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MAKING COASTAL CITIES FLOOD RESILIENT IN THE ERA OF CLIMATE CHANGE

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ABSTRACT: As a consequence of climate change sea level rise and stronger winds will pose an increasing threat to the society living in coastal zones. Parallel the vulnerability will increase as a result of growing cities along the shore. The paper demonstrates that due to the uncertainty of climate change projections and the enormous investments and long implementation periods of more than 20 years raising the flood defence structures is not the best solution to cope with climate change. The study supports the change to the risk based flood management paradigm of the EU Flood Directive. The consequence is the adaptation to the changing marine hydrology through the development of higher level of resiliency. The paper presents innovative methods to accomplish improved resiliency through a cascading flood compartment system and flood adapted built environment. This leads to new water sensitive urban environments, which are resistant to flooding and reduce the probability of flooding outside the compartments. In a case study at the Elbe Island Wilhelmsburg in Hamburg/Germany the efficiency of this new resilience concept is demonstrated at the climate change projection 2085 and proven as being more economic than another dike rising. As resiliency is standing for a process its measures have the flexibility to be adapted to the dynamics of the system. But it needs time to accomplish the transfer, as changes in the social and institutional cultures will be necessary. The adaptation of the built environment to a water sensitive city with floating homes, new water courses and retrofitting of existing buildings will be a longer process which needs to start now for being efficient in 2030 when predicted sea level rise and more intensive storms will lower the probability of flooding and failure of existing flood defence structures to an unacceptable level.

Key Words: climate change, flood risk management, urban development, flood defence strategy

1. INTRODUCTION

The potential risk to human life, economic assets and the environment is significant in coastal regions. According to the United Nations Environment Program (UNEP) more than 1/3 of today's earth population is living near the coast or at least up to 100 km far from the coastline, and this percentage will increase (DKK, 2002). As for Europe, population living in coastal municipalities has reached 70 million inhabitants, and the total value of economic assets located within 500 meters of the European coastline including beaches, agricultural land and industrial facilities was estimated at €500 to €1.000 billion in 2000 (Wood/Gendebien, 2005). In England and Wales about 3-4 million people and values of more than €200 billion are at risk from coastal flooding according to a technical report on WFD Common Implementation Strategies and to the Environment Agency (EA). The capital value at risk in the Netherlands was estimated at €2000 billion in 1992. In Germany (Schleswig-Holstein) along the coastline about 345 thousand people and assets with a value of €46 billion are at risk.

Most of theses areas are protected through a flood defence system composed of dikes, walls, storm surge barriers and pumping stations. Especially as a reaction of the huge storm in 1953 and 1962 the riparian countries of the North Sea have enforced their structures continuously. But again additional dike raising activities seem to be necessary if the projections of the sea level rise and storm surge increase, due to climate change, are correct. But in difference to the past, where the marine hydrology was rather stable and thus predictable, the forecasts of climate change inhere big uncertainty that adaptability and flexibility in coastal flood management are requested, both hardly to fulfill by raising the dikes. Thus the flood defence strategy has to be extended to a flood risk management according to the EU Flood Directive (EC 2007/60/, 2007). The risk of flooding is regarded here as the product of the intensity and probability of flooding (source), the vulnerability of the flooded area (receptor) and the pathway of the flood (exposure). As a consequence of this paradigm change structural measures, which only act on the pathway of the flood through defence systems are extended by mitigation measures, which target at the receptor and its exposure to floods. Through a set of coordinated resilience measures the damage can be kept at an acceptable level if the flood defence structures will be overtopped. But what is the efficiency of these resiliency measures and can they compensate the climate change effect on the residual risk of the flood prone area behind the dikes *(Hinterland)*?

It is the objective of this paper, to demonstrate the limitations and inadequateness of today's coastal flood defence strategy to cope with the impact of climate change. It will give an overview about the different forms of flood defence applied in Europe and shows their consequences in case of failure. As resiliency is based according to Biemans et al (2006) on the safety chain of the ***A's***: **A**lleviation, **A**voidance, **A**wareness and **A**ssistance, this paper will develop integrative concepts of resiliency and show their effectiveness and efficiency to mitigate floods of the Hinterland. It intents to give guidance in the transfer process of flood resilient coastal cities in the era of climate change.

Fig. 1: Urban structures (walls and stairs case ramps) used as flood defence elements in Dordrecht/NL

2. PRESENT PRACTICE IN COASTAL FLOOD MANAGEMENT IN THE NORTH SEA REGION

The dominating flood management strategy in low lying coastal regions are structural defence measures through which the area behind the structures will be protected from flooding up to an design flood level. Independent from the vulnerability of the *Hinterland* the safety level of the system will be the same for a region. However, each region and country has set its own standards for the design of their structures. In UK for example the Thames region, which is exposed to storm surges, is protected by the Thames Barrier and associated flood defences. The defence system is designed for a flood level with a probability of 1 in 1000 years (Internet 1, 2008.) Similar is the flood defence strategy for the Netherlands, where storm surge barriers are installed at all large rivers and the dikes are raised close to the coastline with 1 in 10.000 protection level. But some areas remain in front of the main dike line, as the district Stadswerven, a 30 ha area in the city of Dordrecht. Here the buildings and urban infrastructure are integrated into the flood defence structure (fig. 1), giving a flood protection level of 1 in 2000.

Different is the flood defence strategy at the main large estuaries of the rivers Elbe and Weser in Germany. They are not protected by a storm surge barrier and thus coastal dikes are continuing along these estuaries up to the end of the tidal zone which gives dike length of more than 130 km on both sides of the estuary Elbe and includes large cities as Hamburg, the second largest one of Germany. Similar to Dordrecht in Hamburg are also urban areas, which are in front of the main dike line. They belonged to a dock area that is at present Germany's largest harbor redevelopment project, called HafenCity (http://www.hafencity.com/) Instead of building a new defence structure in front of this area it was decided to leave it exposed to storm surges. The responsibility of flood protection is given to the owners, who are obliged to make their buildings flood-proof up to a design flood equivalent to the main dike line. The flood protection system of the HafenCity guarantees the escape of the people out of the flooded area by a system of catwalks connected to the higher zones of the "Hinterland" (fig. 2).

Fig. 2: Flood Proofed Buildings and Catwalk in HafenCity/Hamburg

To understand what investments and planning periods are necessary the last dike raising programs of the Thames gate and the city of Hamburg will be presented. Starting building process in 1974, £534 million have been invested to install the Thames Barrier in order to protect London against heavy surges coming from the North Sea. The cost of maintenance will be €10 billion over 40 years. In 2003 a storm surge coming close to the dike crest started a new debate of raising the defence structures again. However a new barrier at the Thames estuary mouth will require investments of £500 million at minimum. More than 30 years are estimated for planning, approval and implementation.

The expenditures spent from 1959 to 2007 in the field of coastal and fluvial flood defence in Hamburg add up to €6 billion. The triggering event for those investments was the flood disaster in 1962, when the Elbe Island Wilhelmsburg in Hamburg was flooded and more than 300 people died as consequence of several dike breeches. The economic losses caused by this event have been about €600 million (Munich Re Group, 2005). In the meantime, the dikes have been raised twice. The first enforcement program took about 14 years and has been very much driven by the experience of the event in 1962. The planning of the second dike rising program started in the 90s and its implementation will probably be finished by 2012 requiring investments of 600 Mio. So 20-odd years will be necessary to rise just 1,0 m defence structure over a length of 109 km.

3. IMPACT OF CLIMATE CHANGE ON THE MARINE HYDROLOGY OF THE NORTH SEA

There is no longer any doubt that the sea level will rise and natural phenomena as storm surges will intensify till the end of this century. According to the Chartered Insurance Institute, 2001 the sea level rise is estimated to be 25-100 cm in 2050 in UK. The European Project PRUDENCE, where a global model has been downscaled by a series of regional models, predicts a moderate increase in high wind speeds in most parts of the North Sea during winter. These simulated winds have been used to run a storm surge model (Woth K., 2004). It indicates storm surge increases by a maximum of 30 cm at the mouth of the river Elbe in the German Bay. Von Storch et al, 2005 superposed this storm impact on the mean sea level rise which he assumed to be 40 cm in maximum according to the A2 scenario of IPCC, 2007 leading to a total increase of + 70 cm (maximum value) at the end of the 21st century. Schuchardt, B., Schirmer ,M. et al. 2005 used within the KRIM project the results of IPCC and downscaled them to the North Sea, giving a maximum the sea level rise up to + 55 cm with an increase of tidal fluctuation by 25 cm. They also predict extreme increases of 200cm through storm-surge. Finally Grossman et al, 2006 predicted storm surges for the German Bay and the Elbe estuary, which are up to 85 cm higher in 2085 (including mean sea level rise).

The high variation of the results gained from different models and scenarios proves the considerable uncertainty, which adheres projections of sea level rise and storm surge increase due to climate change. Thus at present the raising of dikes to compensate the climate change effect cannot be build on a reliable flood design level. In consideration of the immense investments and long implementation periods this uncertainty is unacceptable leading to the fact that a further dike rising cannot be recommended at present.

4. HAZARD RESPONSE ANALYSIS IN CASE OF DIKE OVERTOPPING DUE TO CLIMATE CHANGE

But is it already necessary to adapt our flood defence system to the projected changes of the marine hydrology? A study on the impact of climate change scenarios at the Elbe Island Wilhelmsburg in Hamburg shall help to answer this question? The whole island is protected with a ring dike. Today the design high water stage for this dike system is 7.30 m ASL, which is about 85 cm higher than the highest recorded flood. Due to a free board which varies in dependence on the expected wave height, the crest height of the dikes varies between 7.70 m ASL and 8.35 m ASL. In the first climate change scenario a dike breech at the highest ever-recorded water stage of 5.7 m is assumed. For a total breech length of 100 m about 45 million m³ of floodwater will pass the dikes and inundate the whole island with a maximum water depths up to 5.7 m. This will effect an urban district which produces an annual added value of about €4.200 million (HKHH,2006 demonstrating the high vulnerability and exposure of this part of the city of Hamburg. And it will even rise as the City of Hamburg fosters the policy of the “Growing City”, in which the development of this island is given priority with the project “The Jump over the River Elbe”(http://www.sprung-ueber-die-elbe.de), which will create new homes for 30.000 to 40.000 citizens on this island.

In a second scenario the sea level rise from Grossmann et al, 2006 is applied to adapt today’s design storm surge for the dates 2030 and 2085. The hydraulic calculation indicates already for 2030 an overtopping of the dikes and probably about 4,3 million m³ of water will flood the Hinterland of the island. In 2085 the flood volume goes even up to 15,1 million m³. In this case nearly the whole urban area on the island will be flooded similar to the situation of 1962 (fig. 5). The damage will be not as high as within the first scenario of a dike breech, but is considerable and will have a lasting effect on the socio-economic situation of the island. These two scenarios of hazard analysis demonstrate the high vulnerability of this part of the City and that as a result of the climate change a failure of the existing flood defence system can not be excluded latest by 2030. Especially with consideration of the intended further development of this island, which will last at least 20 years and its investments binding for at least another 30 years the risk level demonstrated in this scenario study is not acceptable.

5. A CONCEPT FOR THE DEVELOPMENT OF A FLOOD RESILIENT CITY

As dike rising has been shown not to be an adequate flood mitigation concept for coping with the rising risk due to climate change, alternatives have to be developed by addressing the resiliency of the Hinterland. There have been in the last years a couple of publications addressing this strategy of flood risk management (Zevenbergen, 2007, Ashle et al 2007, Gallopin 2006) and leading to a theoretical framework for resilient cities demonstrating that resiliency must integrate risk awareness, preparedness, hazard response and recovery to a safety chain. However it is not a fixed set of tangible measures but a process of transfer, which needs continuous reassessment and actions of adjustment to the dynamics of the system (climate change, stakeholder capacity, urban development, knowledge of society) leading to greater effectiveness than the tangible measures of traditional response (Ashley et al, 2007). A summary of this type of mitigation measures is given in tab. 1. They can be categorized in the ***4 A's*** of the safety chain of flood resiliency. According to Ashley et al. 2007 some of these measures can be regarded as *traditional* or *understood*, as they are based on legacy, current understanding of systems and good practice. However most of them need to be denoted *emergent* as they refer to this process of transfer and stand for "new" and thus need capacity building at stakeholders for accepting them and applying them in a most effective way. The technology of flood resistant buildings through dry- and wet-proofing is already well established and latest research studies as Defra, 2007 give good guidance to assess the suitability and cost effectiveness of a variety of these measures. Still private stakeholders (dwellers, owners) and professionals need more capacity (knowledge) in order to apply them effectively. And the potential of innovation and technological improvement is considerable that these measures are classified as emergent.

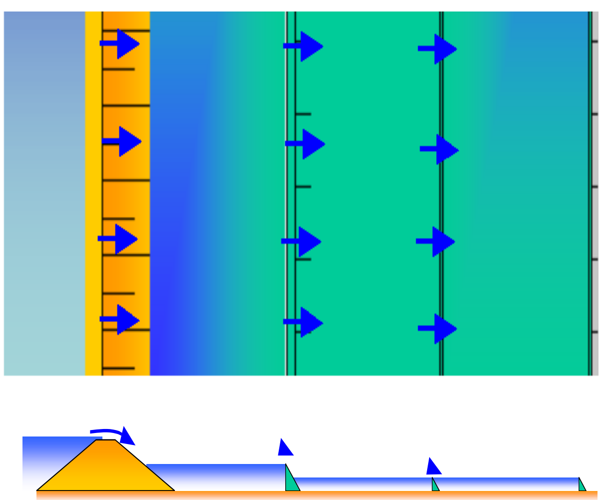

Fig. 3: Principle of a cascading system of flood compartments

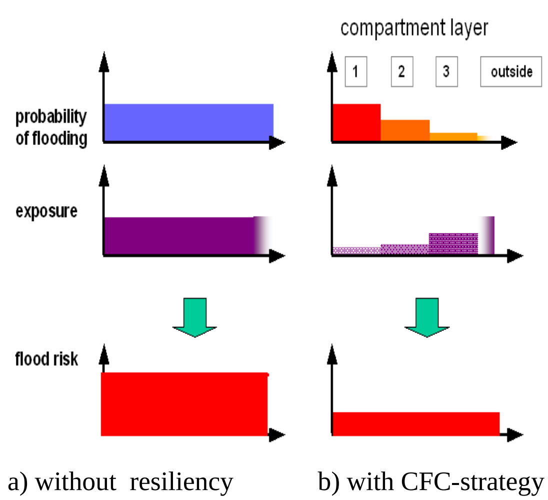

Fig. 4: Risk distribution in the Hinterland in dependence on the resiliency performance

The system of cascading flood compartments (CFC-approach) represents a failure response strategy, which affects both the flooding of the Hinterland and the vulnerability of the objects on the flood plains.

FRM	Type of measure	NS Responses	Effect
Capacity building of human resources A1: Awareness of flood risk	**Information**	Emergent	Stakeholders perform effectively
	Inundation Maps		
	Flood Risk maps		
	Info material (brochures)		
	Education - Communication	Emergent	
	Face-to-face learning		
	Web-based learning		
	Training		
	Collaborative platforms		
Land use control A2: Avoidance of the risk where possible	**Spatial Planning**	Emergent	Adaptation of land use to flood risk
	Flood risk adapted land use		
	Building regulations		
	Building codes		
	Zoning ordinances		
Flood preparedness A3: Alleviation of the effects of the flood	**Flood Resistant buildings**	Emergent	Minimization of exposure
	Wet-proofing		
	Floatable buildings		
	Dry-proofing		
	Cascading flood compartment	Emergent	
	erosion resistant dikes		
	system of inner abatement lines		
Contingency measures A4: Assistance in the event of difficulties	**Financial Preparedness**	Emergent	Support of recovery
	Insurance of residual risk		
	Reserve funds		
	Emergency Response:	Traditional	
	Evacuation and rescue plans		
	Hazard forc. & warning service.		
	Control Emergency Operations	Traditional	
	Providence of emergency response staff	Traditional	
	Emergency infrastructure	Traditional	
	Allocation of temporary containment structures (dismountable flood barriers, sandbags, pumps)		
	Telecommunications network		
	Transportat. & evacuation facilities		
	Recovery: Disaster recovery plans	Emergent	

Tab. 1: Selection of flood resilient measures for flood prone areas behind storm surge defence systems

Inner dikes are built to contain the floodwater in the Hinterland (fig. 3). They are formed to closed lines creating a system of polders termed as flood compartments. Different priorities to flood these compartments are given to cope with the uncertainty of the hazard event. This will lead to a system of cascading compartments. In principle, they are arranged as belts of compartments parallel to the primary dikes establishing a multi-layered buffer zone, which can be regarded as a redundant system of flood containment structures (Fig 3).

Within each compartment different resilience measures have to be applied in order to reach the same risk level as given in Fig. 4. The consequence is that the rate of adaptation to a possible flooding is varying in each compartment in dependence on its position within the compartment cascade. The more compartment layers are between the main dike line and each single compartment the less is the rate of adaptation in it and vice versa. A risk assessment analysis will help to find the right measures. In the end the overall residual risk within the Hinterland will be much lower than without the CFC-approach and it will be everywhere the same no matter being in or outside the compartment cascade. This quality of resiliency is most relevant for the acceptance by the population living in one of these compartments.

The measures of emergency response are regarded as traditional as they are established services for most flood defence systems along the coast. But often they need improvements in technological, operational and staff capacity. Today's standard represents the emergency response system of City of Hamburg. A Central Disaster Office (ZKD) has the authority and responsibility for all actions in case of a disaster. They are supported by emergency units in the district and along the dikes, which coordinate up to 1200 defence forces in the field and supervise their training in regular intervals throughout the year. 8 central transport units are permanently fully equipped and serve 13 material depots in which 220.000 already filled sandbags are permanently available for emergency case. A detailed plan regulates all activities before and during the hazard event. After four alarm levels have been passed, the hazard event will be automatically triggered. Two agencies share the flood forecast responsibilities to increase the reliability and redundancy of the forecast. Predictions are made for 12 hours covering a full tidal cycle. Modern radio-satellite technique and an independent radiotelephone net are used for internal communication.

Each year in September, just before the storm surge season the Hamburg Ministry of Internal Affairs hands out brochures in which all people living in the flood prone areas are informed about the emergency system and their expected behavior in case of a hazard event. The document is delivered to more than 100.000 people in 8 different languages to insure that everybody with different cultural background is able to understand it. A download version is also permanently available (www.katastrophenschutz.hamburg.de). The evacuation plan gives preference to a vertical evacuation within the buildings if they have more than two floors. In other cases, they have to gather at depicted evacuation areas and will be transported by busses, provided by the emergency services to a safe place.

6. AN EXAMPLE OF APPLICATION

At the Elbe Island Wilhelmsburg the resiliency approach has been applied in order to prove its potential to adapt coastal cities to the impact of climate change. Key element of the resiliency concept is the CFC-method. As a hazard control system the height of the inner dikes should be kept low with a maximum of 2,0 m within the first compartment. The dikes of the outer compartment layers should not exceed a height of 1,0 m. In this case, the hydrodynamic load on the inner dike structures is so low that no additional geotechnical measures are necessary to ensure their stability. In addition to earth-fill dams non-permanent dikes are needed to close temporary traffic lines, open places and other areas, which need to be kept clear. In the last years, the technique of dismountable walls has improved so much that nowadays a large number of products are available. They range from very reliable flood barriers, which connect their pillars with permanent foundation structures (Fig. 5a), and simple emergency type systems (Fig. 5b), which are deployed on the surface without any connection to the underground (BWK,2005).

a) movable wall with permanent anchor plates

b) emergency type flood wall without permanent structures

Fig. 5: Dismountable walls for flood containment

Thus they can be applied very flexible and their deployment can be adapted to the needs in case of flooding. In addition the propagation of flood through drainage pipes, sewers and watercourses needs to be prevented through temporary gates. Fig. 7 shows a possible solution for a cascading compartment system for the Elbe island Wilhelmsburg. The different colors indicate the different layers of the cascade. The maximum volume to be retained in this whole system reaches 15,1 million m³ with an average water depth of 1.80 m in the compartments. Consequently the system is able to contain the overtopping floodwater predicted for the climate change scenario 2085. The most developed urban area indicated by the dashed line can be preserved from flooding indicating a substantial efficiency of flood containment.

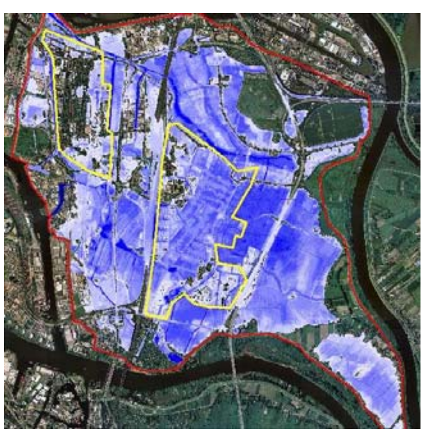

Fig. 6: Predicted flooding of Wilhelmsburg for climate change scenario 2085

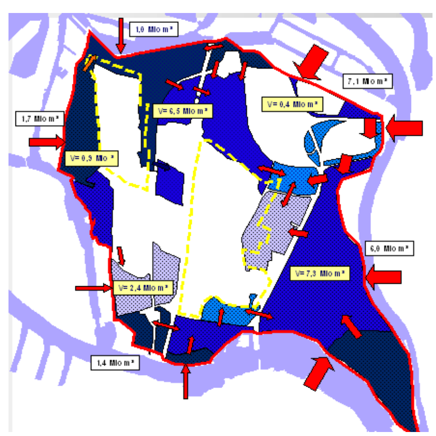

Fig. 7: Possible Cascading compartment system for the Hinterland of Wilhelmsburg

The efficiency of the Cascading Flood Compartment depends strongly on the stability of the main dike in case of overtopping. In general, dikes are not designed for this hydrodynamic load. Thus, part of the resiliency concept must be the enforcement of the dike surface. Various techniques are available (Queißer, 2006) and will not be further regarded here.

Finally the built environment needs to be adapted to the probability of flooding. Together with city planers these adaptation measures in the first compartments behind the dikes have been integrated in an innovative urban developed plan in which floating homes, homes on piles and amphibian homes are arranged in an attractive way creating new urban water fronts with amphibious settlements (fig. 8).

The costs for the structural measures at the main dike line and the inner dikes have been determined to €90 million. This includes the enforcement of the dike surface with the new composite, the elastomeric revetment (Pasche/von Lieberman, 2006), the restoration of the existing sleeping dikes, the purchase of dismountable walls and the installation of gates in the watercourses and drainage system. Alternatively the rising of dikes by 80 cm (necessary to compensate sea level rise due to climate change for the time horizon 2085) will cost about €140 million proofing a higher efficiency of the cascading compartment system than the traditional mitigation measure of dike rising.

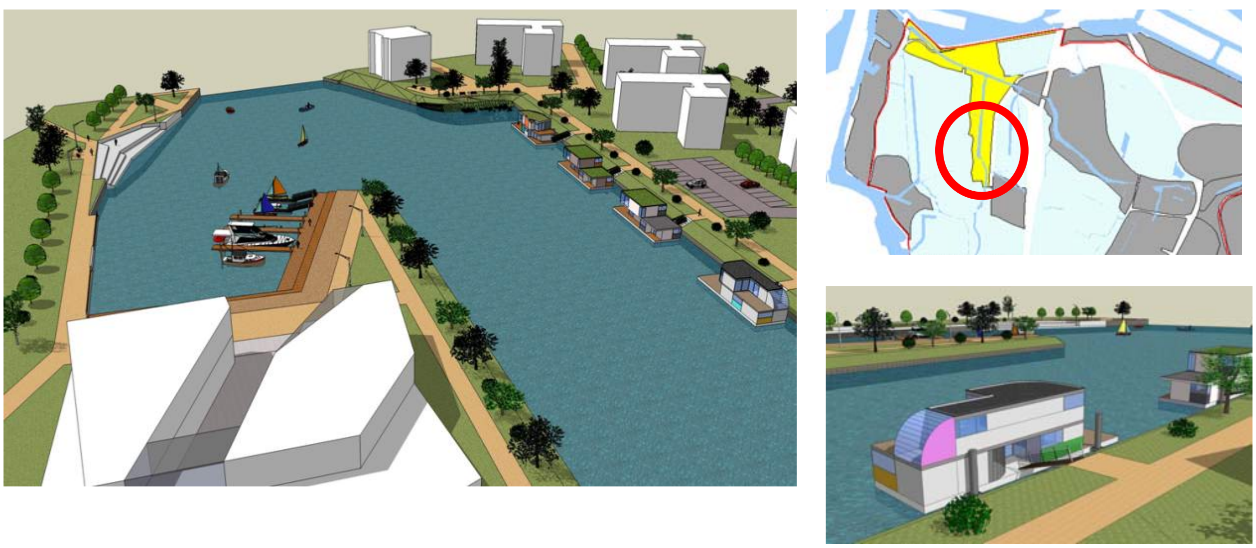

Fig. 8: Visualization of the adaptation plan for the compartment Aßmann Canal on the island Wilhelmsburg

7. CONCLUSIONS

It could be shown that climate change requires a new flood risk policy for the area behind the dikes. The concept of flood resiliency has been found to be an efficient and effective strategy to cope with this increased residual flood risk. It could be shown by a case study at the Elbe Island Wilhelmsburg in Hamburg that this concept can retain under certain conditions all flood water within a cascading compartment system that might overtop the main dikes lines as a consequence of climate change. As a long-term strategy of flood risk management it will be carried out stepwise giving city planners enough time to adapt the built environment to the increased risk of flooding within the compartments. This clears the way for implementing new forms of living at water by creating multi-functional spaces in which the infrastructure and all buildings are resistant to flooding. Compared with the expensive method of dike rising, the new concept has the same efficiency to reduce flood risk. In the presented case study the costs of investment to adapt the first dike lines and to build the inner dikes have been less than raising the dikes by 80 cm. Additionally the necessary adaptation measures at the buildings will keep the risk awareness alive within the population. The greatest advantage is its flexibility to gradually adapt to changes in the climate change process. Thus, flood resiliency with adaptive response to the built environment can be considered as an economical and sustainable concept in managing the increasing risk of climate change in urban environments prone to flooding by storm surges.

8. ACKNOWLEDGEMENT

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