean-up. The use of qualitative material based on the Root Cause Analysis highlighted the importance of informal institutions as, if not more, important than formal institutions in determining responses to flood risk.

10.4 lessons learned

As noted above, the implications of the St Maarten work for risk assessment (through the development of agent-based models), for methodologies for Root Cause Analysis and for analytic approaches to understanding disaster causation are discussed in other PEARL documents. A key implication for further engagement on the island is to understand the underlying root causes of risk, namely:

Small island size, limited resources and colonial marginalisation

The underlying model of development driving up exposure and compounding physical and social vulnerability

The unique social structure which underpins the political process in ways that politicise land use, and a political culture that discourages long-term risk reduction in the interests of immediate economic and political gain

This should not mask key sources of resilience: since 1995 there has been the political and administrative will to address hurricane preparedness and response, which is slowly having a spill-over effect on other types of flood disaster and their management. The small island culture and personal connections also facilitates unique collaborations across the government and non-government sectors which taps into the capacities of the non-government sector.

There is certainly a need for further technical support to ongoing processes of risk management on the island, such as the UNESCO mapping studies of 2006, to which PEARL partners are uniquely placed to contribute. The work being conducted in PEARL has now opened the opportunity for this to involve a wider range of actors across government ministries and businesses / experts (such as the insurance sector and engineering and construction firms). While the political and social dynamics are difficult to address through external interventions – further involvement by PEARL partners could a) use the understandings gained through root cause analysis to highlight the need to address risks with influential actors (such as politicians and the Prime Minister) as well as through the island's media (identified by informants as a key source of political change on the island) and b) support access to international knowledge and finance by government and non-governmental actors on the island, through cross-case learning processes in PEARL, for example.

The application of different methods and tools being develop in the framework of PEARL in St

Maarten aims to have a Holistic Assessment of Risk. The application of such variety of methodologies also generates a unique learning about the methodological challenges for the application of the Holistic Risk Assessment approach:

- The difficulty in quantifying social and political phenomena highlighted by the qualitative methods used in Root Cause Analysis, such as clientelistic relationships. Social segregation has not being incorporated in the ABM model used at UNESCO-IHE, for example. The assumption of conscious and rational decision-making in the ABMs is not reflected in qualitative analysis for the Root Cause Assessments. This demonstrates the importance of retaining the two methods as independent parts of the whole, alongside their integration through model formulation.
- Root Cause Analysis, as based on purely qualitative methods cannot specify quantitative thresholds for decision-making, such as the magnitude or extent of a flood that might trigger changes in policy measures. In conjunction, however, the methods can join the drivers and impacts of flood risk.
- The broad frame for Root Cause Analysis leads to the question of where ABMs should bound the system and what agents or institutions exert the most influence on a given system. Again, the Root Cause Analysis did not weight actors or causes. What this form of RCA can do is clarify and support the assumptions made in this respect.
- Reflecting in the ABM the values and relative judgements about risks held by different stakeholders, which is revealed by the Root Cause Analysis. The 'system' is therefore both objective and subjective – however, the objective aspects are easier to model.

The application of different ABM models to St Maarten have been important because enable modellers to test their methodological frameworks. In general, the available data from the study area from previous studies or available on internet was enough to setup and initialize the models. However, the validation and/or verification of the results of the ABM models is still challenging. This is due to the nature of the ABM modelling paradigm itself, the absence of measured data (traffic loads, counting pedestrian, etc), but also because the response that we want from the different models as the result of an extreme hydrometeor logical event is difficult to measure in reality. Therefore the modelling process relay mainly in assumptions for multiple parameters. The input of the RRCA to the ABM modelling has been valuable since it provides insides about the system, the stakeholders, the drivers and behaviour of the different parts. In particular the ABM model for institutions.

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11 Case Study – Thailand

11.1 Introduction to the case study area

The historic city of Ayutthaya lies in an island on the Chao Phraya River in Thailand and is at risk of flooding. In 2011, much of the island was inundated following heavy monsoon rainfall over a period of 3-4 months that affected much of Thailand. The historic city of Ayutthaya was an important centre for trade and diplomacy, and its remains has been designated a UNESCO World Heritage site, covering much of the island. Understanding the flood risk to the city and its cultural heritage is a challenge as their value cannot be easily evaluated in monetary terms.

The flood risk to the historic city was assessed by combining estimates of hazards and vulnerability. A community based (or participitory) approach to flood risk assessment was developed and applied in the island. The hazard is estimated through an understanding of the flooded depths. A coupled 1D-2D hydraulic model was used to simulate the flood events of 2011 to produce a flood map with information on the depth of inundation. This model was calibrated and validated to provide confidence of its reliability. The vulnerability was estimated through an approach which takes into account the physical, social, economic and cultural dimensions of vulnerability.

11.1.1 General description of the case study area

The city of Phra Nakhon Si Ayutthaya is located approximately 70km north of Bangkok, in the Chao Phraya River valley. The location is shown in Figure 11-1.

Figure 11-1 Location of Ayutthaya Island. Approximately one third of the island is protected by UNESCO as a World Heritage Site (WHS).

Ayutthaya Island covers around 720 ha and has a population of over 40,000 people. The city is located within Phra Nakhon Si Ayutthaya district, which is in the Phra Nakhon Si Ayutthaya

province. The total area of the World Heritage property is 289 ha and its boundaries are also depicted in Figure 1. The Historic City of Ayutthaya was inscribed on the World Heritage List, since it bears "a unique or at least exceptional testimony to a cultural tradition or to a civilization which is living or which has disappeared" (UNESCO, 2013).

11.1.2 Hazard and risk situation in the case study area

Ayutthaya Island is susceptible to fluvial flooding (where river flow exceeds the channel and defence capacity) and pluvial flooding (resulting from extreme intense rainfall, exceeding the capacity of drainage). Additionally, storm surges in the Bay of Thailand can cause increased water levels. The root causes of flooding were identified as the terrain topography in the Chao Phraya River basin, extreme hydro-meteorological conditions, and the lack of proper risk mitigation policies and measures.

To date Ayutthaya Island has experienced two devastating flood events, in 1995 and 2011. During the 2011 flood event the entire island was inundated and the water depth at certain location exceeded two metres. Some images of the flooding are presented in Figure 11-2. The 2011 flood event was caused by a series of consequent tropical storms in the Indian Ocean and lasted longer than one month.

Figure 11-2 The 2011 flood event in Ayutthaya. The entire island was inundated for longer than four weeks.

The 2011 extreme flood event

In late June 2011, heavy rainfall combined with multiple tropical storms happened throughout the extended rainy season, resulting in Thailand's most severe flooding in the last 50 years. Figure 11-3 shows the monthly rainfall totals for 2011, which was above average for the 7 months prior to the floods.

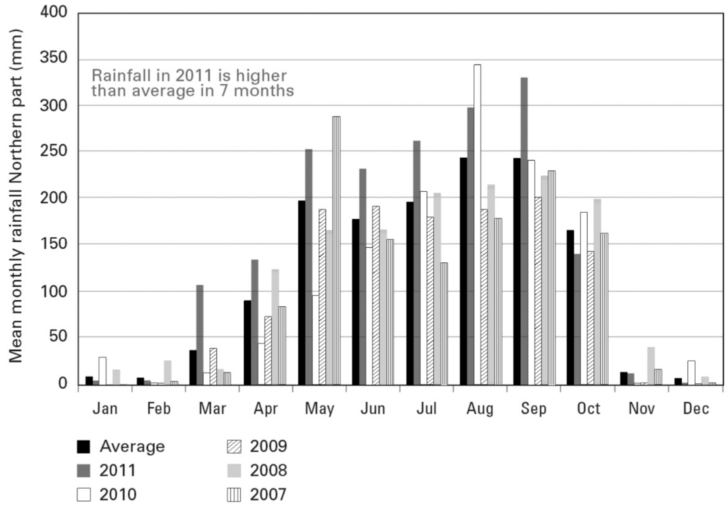


Figure 11-3 Comparison of monthly rainfall in the northern part of Thailand

In mid 2011, heavy rainfall occurred in the North following by a series of monsoons and tropical storms. It started with the arrival of Tropical Storm Haima on June 24-26, followed by Tropical Storm Nock-Ten on July 30 to August 3, accelerating the severity of rainfall across the northern, northeastern, and central parts of the country. The rainfall and floods were again reinforced by Tropical Storm Haitang on September 28, followed by Tropical Storm Nalgae on October 5-6, and Tropical Depression Twenty-four (see Figure 11-4).

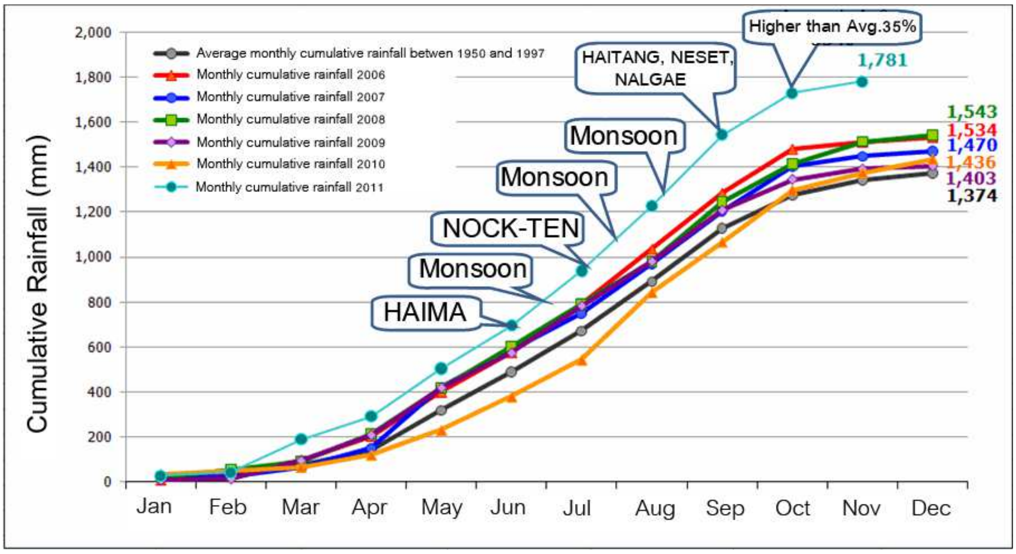


Figure 11-4 Cumulative rainfall and storm events in 2011

When two major dams in the North, the Bhumibol and Sirikit Dams, nearly reached their capacity, they began to discharge excess water. Consequently, more than ten major flood-control structures breached, leading to perfect conditions for severe flooding. The floodwaters flowed southward

towards rivers and then traversed through floodplains. 65 of 77 provinces were affected by high flood levels. The total damage-costs were USD 46.5 billion. Over the next two years and beyond, the rehabilitation and reconstruction costs were estimated at USD 50 billion (GFDDR, 2012). Thailand's economic growth in the fourth quarter of 2011 contracted considerably, reducing GDP growth from 2.6% to 1.0%. Overall, the flooding affected more than 13 million people, and at least 813 fatalities nationwide were reported.

Amongst all the flooded provinces, Ayutthaya Province had the highest numbers of fatalities with 97 deaths. For almost two months, flooding caused damage across the whole province, inundating several governmental offices, public-service buildings, and major industrial estates located near the city. Complex urban areas and historical sites were drowned. In the UNESCO World Heritage Site of Ayutthaya Historical Park (AHP) alone, the damage costs were estimated at USD 22.8 million (Toyoda et al, 2012).

11.1.3 Current institutional and governance practice

Flood protection in Ayutthaya

In ancient times before dams were built, these rivers flooded the Chao Phraya basin in the central region and brought with them silt, which fertilized the rice fields (Charnvit, 2007). The book of de La Loubère also recorded that Ayutthaya faced floods every year and it was advantage to fertilize soil in Ayutthaya. He also mentioned about tide events as sometimes Ayutthaya had been affected by high sea tides from the Gulf of Thailand although Ayutthaya was approximately 90 kilometres from there. As a result, a Siamese house was a one-storied house on an elevated platform (around 13 feet or 3.90metres height from ground level) with an airy, open ground level for ventilation and protection from floods.

Records from foreign visitors around 16th century period mentioned Ayutthaya city wall which was 12.4 kilometres long had 20 water gates for water management system. Behind the wall, the city consisted of canal systems (about more than 10 canals) which were laid along North-South and East-West and all connected together as one system. Moreover, Archaeologist from FAD assumed that these water gates system are closed during floods to protect the city, then after floods it is opened to flow the water into the city and closed again in drought season to collect the water.

After flooding in 2011, several flood mitigation plan have been proposed for Chao Phraya River basin. During the event of 2011, the capacity of Chao Phraya River at Ayutthaya was about 1,500 cms but the total inflow on 4 Oct. 2011 was about 3,300 cms, which led to significant flooding. Figure 11-5 illustrates the lack of capacity in the current system of rivers and canals around Ayutthaya.

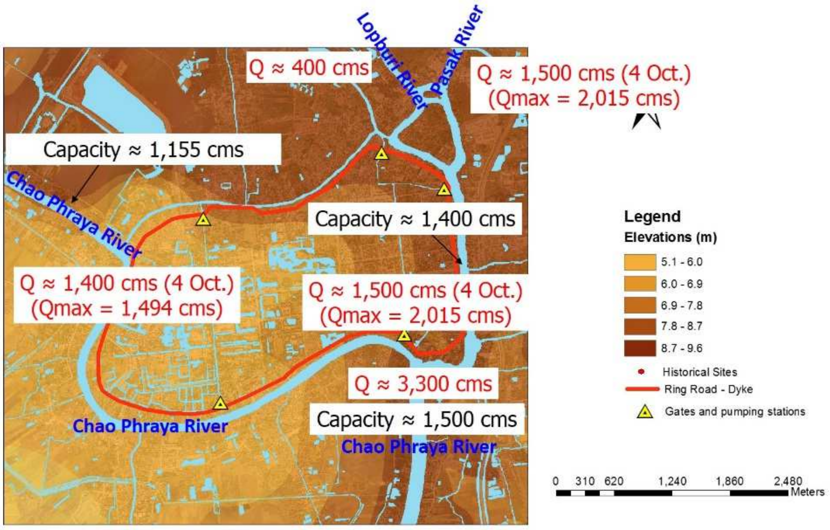


Figure 11-5 Schematization of the capacity of rivers and canals for the flooding event of 2011

Due to the significant amount of water to be transported the studies or developed plans consider mitigation measures at two level of interventions at regional and local scale.

The regional mitigation measures have been identified for the scope of this study. These include an Ayutthaya bypass channel with a capacity of 1,200m3 and the Chainat-Pasak canal with a capacity of 1,000m3. Local mitigation measures include increasing retention/detention pond areas, reviving ancient canals, and increasing the dike height (around the U-Thong Road which runs along the edge of the island).

The main flood management issues in the present situation can be summarized as follows:

- Inadequate drainage capacities;
- Poor condition of natural floodways and retentions;
- Rivers are confined (no room for expansion);
- Many natural floodways and retentions have been deteriorated.
- The main flood protection of Ayutthaya's island is a ring-road which serves as a dike.

11.1.4 Available data used for research activities

The availabe data set that were used for the research activities is presented in Table 11-1.

Table 11-1 Available information and data sets

Data set	**Description**
DEM	10 x 10m resolution grid → resampling to 20 x 20m.
Hydrological Data	Max. Annual Discharges, water levels and rainfall TS.

Land Use	Cultural, Residential and Agricultural areas.
Location of Cultural Assets	Heritage Sites, Non-Heritage Sites.
Chao Phraya 1D Model	Existing model from previous study.
Existing Plans of Mitigation Measures	Projects being studied to reduce flooding.
River Geometry and Hydraulic Properties	XS data, profiles, roughness coefficients, etc.
Flood Protection / Drainage System Data	Elevation and location of dikes.

11.2 Key research activities and results

The research conducted in Ayutthaya has been supervised by AIT and UNESCO-IHE in the form of a Master of Science thesis of Daria Golub, Weeraya Keerakamolchai in 2014, Juan Camilo Polania in 2015, Phyllis Togarepi in 2016 and Geofrey Hilly, Abdul Naser Majidi, Jose Patiño in 2017. This work has been co-supervised among others by Sutat Weesakul, Mukand Babel from AIT and Zoran Vojinovic from UNESCO-IHE. From UNESCO-IHE serveral researches have been invlved in mentoring the MSc research among others Vorawit Meesuk, Alida Alves, Neiler Medina and Arlex Sanchez. The research focuses on different components of flood risk management (FRM). The results obtained so far will be summarize in line with the different work packages as thematic areas structured in the framewokr of PEARL.

11.2.1 WP1

Stakeholders participation and analysis

Public involvement is critical in the flood risk assessment process and the development of a disaster risk mitigation plan. Communities living within the study area and other stakeholders know much about the flooding and the capacities required to cope with a disaster. Thus, a range of activities were organised in Ayutthaya in order to exploit local knowledge and to contribute to building capacity among stakeholders. The identified stakeholders included organisations at different levels in the governmental hierarchy ranging from local government, through national government and international organisations, is shown in Table 11-2.

Table 11-2 Identified stakeholders with respect to flood risk mitigation in Ayutthaya.

Position in a governmental hierarchy	Organizations
International organization	UNESCO Bangkok World Monument Fund

Position in a governmental hierarchy	Organizations
National government	The Fine Arts Department Department of Public works and town and country planning Department of disaster prevention and mitigation Office of the National Water and Flood Management Thai Meteorological Department Royal Irrigation department Tourism Authority of Thailand Transportation Operation, Regional Marine Office Internal Security Operation Command
Provincial government	Ayutthaya district authority Historic Park of Ayutthaya World Heritage Site Ayutthaya province authority Chamber of Commerce Ayutthaya Provincial Administrative Organisation Provincial Federation of Thai Industries of Province Public welfare office
Local government	Ayutthaya municipality Schools, Hospitals Centre of Ayutthaya studies
Local non-governmental organisations	Local Communities Interest groups Buddhism office

Stakeholders were invited to meetings and they were involved at different stages of the flood risk assessment process (e.g. data collection, evaluation of mitigation measures, vulnerability analysis, and evaluation of mitigation measures). Images of these events are shown in Figures 11-6 and 11-7.

Figure 11-6 Consultation meeting with stakeholders

Figure 11-7 More than 100 participants attended the workshop with

Community representative.

A socio-organigram of these organisations and their relations are shown in Figure 11-8. This diagram presents the organisations, where they sit in the governmental hierarchy, the nature of their collaboration and communication flows, as well as their responsibilities related to flood risk management.

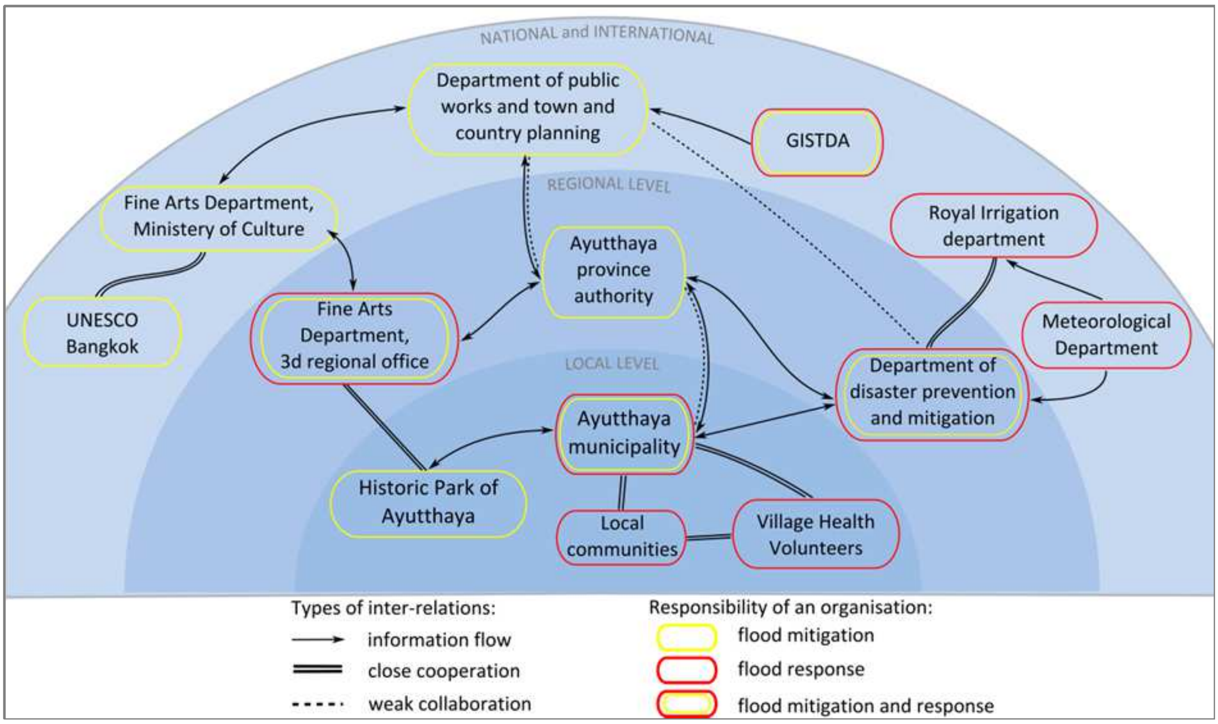


Figure 11-8 The organi-sociogram produced for stakeholders involved in flood risk mitigation and response in Ayutthaya.

Vulnerability Assessment

The vulnerability of the island and its communities to flooding in the existing situation (before the application of any mitigation) is assessed following a multidimensional approach.

Physical Dimension

Four types of building-use were differentiated for the physical vulnerability assessment on Ayutthaya Island: residential buildings, cultural properties, critical infrastructure and roads. For each type of buildings appropriate parameters were defined that affect the degree of potential damage from flooding

The results of the categorisation and assigning of vulnerability classes are summarised in Figure 11-9

Figure 11-9 Categorisation of build environment into different classes of vulnerability

Critical facilities were identified during the group mapping exercise with community representatives. People pointed out the importance of structures such as hospitals, schools and the university (potential evacuation centres), and some active templates. Moreover, people highlighted that in case of a flood event ATMs do not function which causes serious problems, as people are unable to access cash.

Social Dimension

The community was chosen as the appropriate scale for assessing social vulnerability. It was determined that Ayutthaya consisted of 33 unique communities through consultation with the director of the Public Affairs Department, Ayutthaya Municipality. A methodology originally developed by the United Nations University was introduced to develop indicators for social vulnerability assessment. In summary, indicators are identified that can measure qualities of the community of interest and their relationship with vulnerability. Data should then be collected to put values against these indicators. These values can be normalised between 0 and 1, and then combined by weighting the importance of the separate indicators, to form a composite index value. Finally, these values can be mapped. In this study, 22 indicators were selected that covered 8 categories (see Table 11-3).

Table 11-3 Parameters and indicators for assessment of the social dimension of vulnerability at a community level.

Parameters	Indicators
Susceptibility	
1. Health risks caused by floods	1. Injuries, water-borne diseases caused by floods 2. Access to medical services
2. Vulnerable groups	3. Existence of people with special needs 4. Availability of social support
3. Flood effect on income/livelihood	5. Income lost 6. Access to basic needs during a flood
4. Flood effect to property	7. Type of housing 8. Flood protection measures 9. Property insurance 10. Building conditions
Capacities	
5. Flood awareness	11. Awareness about flood risk 12. Availability and accessibility of flood risk information
6. Flood preparedness	13. Early warning system 14. Emergency response plan 15. Leadership
7. External support	16. Capability to receive support from local authority 17. Capability to receive support from NGOs
8. Community cohesiveness and education	18. Social network 19. Flood effect on psychological health 20. Literacy and education 21. Cultural participation and spirituality 22. Sense of community and belonging

A questionnaire was developed with 42 multiple choice questions to ascertain the values for each indicator. The questionnaire was presented during Focus Group Discussions (FGDs) with approximately 180 representatives from 30 communities.

Economic dimension

The analysis of the economic dimension of vulnerability is intended to understand the capacity of the local economy to cope with or adapt to a disaster. The economic dimension of vulnerability was assessed by analysing the response of businesses to flooding during the event and afterwards, in the recovery period. Business Continuity Management theory was used to assess economic vulnerability. Here, a business is considered resilient to flooding if it implements a business

continuity plan (PACE, 1998). The vulnerability of a given economic activity was assessed by considering the following parameters:

- Duration of complete shutdown of the business due to a flood event;
- Duration of reduced business activity caused by a flood event; and
- Operational capacity during reduced activity.

20 semi-structured interviews were completed with representatives of business owners in order to evaluate a set of parameters for economic vulnerability. Interviewees were asked to answer questions based on their experience from the 2011 flood event. The economic vulnerability score was calculated using the following equation:

$$VS = I * T_{sd} + I * T_d * C_d,$$

Where: **VS** denotes vulnerability score, I denotes income level before the 2011 flood event, **Tsd** denotes the duration of complete shutdown [months], **Td** denotes the duration of reduced activity [months], and **Cd** denotes operational capacity during downsizing phase [portion in comparison to normality].

Seven business sectors were identified (non-tourist accommodation, non-tourist goods and foods, non-tourist transportation, tourist accommodation, tourist food and drink, tourist services and tourist transportation). Based on threshold scores of 0-2, 2-4, and 4-6, economic vulnerability was assessed as low, medium, or high. The interviewers went door-to-door to collect data about flood experiences in 2011 and to directly observe some evidence of the damages, such as water stains from previous floods, and broken furniture.

Cultural dimension

The cultural dimension of vulnerability was differentiated from other dimensions to capture the effect of flooding on cultural values embodied in various properties. Cultural values include the historical, spiritual, aesthetic, social and other intrinsic values that constitute the cultural significance of a property (Torre, 2002; Vecvagars, 2006). These values can be associated with different attributes of a cultural property, such as its location and setting, materials, form and shape (UNESCO World Heritage Centre, 2012). The level of cultural vulnerability was assessed by considering the significance and sensitivity of the cultural assets in areas exposed to flooding. Both of these characteristics can be assessed qualitatively. The significance was assessed by consultation with the responsible government department and local community. Each property was assessed on a scale of 1 to 5, where 1 indicates that a property is not culturally significant, and 5 represents very high cultural significance.

The sensitivity of each property was assessed on a scale of 1 to 4, where 1 indicates low sensitivity to floodwaters, and 4 represents high sensitivity. The assessment was completed using expert opinion.

Archaeological remains that are considered significant because of the nature of the materials used in the structure, and where those materials could be damaged or compromised by floodwaters,

were assessed as being highly sensitive to flooding. Table 11-4 shows the matrix to define the vulnerability of cultural buildings.

Table 11-4 Matrix to define a level of vulnerability for cultural properties

		Score of property sensitivity			
		low	medium	medium-high	high
Level of property significance	very low	low	low	low	medium
	low	low	low	medium	medium
	medium	low	medium	medium	high
	high	medium	medium	high	high
	very high	medium	high	high	high

Vulnerability Analysis

The data collected on each dimension of vulnerability were analysed and mapped in a GIS environment, with vulnerability ranging low (1) to high (3).

Physical vulnerability was assessed using the methodology described previously. Social vulnerability was calculated for each of the identified 33 communities, by combining the scores from 8 variables, using the weights shown in Figure 11-10.

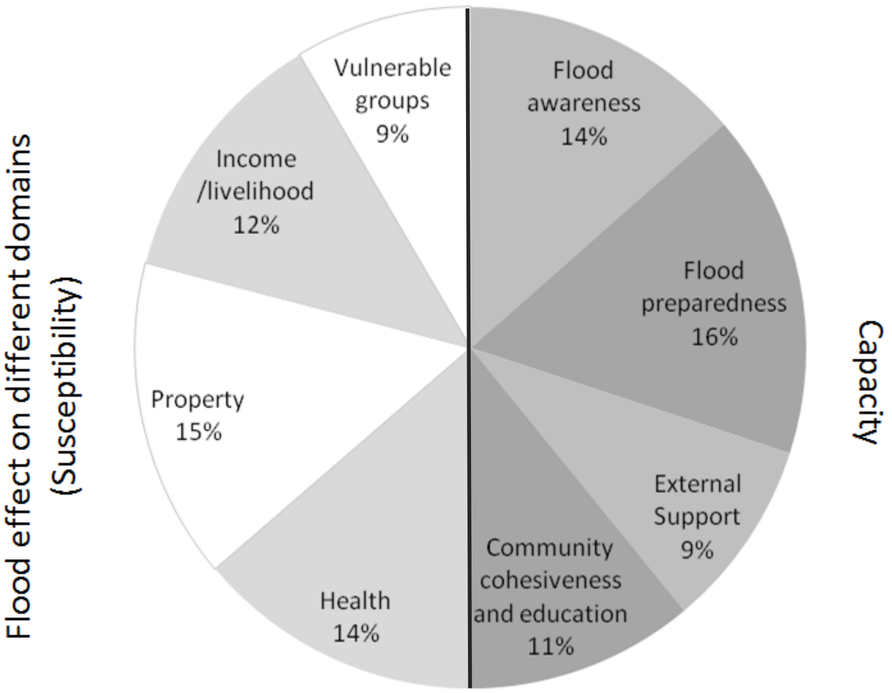


Figure 11-10 A set of eight parameters to assess social dimension of vulnerability at the community level. The percentage indicates the weight of each parameter into overall vulnerability score.

Economic zones were identified through the field work and the level of vulnerability for each type of economic activity was evaluated using three parameters described previously. Vulnerability scores were calculated for seven business sectors (Table 11-5).

Table 11-5 Scores of economic vulnerability for each type of business.

Type of businesses	Shutdown phase [months]	Reduced business activity [months]	Operational capacity during reduced activity [portion in comparison to normality]	Vulnerability score
Non-tourist: accommodation	1	2	0.9	2.8
Non-tourist: goods stores and food	1	3.5	0.2	1.7
Non-tourist: transportation	1.5	2.5	0.2	2.0
Tourist-oriented: accommodation	2.0	3.7	0.7	4.6
Tourist-oriented: food and beverage	3.7	4.0	0.2	4.6
Tourist-oriented: services	2.0	1.5	0.4	2.6
Tourist-oriented: transportation	2.5	3.0	0.8	4.9

Finally, the map of the cultural dimension of vulnerability captures the vulnerability of intangible values embodied within cultural properties (e.g. historic, symbolic, social, spiritual, aesthetic values). The level of cultural vulnerability was identified as a product of the significance of cultural property and its sensitivity to flooding.

Figure 10a depicts the footprints of the buildings and infrastructure and their associated levels of vulnerability. The estimated social vulnerability is mapped in Figure 10b. The results for economic vulnerability are mapped in Figure 10c and the results of the cultural dimension of vulnerability are mapped in Figure 10d.

A combined vulnerability map was created by weighting the scores from the separate four dimensions, following a survey at the final consultation workshop. However, because of political upheaval, only 8 participants attended this workshop. This number of participants was not deemed sufficient to obtain accurate results for the appropriate weights. It was therefore decided to give

each of the four vulnerability dimensions equal weight. The combined vulnerability map is shown in Figure 11-11.

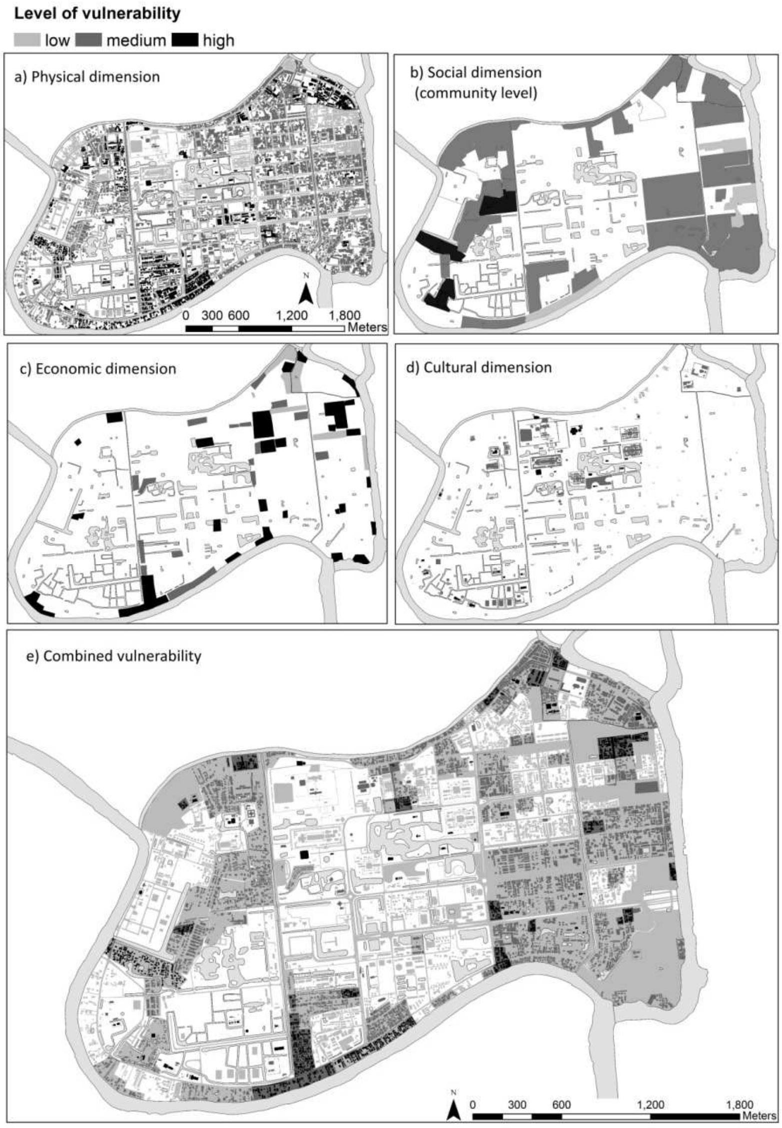


Figure 11-11 Vulnerability maps

11.2.2 WP2

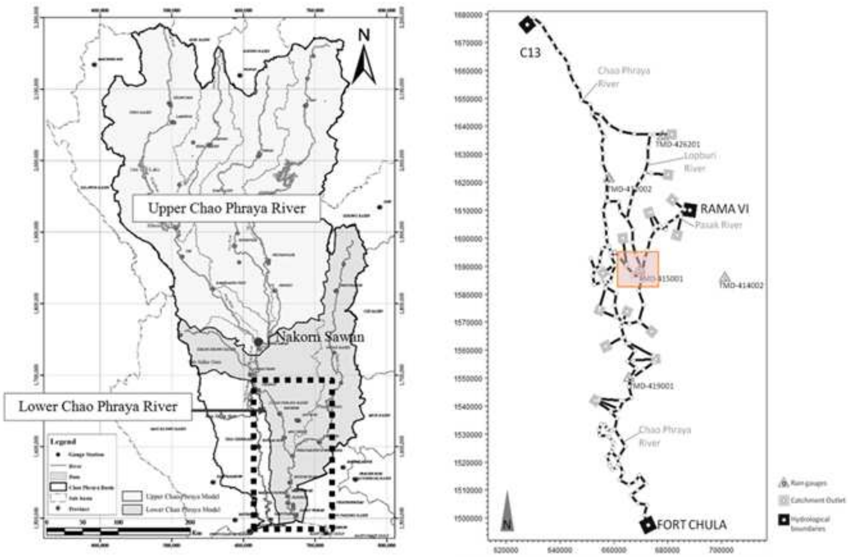
Hazard Modelling and Analysis

The hazard component was determined from a simulation of the 2011 flood event. A coupled 1D-2D numerical model using the DHI MIKE FLOOD software was developed to investigate the

propagation of excess floodwater from the 1D river model (using DHI-MIKE11) to the 2D floodplain model (using DHI-MIKE21) for the study area.

The domain of the 1D numerical model (see Figure 11-12) represents the flow dynamics of the lower Chao Phraya Riverbasin (lower CPR) starting from the downstream of Nakorn Sawan province (called the Lower CPR Domain). Another sub-domain of the 1D model (see Figure 11-12b) is focused on Ayutthaya Island (called Ayutthaya Domain) which is the main focus of this study. All 1D numerical setups and calibrations were facilitated by the Asian Institute of Technology (AIT) in Bangkok.

1D modelling setup for the 'Lower CPR Domain' model.



(a) (b)

Figure 11-12 (a) the boundary scheme of the 1D numerical model at lower CPR (map sources: Punya Consultant, 2009), (b) the boundary scheme of the coupled 1D-2D model marked on the 1D model layout.

The time-series of rainfall from five weather stations (see Figure 11-13) recorded by the Thai Meteorological Department (TMD) were used as a boundary condition for a lumped and conceptual catchment rainfall-runoff (hydrological) model using NUM in DHI-MIKE11.

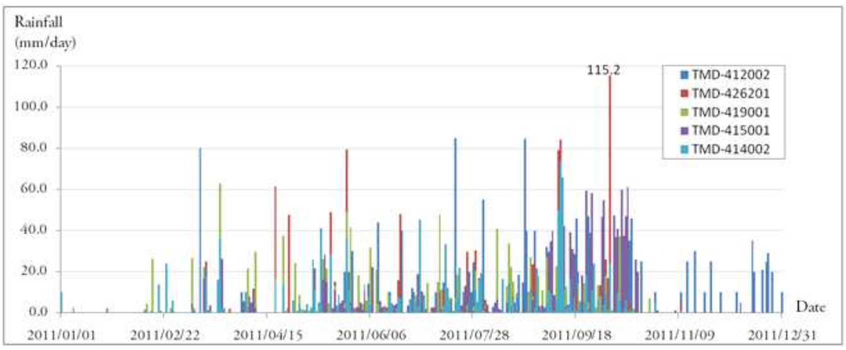


Figure 11-13 Rainfall time-series recorded by five TMD stations

The computed discharge at station C13 (see Figure 11-14), the regulated discharges of Rama-VI dam (see Figure 11-15) collected by the Royal Irrigation Department (RID), and the tidal levels at Fort Chula (see Figure 11-16) collected by the Hydrographic Department of the Royal Thai Navy were used as the boundary conditions to the lower CPR domain model.

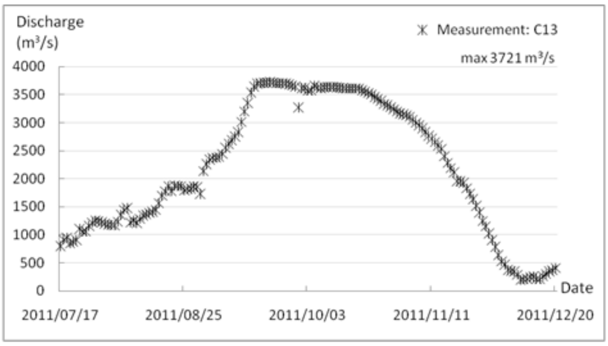


Figure 11-14 Time-series of discharges at Chaophraya River C13

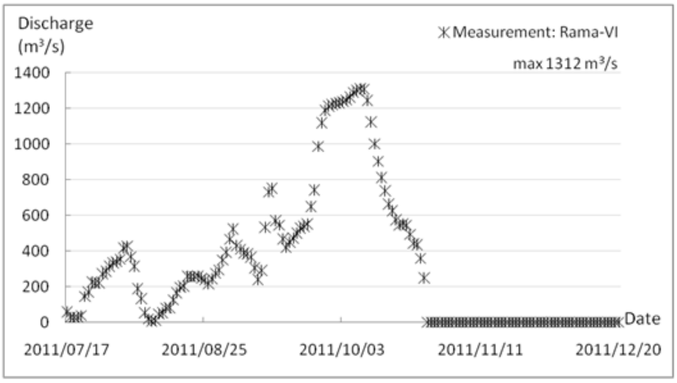


Figure 11-15 Time-series of discharges at Pasak River Rama-VI

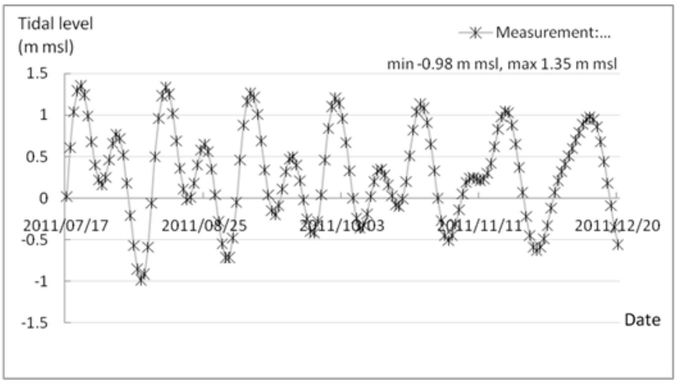


Figure 11-16 Time-series of tidal levels at Chula fort

1D modelling setup for 'Ayutthaya Domain' model

The total length of river modelled is 52 km (see Figure 11-17) surrounding the island by four channels: Chao Phraya River, Pasak River, Lopburi Rive, and Maung Canals. A Manning friction coefficient n of 0.02 was applied uniformly to the constructed 1D river networks and following the criteria defined by Chow (1959).

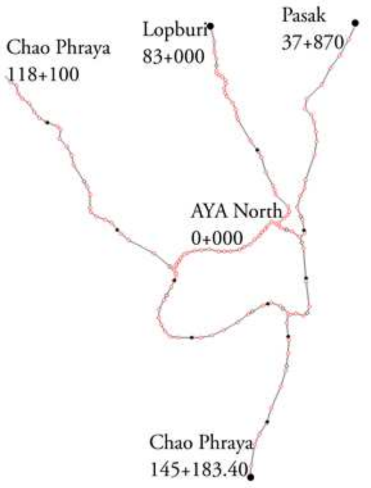


Figure 11-17 1D model layout of the Ayutthaya domain and its boundary chainages

From the Lower CPR simulations, the time series of discharge and water level were transposed, which have then been used as input boundary setups for the Ayutthaya Domain. The boundary conditions were: the discharge and water levels (see Figure 11-18 and 11-19) of Chao Phraya River, the discharge of Pasak River (see Figure 11-20), and the discharges of Lopburi River (see Figure 11-21). However, the model was recalibrated with observed data of discharge and water level at C.35 and S.5 station in the year 2011 by adding site flow at Chao Phraya and Pasak as the boundary conditions.

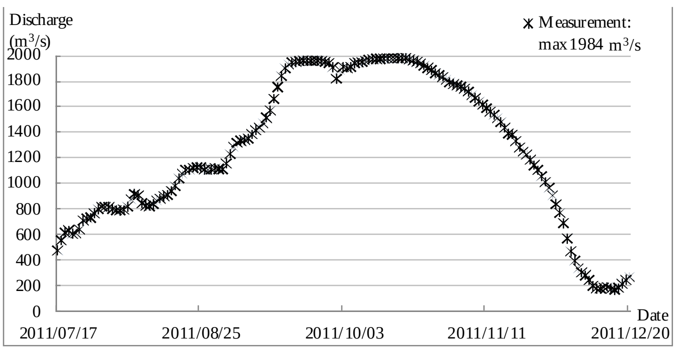


Figure 11-18 Computed time-series data of discharges at chainage 118+100 of Chao Phraya River

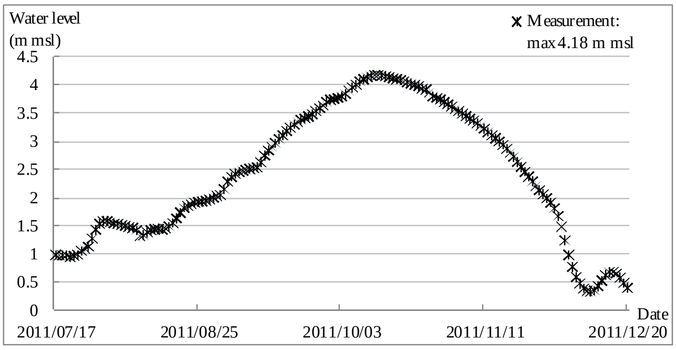


Figure 11-19 Computed time-series data of waterlevel at chainage 145+183.40 of Chao Phraya River

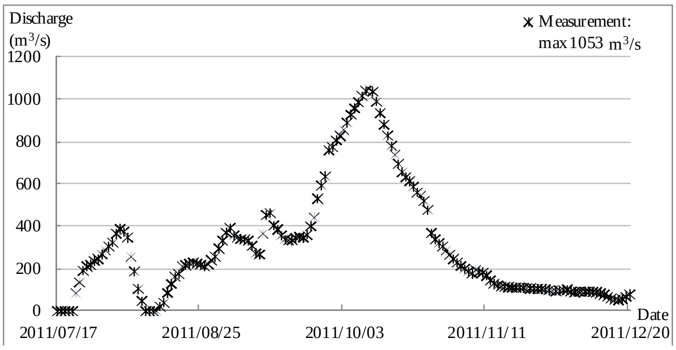


Figure 11-20 Computed time-series data of discharges at chainage 37+870 of Pasak River

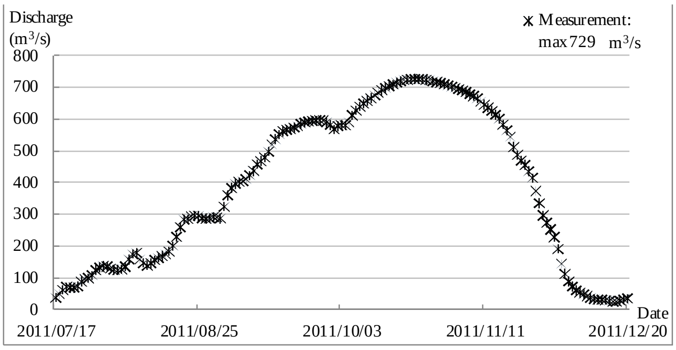


Figure 11-21 Computed time-series data of discharges at chainage 83+000 of Lopburi River

Coupled 1D-2D modelling setup

A coupled 1D-2D model of Ayutthaya was developed to investigate the propagation of excess floodwater from the 1D channels: Chao Phraya Rivers, Pasak, Lopburi, and Maung Canal into the 2D urban area, using the DHI MIKE Flood software.

The 1D model setup was described in the previous section. For the 2D model setup, a 20 m resolution aerial LiDAR DEM was used as the bathymetry input data. The simulation setting of the drying depth is 0.01m and the flooding depth is 0.02m. A Manning's n coefficient of 0.033 was used following an earlier study by Keerakamolchai (2014). The time step is 5 seconds with a simulation period from 1 July to 30 November 2011. The schematization of the coupling models is shown in Figure 11-22.

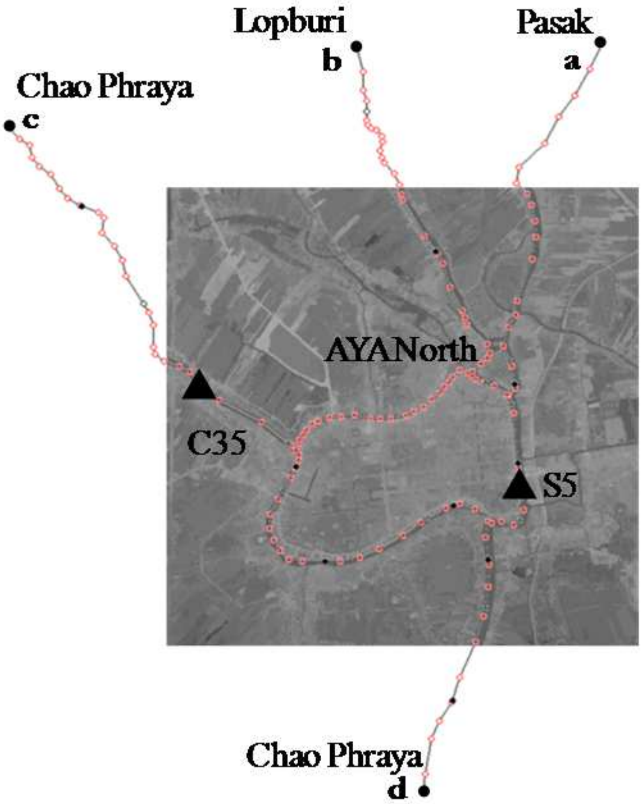


Figure 11-22 A coupled 1D-2D modelling setup.

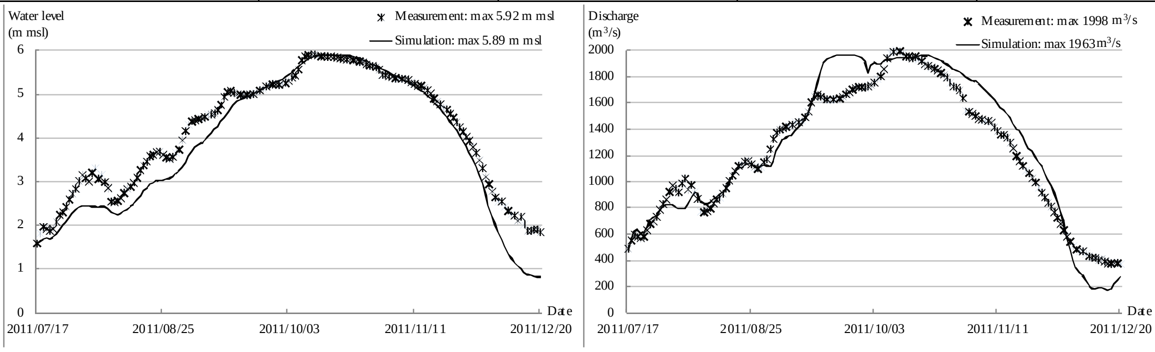
Validating simulation models

The 1D component of the model was calibrated using observed discharge data at two locations (Station C35 at the Chao Phraya River and Station S5 at the Pasak River). Two metrics are used to quantify the agreement between the modelled and observed daily discharge and river stage (level). The first is the coefficient of determination (R^2). The second is the Root Mean Square Area (RMSE) the indicators are presented in Table 11-6. Figure 11-23 shows the simulated and observed discharges (a) and river stages (b) at Station C35. Figure 11-24 shows the simulated and observed discharges (a) and river stages (b) at Station S5.

Table 11-6 R^2 and RMSE values to measure agreement between observed and measured discharge and rive level at river stations C35 and S5.

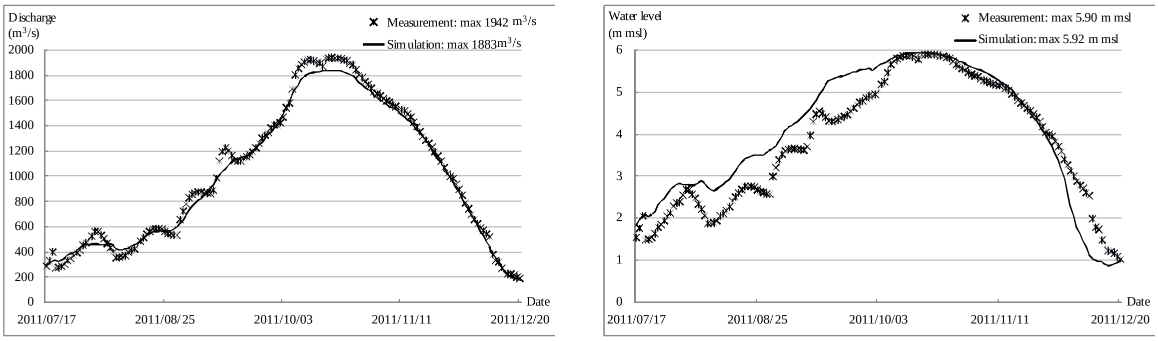
	Discharge	Stage

Station	R^2	RMSE (m^3/s)	R^2	RMSE (m)
C35	0.98	152	0.99	0.45
S5	0.99	56	0.97	0.55



(a) (b)

Figure 11-23 Validation of computed results and measurements at C35 station on Chao Phraya River: (a) discharges, (b) water levels.



(a) (b)

Figure 11-24 Validation of the computed results and measurements at S5 station on Pasak River: (a) discharges, (b) water levels.

At the C35 station on Chao Phraya River, the coefficient of determination (r2) of discharges in the simulation was 0.98 with the root mean square error (RMSE) differed from the measurements by 152 m3s-1 (see Figure 21 a). Whereas, the r2 of water level in the simulation was 0.99, the RMSE was 0.45 m msl (see Figure 21 b). At the S5 station on Pasak River, the coefficient of determination (r2) of discharges in the simulation was 0.99 with the RMSE was 56 m3s-1 (see Figure 22a). Whereas, the r2 of water level in the simulation was 0.97, the RMSE was 0.55 m msl (see Figure 22 b).

The validation of the 2D component of the model was carried out using flood depths in the Ayutthaya area; The Manning's roughness values were adjusted so as to match simulated and observed flood extents and depths on the island. The average recorded flood depth is approximately 2.0 m while the computed average flood depth was 1.97 m.

Hazard is defined based on the depth of inundation alone. Floodwater velocities in the site are known to low (less than 1 m/s) and can be neglected. A body of research is available about the relationship between flood characteristics and negative consequences, such as the threat to human life (Penning-Rowsell, 2005; Jonkman et al., 2008; Peters-Guarin et al 2012). In this research, threshold depths of < 0.5m, 0.5-1.5m, and >1.5m were used to define the flood hazard as low, medium and high respectively.

11.2.3 WP3

Flood Risk Assessment

Methodologies for flood risk assessment have typically been based on the views and knowledge of experts, excluding the views of the community at large, while employing a technocratic or technocentric approach. The adverse effects of floods often entail far-reaching socio-economic and environmental implications, and may include loss of life and injuries, psychological effects, environmental degradation, and diminution of intrinsic values. Importantly, not all of the impacts can be expressed in monetary terms or other quantifiable units. Therefore, qualitative approaches can be employed to address these factors. The assessment of many of the aforementioned consequences is difficult through expert estimation alone. Therefore, participatory approaches, that facilitate the involvement of various stakeholders, including communities at risk, have been actively developed in recent years.

Vojinovic and Abbott (2012) consider stakeholder participation as a means for realising social justice in flood risk management. The purpose of stakeholder participation is to induce a change in the built and managed environment that aligns with a positive change in the social environment. The same authors state that successful stakeholder participation requires the traditional engineering way of thinking to change into one where ideas emerge from social concerns and which serve humanity.

The approach used in the study area combined both quantitative and qualitative data and methods,. Traditionally, there has been a focus on using quantitative methods alone to assess risk. The assessment of flood hazard relies on the collection of physical data such as topography and land cover, and combines these with hydrological data to produce physical models of the hazard. The four dimensions of vulnerability are assessed using quantitative data. Physical and economic vulnerability is assessed in monetary terms. A statistical analysis of social and cultural data is conducted to assess vulnerability in those two dimensions.

A qualitative assessment of risk through an estimation of the hazard and vulnerability is conducted using local and expert knowledge to identify vulnerable assets, and questionnaires and workshops to gain knowledge on the expected hazards and the vulnerability of communities.

The quantitative and qualitative assessments are not carried out in isolation, and at each stage, the two assessments are informed by each other. For example, the risk analysis relies largely on quantitative data processing. However, this can be updated with information from stakeholders, and communicated to stakeholders through fora or other means.

Risk analysis

The combined vulnerability hazard maps are raster files with values from 1 to 3, where 1 means low level of vulnerability/hazard, 2 means medium level, and 3 means high level. In order to produce a risk map the vulnerability and hazard raster files are multiplied. An example of a flood risk map produced for the extreme flood event similar to the 2011 flood event is presented in Figure 11-25.

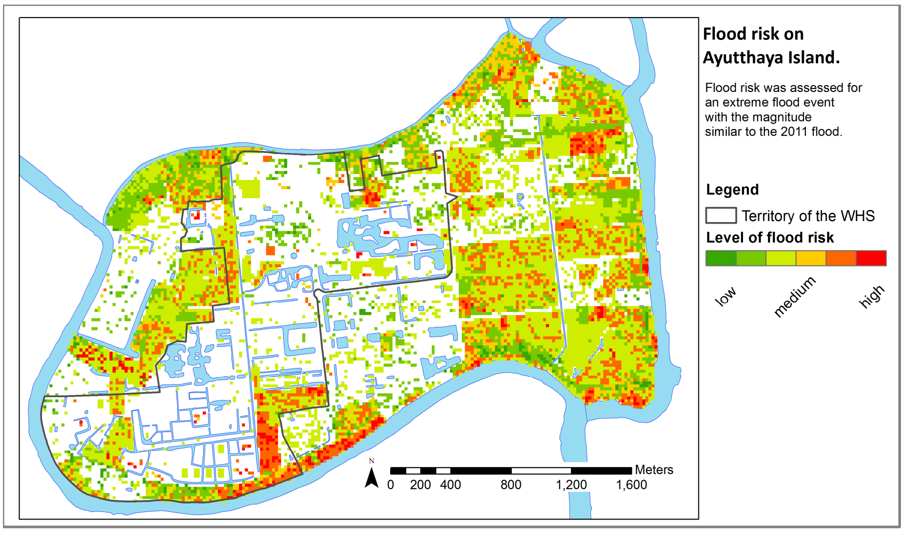


Figure 11-25 Flood risk map of Ayutthaya Island with the current state of flood protection

Risk perception

Data collection

A group mapping exercise was used to assess the perception of risk by local communities. Figure 24 presents photographs of this exercise. The facilitator of the exercise first provided an introduction to the concept of risk and then encouraged participants to share their feelings about flood risk in the area of their residence and to voice their thought process out loud. Afterwards, a group of 10-15 people worked together to create a map of the perceived risk for a given area. Participants were encouraged to express an agreed level of risk by colouring in a blank map. Three different colours were used to indicate areas of low, medium or high perceived risks, Figure 11-26.

Figure 11-26 The process and an output example of the group mapping exercise with community representatives.

The direct observations from the discussions demonstrated that from the outset participants tended to assign high level of risk for the entire island. The accompanying comments explain that: "We have an elevated road (U-Thong Road) but when a flood breaches this road, our island is turned into a basin. Inside the island, many roads are elevated to at least +.50 m, thus our small community in the low land area is like a puddle".

Data analysis.

All the information received was converted into a GIS format and a single risk perception map was created for Ayutthaya Island, as shown in Figure 11-27. Even though participants of each group were invited and encouraged to discuss and to colour the area of the Historic City of Ayutthaya, none of the groups did it. It was noticed, that participants were more interested in the areas of their own communities and did not show much interest in the World Heritage Site. Some participants commented that it is the responsibility of appropriate experts to judge the risk for the World Heritage Site and not local residents. Communities' representatives said that they were not aware of the vulnerability and condition, as well as the possible effects of flooding on the properties.

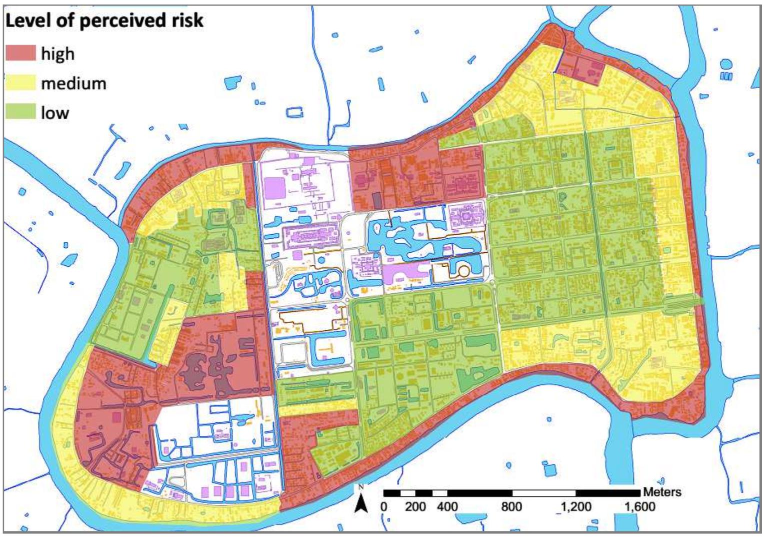


Figure 11-27 Risk perception map based on group mapping exercises.

Risk Communication

Characterization of communication means

A range of relevant flood risk related information was identified (e.g. flood magnitude, vulnerability level) which would aid communication in the project. Furthermore, various means and techniques could be employed for risk communication, such as maps, graphics, tables, and charts. Data to analyse the effectiveness of various means were gathered by direct observations during workshops and by questionnaires.

Perception of information from different means

The main objective of the investigation of risk communication means was to understand the ability of local residents and stakeholders to perceive and share information and knowledge through maps and other means. Figure 11-28 shows participants during the workshops.

Figure 11-28 Presentation of the model results to the stakeholders (left). Community representatives work with the satellite image at the municipality office (right).

Workshop activities demonstrated that local residents and stakeholders are able to share flood risk related information (e.g. flood magnitude of past events (duration, depths of flooding), vulnerable areas, and history of flood events). The preferred means of communication by residents was orally, by telling stories. Participants could easily and precisely describe flood levels during past events at different places beyond their own community with this method.

Most of the workshop participants were literate and could read written materials or respond to questions in written form. However, it was noticed that residents had difficulty in interpreting information from maps and identifying locations. Residents preferred to receive illustrated information rather than written descriptions. For instance, they could easily understand the location when the references to local landmarks were used or photos of the places were provided. Residents talked about depths of inundation and described water levels above the ground, rather than mean sea level. Local units were used for spatial measurements instead of SI units. In contrast, local institutions and the key stakeholders preferred maps and statistical data, both as charts and graphs, as communication means. Table 11-7 summarizes the preferences of local stakeholder to different risk communication means.

Table 11-7 Matrix showing the level of information perception by different stakeholders from various communication means.

Type of information	Location		Depth of inundation			Vulnerabilities	
Communication tool	Map	Descriptive text with references	Map	Descriptive text		Map	Statistic (tables, charts)
				water level above the	water level above the		

		to local landmarks		ground	mean sea level		
Local residents	-	++	-	++	-	-	+
Ayutthaya Municipality	+	++	+	++	+	+	+
Fine Art Department, Provincial office	+	+	+	+	++	+	++
Hydro- and Agro-Informatics Institute	++	-	++	-	++	++	++
Asian Institute of Technology	++	-	++	+	++	++	++
UNESCO Bangkok	++	-	+	+	+	++	++

"-" — not possible to perceive information
"+" — low or moderate level of information perception
"++" — very good information perception

Preferable channels of information

150 copies of the questionnaire regarding the appropriate sources of flood related information were distributed at the community workshop. 94 completed copies were collected. The results are presented in Figure 11-29.

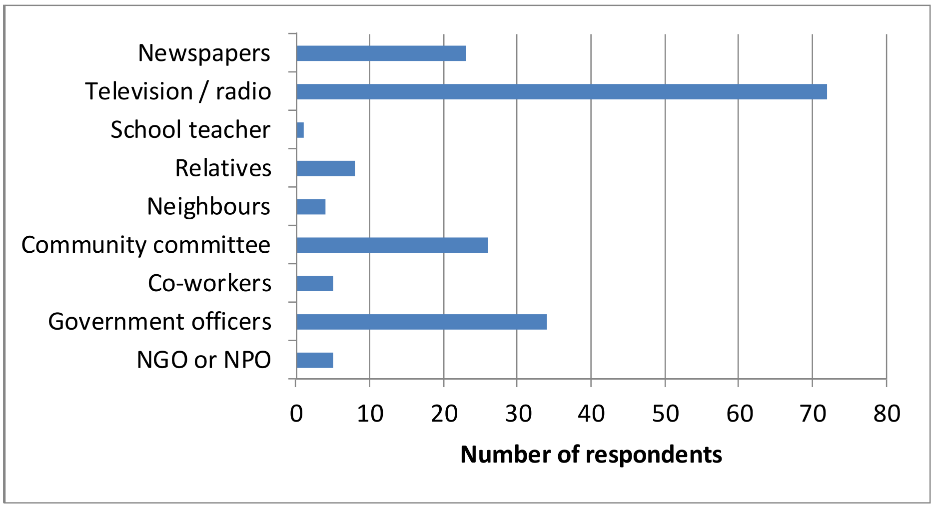


Figure 11-29 Use of different information sources in the context of risk communication among Ayutthaya residents[18]

The results show that 72 from 94 respondents (77%) preferred to receive flood risk related information through broadcast channels such as television or radio. Respondents indicated the timeliness of announcements and easy access as reasons for using these channels. The second most popular source of information was "newspapers", and 23 respondents (24 %) mentioned this medium. 53 respondents (56%) mentioned that they would first follow the news on a television or a

[18] NGO refers to Non-Government Organisation, and NPO refers to Non-Profit Organisation

radio, and then try to verify information using newspapers. 34 of 94 respondents (36 %) mentioned that information provided by the local government (Ayutthaya Municipality) is also essential. Residents pointed out that Ayutthaya Municipality has a responsibility to take care of local residents and respondents trust this source of information. Particularly, residents rely on the Municipality when information is needed to make a decision to evacuate. During the 2011 flood event, residents could find it difficult to evacuate without guidance from Ayutthaya Municipality.

The majority of the respondents were elderly people, therefore the internet was not considered to be a popular information channel. These residents usually do not use the internet. However, respondents mentioned that in case they need urgent information updates, they would contact younger friends, family members or acquaintances for support. Thus, respondents expressed an understanding of the benefits that the internet could provide in case of emergencies.

Implementation of scenarios

Flood mitigation scenarios can be implemented and evaluated in the hydraulic model by amending the model set up including its geometry and other parameters. The baseline scenario is the existing situation, referred to as Case 1. In this baseline situation (Case 1), the dyke that surrounds the island (U-Thong Road) is maintained at +5.30m, and no other mitigation measures is implemented.

Flood simulation results

By using a 20 m resolution of LiDAR-DTM as topographic input data for the coupled 1D-2D modelling, a simulated result of the Case 1 scenario shows that the maximum floodwater depths were over 6 m msl in rivers and ponds. In Ayutthaya Island, the area of ~7.8 km^2 was inundated to a depth of approximately 2 m (see marked boundary in Figure 11-30) and the estimated flood volume is ~ 13 million m^3.

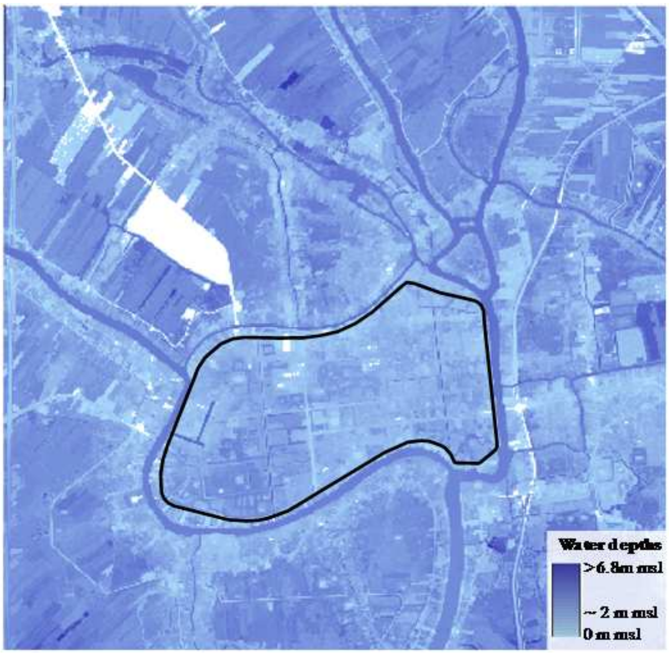


Figure 11-30 Maximum flood depths of the Case 1 scenario when using 20 m resolution of LiDAR-DTM as topographic input data for the coupled 1D-2D modelling

11.2.4 WP5

Selecting multi-functional green infrastructure to enhance resilience against urban floods

In the area of urban drainage management, similar concepts are named with different terms in different parts of the world. Terms such as BMPs (best management practices), LIDs (low impact development), WSUD (water sensitive urban design), SuDS and GI are broadly used. Taking this into account, a careful use of terminology should be achieved, to minimise the possibility of miscommunication (Fletcher et al., 2014). In this work, the names GI, non-traditional measures and sustainable solutions, are used to name all the different sustainable measures (BMPs, LIDs, SUDS, WSUD, GI, etc.). While traditional or grey infrastructure are used to refer to conventional solutions.

It is through the analysis of the multiple aspects of applying GI, that the multiple benefits from them obtainable in urban spaces can be visualised. These benefits are for instance, stormwater detention, reduction of extreme heat events and energy consumption, improvement of water and air quality, reduction of potable water consumption, biodiversity enhancement, opportunities for education, and health benefits. Furthermore, the synergies between GI for stormwater management and other benefits have the capacity of saving costs. Considering this, GIs appear as cheaper in terms of investment and maintenance costs than strictly conventional strategies (Tzoulas et al., 2007; Ashley et al., 2011; USEPA, 2013; European Commission, 2012; CIRIA, 2013).

This work proposes a procedure for selection, or screening, of promising measures to cope with urban floods, considering local constraints and environmental aspects, through the evaluation and integration of multiple benefits. In order to facilitate the application of the proposed methodology, the process has been coded into a software program. The method is tested in two case study sites in Thailand to prove its effectiveness. The outcome of this work is seen as a useful approach for helping decision making processes with the aim of reducing urban flood risk in a sustainable way, allowing the improvement of other environmental aspects

Methodology

This work develops and applies a framework which includes the screening and ranking of options among all possible measures for stormwater management. The measures to be analysed are selected from an extensive Knowledge Base (KB) being developed for PEARL Project (see http://pearl-kb.hydro.ntua.gr, Karavokiros et al., 2016).

The methodology is divided into two steps. The first step consists in measures screening, the criteria considered here are the type of floods and local physical constraints. The first criterion for screening removes the options that do not fulfil the requirements according to the flood type affecting the area. While the second one considers local characteristics which could prevent the use of some measures. For instance, if soil in the area is impervious, infiltration measures are most likely eliminated from this list.

The second step will consist on ranking the remaining measures according to two factors. The first ranking analyses local space characteristics to identify the most suitable measures according to

the urban shape. The second ranking considers the co-benefits that the screened measures can provide, and which of them are identified as more relevant for the case according to local preferences.

With the objective of enabling the implementation of this methodology in an easy process, a tool was coded in Pascal using Embarcadero RAD studio X6. Through this tool the user can apply the method following the different steps and answering questions about local characteristics and benefits preferred. The achievement of good results depends on the availability of local experts, in order to get proper answers about local characteristics. After following all the required steps, a short and ordered list of measures is obtained

The study area considered is Ayutthaya as it was described in the section above. From the discussion of the hazard assessment and modelling it can be concluded that the most devastating flood events are a consequence of high water levels of these three rivers. However, the area also experiments pluvial floods. Almost half of the study area is covered by a World Heritage Site, while the remaining areas are used as residential zones, education purposes facilities, commercial installations, and public building (Keerakamolchai, 2014).

Results and discussion

The proposed methodology was applied for Ayutthaya and The results obtained in this case are showed in Figure 11-31 and Table 11-8. The selected measures are divided into three different categories, presented again with colours on the graph (red for the best measures, yellow for medium preferred measures, and green for the least preferred). Table 11-8 shows the correspondence between the reference numbers used in the graph are the measures names, the measures classification is also presented (categories 1, 2 and 3, for best, medium and least preferred measures, respectively).

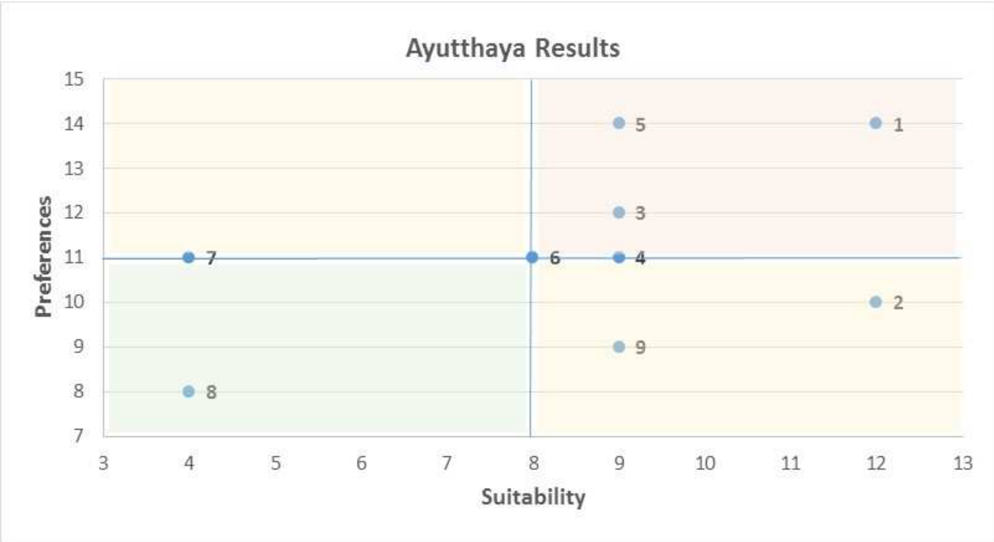


Figure 11-31 Rankings scores for selected measures in Ayutthaya Area case.

Table 11-8 Selected measures for Ayutthaya Area.

Measure		Score		Category
		Suitability	Preferences	
1	Open Detention Basin	12	14	1
2	Floating/Amphibious Buildings	12	10	2
3	Temporary/Demountable Barriers	9	12	1
4	Wet Flood Proofing	9	11	2
5	Dry Flood Proofing	9	14	1
6	Non Return Valves	8	11	2
7	Polder	4	11	3
8	Pumping System	4	8	3
9	Raising existing dikes	9	9	2

In this case there is a notoriously preferred measure, which is Open Detention Basin. Additionally, temporary solutions as Demountable Barriers, and Dry Flood Proofing are chosen. In this case the preferred solution to cope with pluvial floods is a centralised option, this measure requires availability of space which is not a major constraint in the area.

11.3 Additional research activities and results

11.3.1 WP3

Modelling land use changes in Ayutthaya

Aiming at assessing the consequences of various scenarios within WP3, spatially based urban growth models which are able to address the future land change will be utilised. For the development of this task Dinamica EGO (Soares et al, 2011) was used as a land use change model engine to simulate the different scenarios. Dinamica Ego is being used by different researchers to assess scenarios of urban growth (e.g, Pathirana, 2011, Sanchez A. et al, 2014, Sanchez A. , 2013, CORFU, 2014).

DINAMICA employs, as inputs, a set of maps, including the initial and final map of land use, also known as landscape maps, where a landscape is viewed as a bi-dimensional array of land use types, and two sets of ancillary maps: the static and dynamic variables, the latter so named because they are updated by the model iteration. The sets of variables are used to calculate land use transitions.

Land use maps were collected for Ayutthaya for different years. Depending on the study area these sets can be used to calibrate and validate the model. The following data was collected:

- Satellite Images from Google Maps.

- Shape Files (Buildings, Roads, Railways, Waterways, Places, etc).
- Web documents on case studies cities; both: general and flood related.

Figure 11-32 presents the results of the cellular automata model after calibration for Ayutthaya.

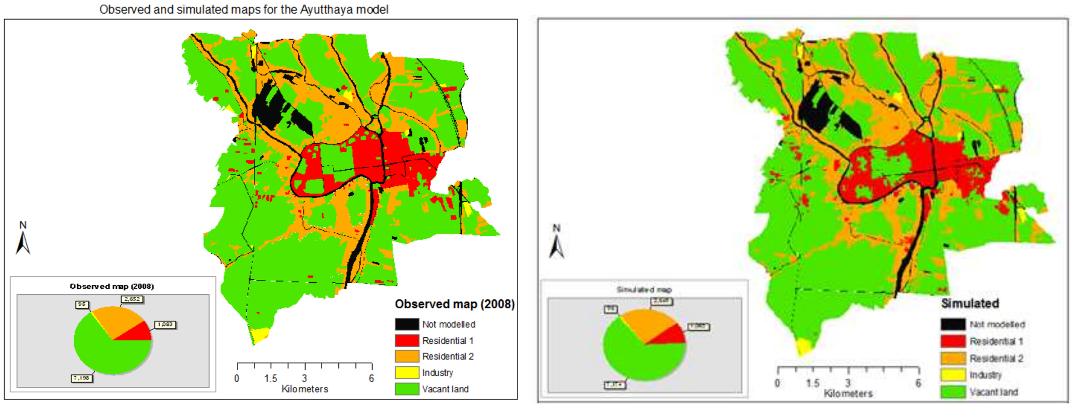


Figure 11-32 Observed and simulated land use map in Ayutthaya after calibration

The simulation of urban growth for the next 30 years allowed an opportunity to explore the possible outcomes of three defined possible scenarios namely, business as usual, sprawl and compact growth. Figure 11-33 shows the results for scenarios of future growth in Ayutthaya. Results show that significant growth would be experienced that have potential to cause gentrification around cultural heritage sites, impact the watershed hydrology, increase the fragmentation of landscapes, change demand for water supply and increase the costs of supplying basic water supply and waste water drainage services to new development areas as well as increase the demand and pressure for services around the areas of cultural heritage

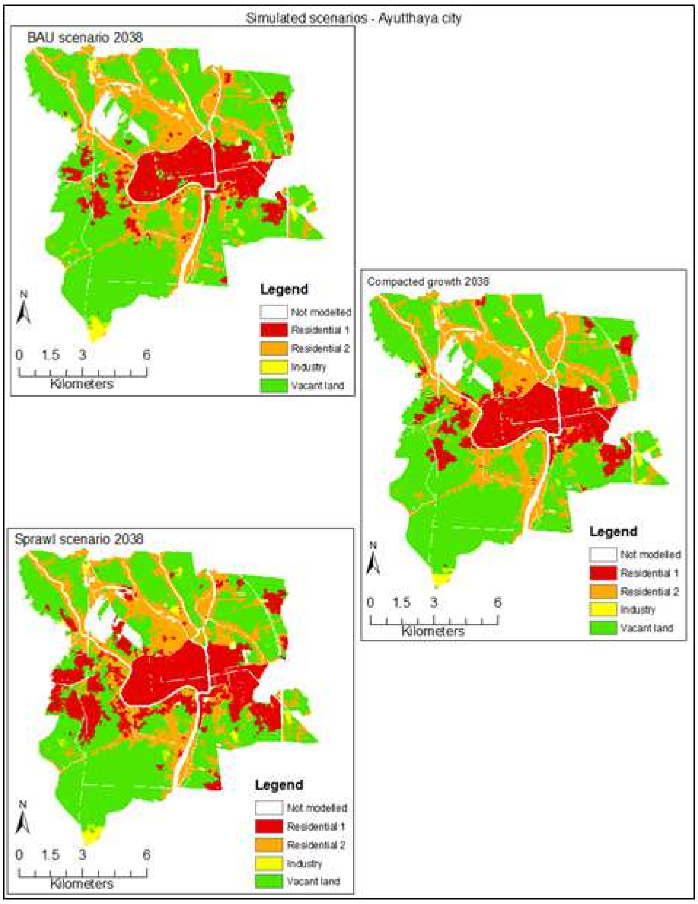


Figure 11-33 Assessment of scenarios of land use change for 30 years

Modelling pathogens to estimate the impacts of flooding in public health

Case Study Area

The study area of Sukhumvit is located at the eastern side of Bangkok and it is part of the central business and commercial districts. The catchment lies within two district of Bangkok namely Wattana and Khlong Toei and the total population in these districts is 185,275 inhabitants (Shrestha, 2013). The elevation of the study area is between 0.4 and 4 MASL. As the Sukhumvit area is relatively flat, pumps are used to drain water to the main drainage. The existing network in Bangkok is a combined sewer system, where the primary drainage consists of 10 polders as the secondary drainage system. This system was able to prevent fluvial floods caused by Chao Phraya River overflow in 1995 and 1996 (Boonya-aroonnet, et al., 2001).

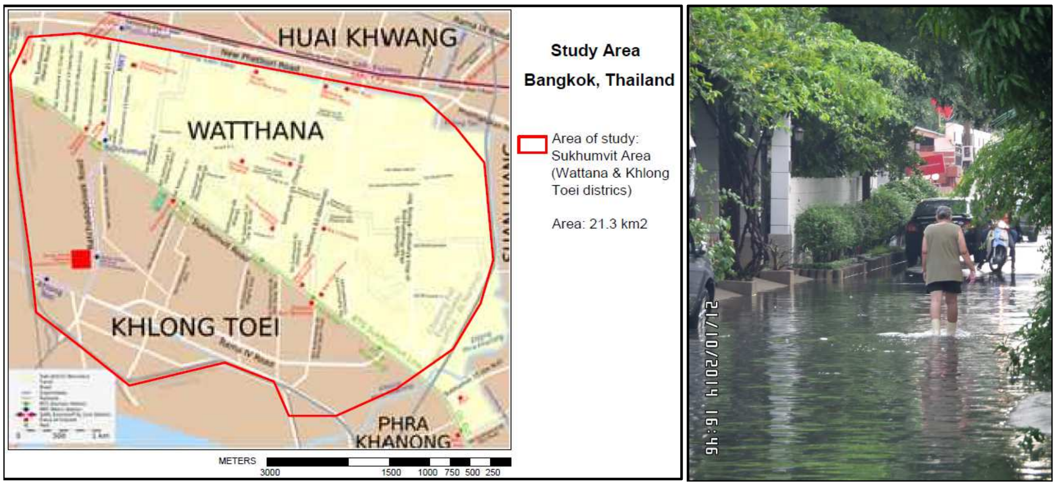


Figure 11-34 Study area. Wattana and Khlong Toei districts and flooded streets at Sukhumvit Soi 26 after a rainfall event on 21/10/2014

Bangkok's central business district has suffered some fluvial flooding events in recent years, in particular in 2011. However, pluvial flooding is more common and as a result, contact with contaminated water is commonly experienced by children, pedestrians and cyclists. Figure 11-34 shows some flood waters at Sukhumvit Soi 26 after a rainfall event on 21 October 2014.

Hazard Estimation

The estimation of flooding hazards has been done in the area with the use of Mike by DHI modelling tools. The first calibration of the model was conducted by Chingnawan, (2003) and the observed data from three stations on 5th October 2002 was used. The validation of the model was done with data of the 7th October 2002. Nguyen (2009) performed a second calibration using precipitation data and three stations' water level data from 16th November 2004 and 20th November 2004. A coupled 1D/2D model was developed by Shrestha, 2013. This model was used in this study.

The calculated water depth from MIKE Flood shows that the maximum flood water depth for the rainfall event on 11 October 2014 varies between 0,0002m to 0,36m. The spatial distribution of the flooding results are similar to the flood prone areas map given by the local authorities, almost the same streets are prone to flooding. Therefore, the validation of the 2D hydrodynamic model is considered as "good "for the Sukhumvit area (Figure 11-35).

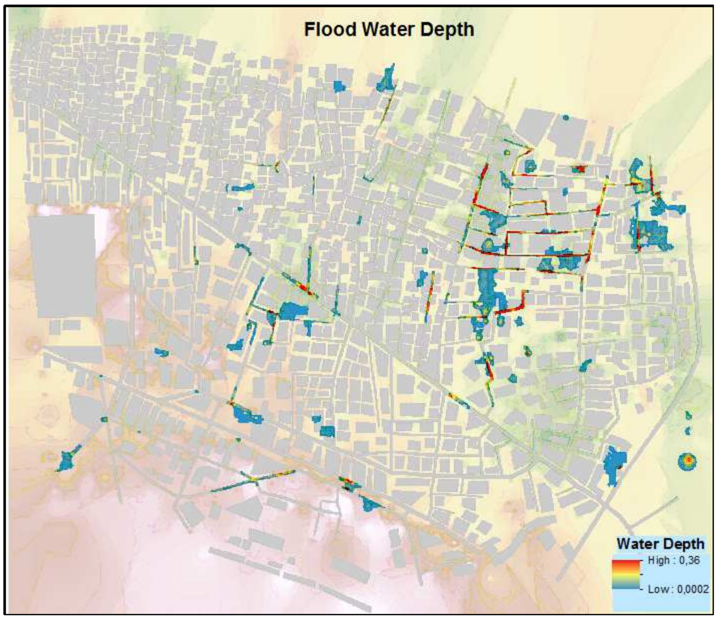


Figure 11-35 Flooding area and water depth calculated for Sukhumvit

Water quality and pathogens

Water quality samples of flood waters and dry weather flow waters were taken on three different day at different locations, in order to know the variation of E.coli concentrations in time and space.

The component (substance) E.coli is included in the Advection-Dispersion computation, with an initial concentration according to the laboratory results, and a linear decay constant of 1 s-1. The results of the simulated E. coli concentration are presented in figure 11-36.

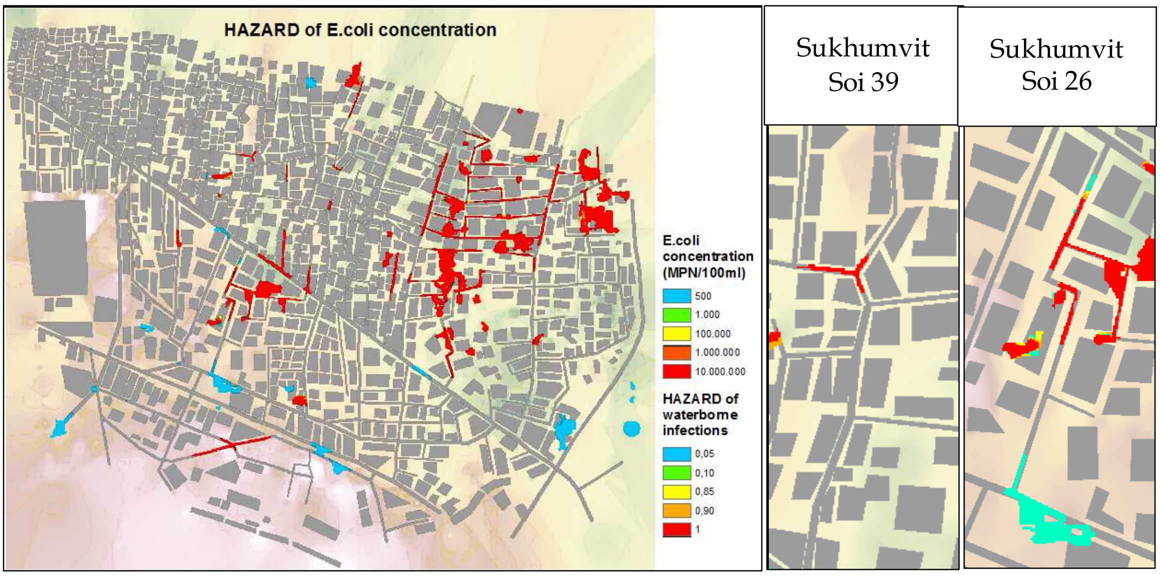


Figure 11-36 Hazard of E.coli concentration

The values E. Coli concentration were classified and together with the water depth (Figure 11-36) and the duration of the flooding (Figure 11-37) are used to generate the waterborne infection map.

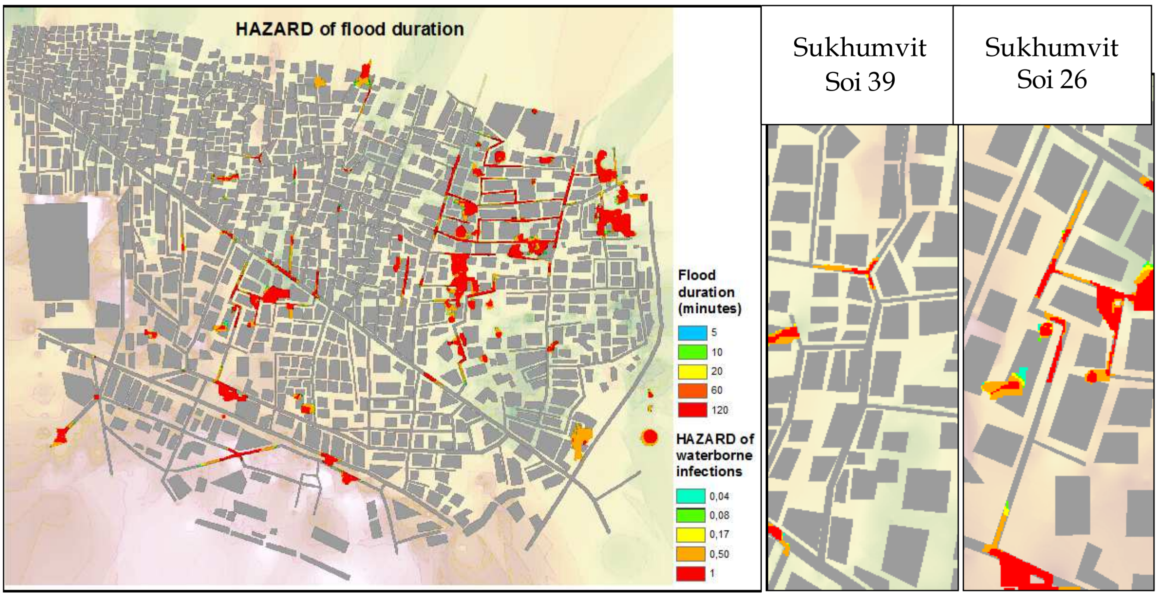


Figure 11-37 Hazard of flood duration

Most of the areas exceed the flood duration of 60 minutes in a rainfall event on 11 October 2014 that lasts 1:15 hours, which means a hazard value of 1 for waterborne infections. Only few areas at Sukhumvit area have a hazard value of flood duration lower than 1.

The hazard of waterborne infections is the average of the three components: maximum flood water depth, flood duration and maximum concentration of E.coli. In this way, the hazard map of waterborne infection during the rainfall event on 11 October 2014 is shown in Figure 11-38.

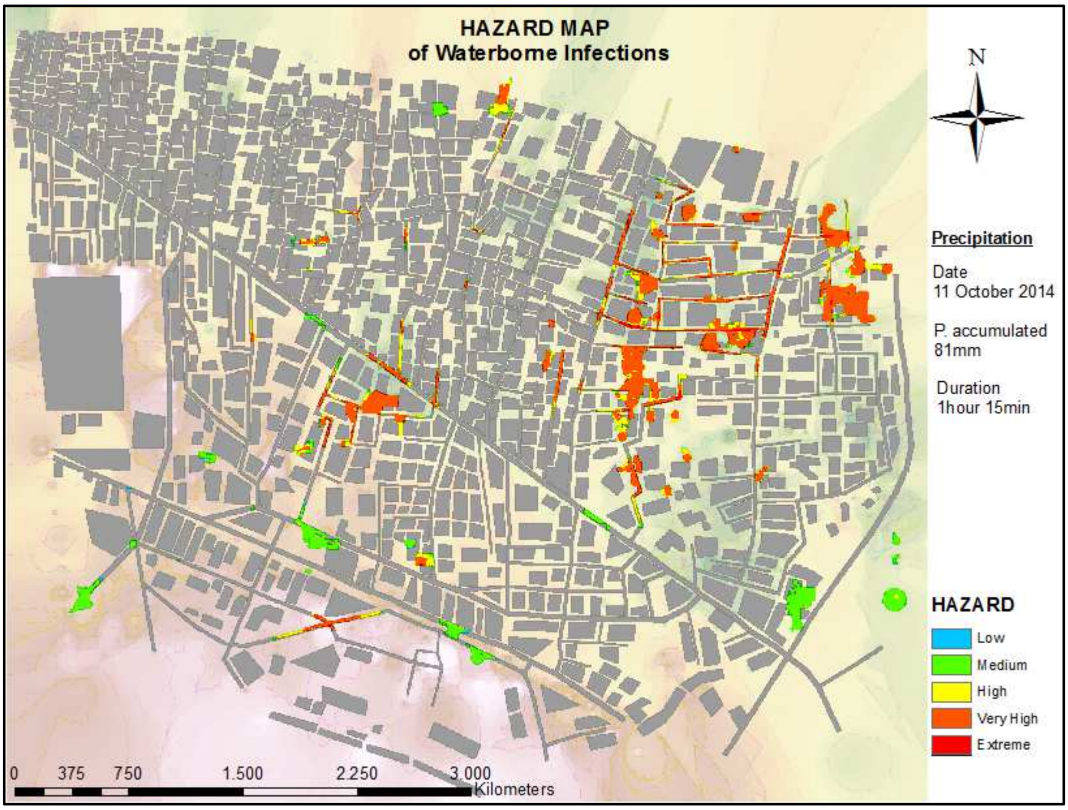


Figure 11-38 HAZARD MAP for waterborne infections

Most of the flooded areas present a very high hazard for waterborne infections due to the long duration of the flood and the high concentration of E.coli, while there are some streets with a medium or high hazard classification, since the flood water depth is not too high. There are no areas with low hazard. The simulated rainfall event occurred during lunch time, when many people from the business and commercial areas are out looking for food. This generates a significant public health risk since more people (pedestrians) is exposed to this hazard. This stuyd has contribute to the demonstration of the model developed in deliverable 3.2.

Analysing Cascading Effects of Flood Events and Assessing their Impacts on Critical Infrastructure: the Case Study of Sukhumvit, Bangkok, Thailand.

The overall objective of this research is to develop a methodological framework for analysing cascading effects of flooding and assessing their impact on critical infrastructure. This research is on going and it is expected to finish in june 2017. However a short summary of the activites being done so far are presented here.

The case study area and the description of the approach to estimate the flood hazards was presented in the previous section. The methodology that is beiing developed and applied is having the following considerations:

- Cascading impacts happen inside and outside flood affected area and are mostly related to socio and economic damages.
- Can be resulted from infrastructure damages/failure or floodwater.
- Size and duration of impacts depend on type of infrastructure and type (nature) of damage and recovery duration (e.g. in agriculture)
- Four urban critical services are advocated in this study:
- Transportation, energy, water and sanitation.
- The higher the direct damages the higher the cascading impact.
- Framework can be used to identify potential or actual direct damages and indirect impacts.
- Case study area Sukhumvit is suffering from frequent pluvial flooding and is vulnerable to fluvial and coastal flooding.

Interviews and data collection

The main stakeholders and critical was identified and interviews have taken place. The following institutions have been visited and key personnel was interviewed. Figure 11-39 shows some photos of the interviews and work done. The inverviews were done with personel from the following stakeholders:

- Metropolitan Waterworks Authority (MWA)
- Metropolitan Electricity Authority (MEA)
- Department of Drainage and Sewerage (DDS)
- Traffic and Transportation Department (TTD)
- Soi Sukhumvit 26, 34, 39 and 63.
- Residents and Businesses – 34 houses
- Drivers (Motorbikes and Taxis) – 27 drivers

Figure 11-39 Interview with key actors from critical infrastructure.

Table 11-9 summaraizes the main findings in relation to critial infrastructere and flood events.

Table 11-9 Effects of flooding on critical infrastructure

MEA (electricity)	MWA (Water)	DDS (Drainage)	TTD (trafic)
• Substations, transformers & meters are elevated. • Mainly delay on O&M only. • Customers depend on their own	• Leakage repair delay 2hr KPI • Diving into valve chambers • 600 leaks for service pipe and 100 leaks distribution • Confusion pipe leak vs flood	• Avg. 200 min. to drain floods. • Plan to reduce to 90 min. • O&M cost on personnel and power.	• Road signs, debris cleaning. • No special attention on flooding problem. • Traffic police take care of traffic problems.

Based on the answers of the interviews figure 11-40 shows the percentage of people that consideres which infrastructure to be the most affected when flooding occurs.

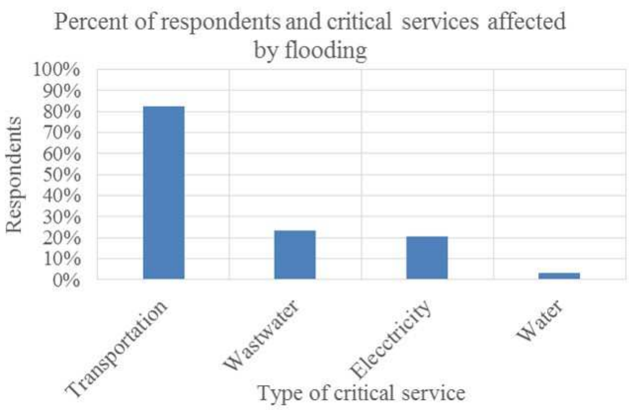


Figure 11-40 Critical infrastructure affected by flooding

Based on this results the road network is the most exposed critical infrastructure to the flooding events and road transportation is the key to all other infrastructure services and also a major link to other means of transportation (air, water and even train). The researhc is still on going and is focusing in acquaring data from the traffic disruptions to estimate indirect impacts and economic losses. In Figure 11-41 a causal loop diagrame for the study area has been developed.

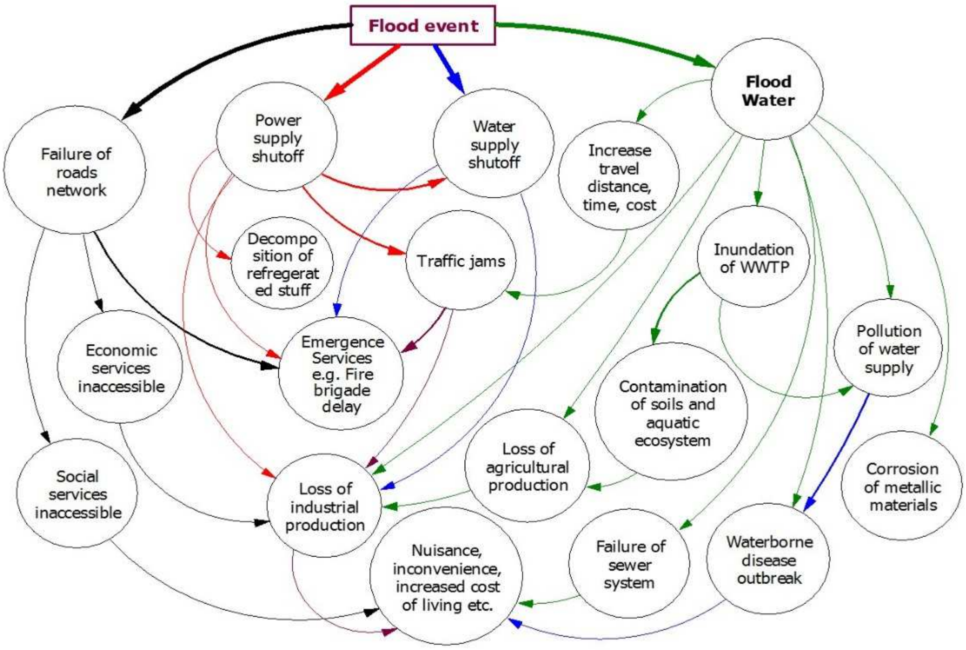


Figure 11-41 Causal loop diagram for visualization of the cascading effects of flooding

The causal loop diagram can be used as a visualization tool to explain and show the results of the analysis to the local stakeholders.

11.4 Summary and lessons learned

The research conducted in Ayutthaya has been supervised by AIT and UNESCO-IHE in the form of a Master of Science thesis of Daria Golub, Weeraya Keerakamolchai in 2014, Juan Camilo Polania in 2015, Phyllis Togarepi in 2016 and Geofrey Hilly, Abdul Naser Majidi, Jose Patiño in 2017. This work has been co-supervised among others by Sutat Weesakul, Mukand Babel from AIT and Zoran Vojinovic from UNESCO-IHE. From UNESCO-IHE serveral researches have been invlved in mentoring the MSc research among others Vorawit Meesuk, Alida Alves, Neiler Medina and Arlex Sanchez. The research focuses on different components of flood risk management (FRM). The results obtained so far will be summarize in line with the different work packages as thematic areas structured in the framewokr of PEARL.

Some of the methods and tools being develop in the framework of PEARL has been tested in the Ayutthaya case study area. This process is still on going and the it has been valuable to researches both at AIT and local institutions in Thailand and for UNESCO-IHE. This research aims to develop and enhance a holistic view of risk, where a systemic approach is needed to analysis different mechanisms that can generate risk at different levels.

In terms of flood risk assessment, two different approaches have been applied in Ayutthaya, namely traditional (or technical) and risk perception (social) approaches. These approaches differ in many ways, including the definition of the term "risk", the characteristics of the disaster concerned, and the techniques for data analysis. Social perspective on risk assessment focuses on the root causes of flood risk related to human mental processes and the human scale. This research has demonstrated that flood risk is inherently a social process with social roots. Both

approaches reveal valuable insights into the phenomena and as such they both should be used in the process of flood risk management.

There are several benefits to the approach taken in this study. First, the traditional approach provides the possibility of testing potential flood risk reduction measures. It has been shown in some studies that the success of certain measure is at least partially dependent on the perception of risk. Precautionary measures that rely on residents perceiving the risk will fail, if residents are unaware of the risk they face. Flood risk manager can identify areas of the highest risk based on the map derived with the traditional approach. However, both the legitimacy of flood risk reduction plan and risk behavior of local residents rely heavily on the level of perceived risk.

Traditional approach provides raster flood risk map with fixed the cell size of a few metres, whereas risk assessed by local communities tend to assess risk on a large scale. This raises interesting questions over the best way to communicate flood risk. An over-reliance on the results of computational models may not be the most appropriate.

12 Overall conclusions and lessons learned

Tools and methods developed within the PEARL project are applied to a number of case study areas all over the world. European case study areas cover a wide range of geograpahical/topographical, risk and hazard as well as socio-economic conditions and each of the case studies experienced different hydro-meteorological extreme events in the past. Trough the international case studies the project benefits from the international experience on extreme events. They extend the range of extreme events by e.g. cyclone, hurricanes and tsunamis. Different socio-economic conditions, risk and governance practises are also of importance.

The research activities in the respective case study areas revealed that holistic risk assessment can be the initial step in order to define comprehensive flood risk management and mitigation strategies. Holistic risk assessment helps to gain an insight in the formation of risks and hazards and the impacts of extreme events.

It became evident, that flood risk management and mititgation as well as risk governance have different level in the case study areas. It can be considered, that several super-ordinate policies regarding institutional and governance pracitices do exist, but are not incorporated into the current flood risk management and mitigation frameworks and policies of the municipilaties and authorities. It has likewise become evident, that municipilaties rely on post disaster management and reconstruction, instead of flood prevention and mitigation. Lack of awareness raising activities and inadequate information of the pubic plays its part. Against this background, the PEARL LAA methodological framework represents a excellent possibility to provide significant support to the municipality and authorities towards an enhanced flood management and disaster risk mitigation.

The Hamburg/Elbe estuary represents here an exception. On the one hand, there is already a high level of the risk awareness, in particular due to devestating flood events of 1962 and 1976. Stakeholder, authorities and the public know about the flood issues and the flood protection infrastrucuture has been designed adequately. On the other hand, LAAs and stakeholder workshops have been conducted already in the scope of several initiatives and participatory planning actions within several previous national and international projects related to climate change and flood issues in the Elbe estuary. As a consequence, stakeholders in the case study area have a high awareness of the relevance and benefits of such stakeholder involvement activities, but at the same time caused a certain fatigue towards these activities.Building upon this experience, a more tailored approach adjusted to the specific features of the stakeholder involvement in the area, local culture and the level of risk awareness has been followed.

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Annex 1 – Marbella Case Study

Annual SCC Values: 2010-2050 (2007€/metric ton CO_2)

Source: adapted[19] from TSD (2015)

Discount rate Year	5.0% Avg	3.0% Avg	2.5% Avg	3.0% 95th
2010	7	22	36	62
2011	8	23	37	65
2012	8	24	38	67
2013	8	25	39	70
2014	8	25	40	73
2015	8	26	41	76
2016	8	28	41	78
2017	8	28	43	81
2018	9	29	43	84
2019	9	30	44	87
2020	9	30	45	89
2021	9	30	46	91
2022	9	31	46	94
2023	9	32	47	96
2024	9	33	48	98
2025	10	33	49	100
2026	10	34	50	102
2027	11	35	51	104
2028	11	36	51	106
2029	11	36	52	108
2030	12	36	53	110
2031	12	37	54	112
2032	12	38	54	115
2033	12	38	55	117
2034	13	39	56	119
2035	13	40	57	122
2036	14	41	57	124
2037	14	41	59	126
2038	14	42	59	128
2039	14	43	60	130
2040	15	43	61	133
2041	15	44	62	135
2042	16	44	62	137
2043	16	45	63	139
2044	17	46	64	141
2045	17	46	65	143
2046	17	47	65	145
2047	17	48	67	147
2048	18	49	67	149
2049	18	49	68	152

[19] The conversion factor used is the 2007 EUR/USD average that is 1.3795.

2050	19	50	69	154

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Indirect Damages for different scenarios

7	Agricultura, ganadería, silvicultura y pesca	Industria	Construcción	Comercio, reparación de vehículos de motor; transporte, almacenamiento; hostelería	Información y comunicaciones	Actividades financieras y de seguros	Actividades inmobiliarias	Actividades profesionales, científicas y técnicas; actividades administrativas y servicios auxiliares	Administración pública y defensa; seguridad social obligatoria; educación; actividades sanitarias y de servicios sociales	Actividades artísticas, recreativas y de entretenimiento; reparación de artículos de uso doméstico y otros servicios	Total danys directes que causen indirectes per sector	Danys indirectes calculats amb el model
18/05/2011	188274,532	283895,136	189571,346	2071019,85	192164,975	192164,975	192164,975	192164,975	192164,975	192164,975	3885750,71	2475400
15/02/2010	22128,241	549509,065	1865726,48	506654,134	24809,815	24809,815	24809,815	24809,815	24809,815	24809,815	3092876,81	477688,9
07/11/2006	88748,227	92184,4	90062,14	976230,497	92689,966	92689,966	92689,966	92689,966	92689,966	92689,966	1803365,06	1171900
27/03/2004	61415,498	63703,3635	63703,3635	675570,478	68279,0945	68279,0945	68279,0945	68279,0945	68279,0945	68279,0945	1274067,27	881468,3
27/09/1997	29087,5045	168781,446	29660,386	319962,55	30806,149	30806,149	30806,149	30806,149	30806,149	30806,149	732328,78	505144,9
28/09/2014	22609,3605	24622,1045	23041,1045	248702,966	23904,5925	23904,5925	23904,5925	23904,5925	23904,5925	23904,5925	462403,09	309697
21/12/2007	16478,1115	16478,1115	16478,1115	181259,227	16478,1115	16478,1115	16478,1115	16478,1115	16478,1115	16478,1115	329562,23	211423,6
02/02/1998	8234,834	9263,1325	9263,1325	90583,174	11319,7295	11319,7295	11319,7295	11319,7295	11319,7295	11319,7295	185262,65	162968,9
27/11/2014	4392,7605	5163,7935	5163,7935	48320,3655	6705,8595	6705,8595	6705,8595	6705,8595	6705,8595	6705,8595	103275,87	102981,8
18/12/2009	4561,5775	4840,5775	4840,5775	50177,3525	5398,5775	5398,5775	5398,5775	5398,5775	5398,5775	5398,5775	96811,55	80115,1
02/10/2007	6948,371	6948,371	6948,371	76432,081	6948,371	6948,371	6948,371	6948,371	6948,371	6948,371	138967,42	95225,6
02/03/2010	454,5545	454,5545	454,5545	5000,0995	454,5545	454,5545	454,5545	454,5545	454,5545	454,5545	9091,09	9771,9
21/09/2007	3326,3335	73236,5835	3326,3335	36589,6685	3326,3335	3326,3335	3326,3335	3326,3335	3326,3335	3326,3335	136436,92	107396,7
18/03/2006	4929,648	4929,648	4929,648	54226,128	4929,648	4929,648	4929,648	4929,648	4929,648	4929,648	98592,96	71080,4
22/12/2000	2675,5815	2675,5815	2675,5815	29431,3965	2675,5815	2675,5815	2675,5815	2675,5815	2675,5815	2675,5815	53511,63	42199,4
18/12/2010	4013,1285	12706,8645	4582,4745	44144,4135	5721,1665	5721,1665	5721,1665	5721,1665	5721,1665	5721,1665	99773,88	95102,3
25/12/2000	1296,685	6396,415	1296,685	14263,535	1296,685	1296,685	1296,685	1296,685	1296,685	1296,685	31033,43	29943
06/01/2010	2706	5911,71	2706	29766	2706	2706	2706	2706	2706	2706	57325,71	46641,2
25/02/2004	3602,06	3602,06	3602,06	39622,66	3602,06	3602,06	3602,06	3602,06	3602,06	3602,06	72041,2	55231
31/10/2008	2381,872	2381,872	2381,872	26200,592	2381,872	2381,872	2381,872	2381,872	2381,872	2381,872	47637,44	38137,4
08/12/2003	539,343	539,343	539,343	5932,773	539,343	539,343	539,343	539,343	539,343	539,343	10786,86	11465,1
22/10/2011	3270,982	3270,982	3270,982	35980,802	3270,982	3270,982	3270,982	3270,982	3270,982	3270,982	65419,64	50533,5

06/03/2010	475	475	475	5225	475	475	475	475	475	475	9500	10180,8
12/09/2014	2790	2790	2790	30690	2790	2790	2790	2790	2790	2790	55800	43796,5
21/02/2010	666,251	666,251	666,251	7328,761	666,251	666,251	666,251	666,251	666,251	666,251	13325,02	13999,7
22/08/2007	2173,168	2173,168	2173,168	23904,848	2173,168	2173,168	2173,168	2173,168	2173,168	2173,168	43463,36	35301
25/10/2006	385,836	385,836	385,836	4244,196	385,836	385,836	385,836	385,836	385,836	385,836	7716,72	8416
17/12/1996	570,9725	570,9725	570,9725	6280,6975	570,9725	570,9725	570,9725	570,9725	570,9725	570,9725	11419,45	12087,1
15/04/2004	1782,9205	1782,9205	1782,9205	19612,1255	1782,9205	1782,9205	1782,9205	1782,9205	1782,9205	1782,9205	35658,41	29989,6
05/02/1996	1984,798	1984,798	1984,798	21832,778	1984,798	1984,798	1984,798	1984,798	1984,798	1984,798	39695,96	32734,7
20/11/2011	1006,591	1006,591	1006,591	11072,501	1006,591	1006,591	1006,591	1006,591	1006,591	1006,591	20131,82	19780,6
30/12/2010	1712,5225	1712,5225	1712,5225	18837,7475	1712,5225	1712,5225	1712,5225	1712,5225	1712,5225	1712,5225	34250,45	29038,5
27/09/2008	1372,028	1372,028	1372,028	15092,308	1372,028	1372,028	1372,028	1372,028	1372,028	1372,028	27440,56	24600,9
01/06/2014	1059,0895	1059,0895	1059,0895	11649,9845	1059,0895	1059,0895	1059,0895	1059,0895	1059,0895	1059,0895	21181,79	20474,7
26/10/2003	578,509	578,509	578,509	6363,599	578,509	578,509	578,509	578,509	578,509	578,509	11570,18	12236,9
03/02/2007	1253,9375	1253,9375	1253,9375	13793,3125	1253,9375	1253,9375	1253,9375	1253,9375	1253,9375	1253,9375	25078,75	23083,8
19/06/2011	1194,602	1194,602	1194,602	13140,622	1194,602	1194,602	1194,602	1194,602	1194,602	1194,602	23892,04	22299
10/10/2008	1007,19	1007,19	1007,19	11079,09	1007,19	1007,19	1007,19	1007,19	1007,19	1007,19	20143,8	19792,3
22/03/2010	0	0	0	0	0	0	0	0	0	0	0	0
23/01/2010	638,013	638,013	638,013	7018,143	638,013	638,013	638,013	638,013	638,013	638,013	12760,26	13425,1
07/02/2003	136,9645	136,9645	136,9645	1506,6095	136,9645	136,9645	136,9645	136,9645	136,9645	136,9645	2739,29	3246
03/05/2004	0	0	0	0	0	0	0	0	0	0	0	0
22/04/2003	395,7975	395,7975	395,7975	4353,7725	395,7975	395,7975	395,7975	395,7975	395,7975	395,7975	7915,95	8612,5
28/12/1996	246,8255	246,8255	246,8255	2715,0805	246,8255	246,8255	246,8255	246,8255	246,8255	246,8255	4936,51	5741,9
13/09/2007	0	0	0	0	0	0	0	0	0	0	0	0
23/01/1996	0	0	0	0	0	0	0	0	0	0	0	0
26/11/2010	689,523	689,523	689,523	7584,753	689,523	689,523	689,523	689,523	689,523	689,523	13790,46	14459,7
30/12/1998	533,8645	533,8645	533,8645	5872,5095	533,8645	533,8645	533,8645	533,8645	533,8645	533,8645	10677,29	11358,4
04/01/1996	661,263	661,263	661,263	7273,893	661,263	661,263	661,263	661,263	661,263	661,263	13225,26	13894,9
08/11/2012	0	81,506	81,506	0	244,518	244,518	244,518	244,518	244,518	244,518	1630,12	6443,9
19/02/2008	625,398	625,398	625,398	6879,378	625,398	625,398	625,398	625,398	625,398	625,398	12507,96	13178,6
28/04/1996	603,9055	603,9055	603,9055	6642,9605	603,9055	603,9055	603,9055	603,9055	603,9055	603,9055	12078,11	12744,6
14/12/1995	164,482	164,482	164,482	1809,302	164,482	164,482	164,482	164,482	164,482	164,482	3289,64	3898,2

26/02/2006	586	586	586	6446	586	586	586	586	586	586	11720	12385,7
23/03/1999	344,7045	344,7045	344,7045	3791,7495	344,7045	344,7045	344,7045	344,7045	344,7045	344,7045	6894,09	7607,6
22/09/2001	0	2930,57	0	0	0	0	0	0	0	0	2930,57	4625,8
28/09/2013	474,944	474,944	474,944	5224,384	474,944	474,944	474,944	474,944	474,944	474,944	9498,88	10179,6
19/04/2003	0	0	0	0	0	0	0	0	0	0	0	0
15/04/2010	0	0	0	0	0	0	0	0	0	0	0	0
02/01/2008	0	0	0	0	0	0	0	0	0	0	0	0