Assessment of Clusters
D5.7

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1. Introduction

1.1. What is a cluster of innovations?

Within BRIGAID project, clusters of innovations mean combinations of innovations scoped to reduce risk in a given area. Innovations include technological and non-technological solutions, i.e. hard defences such as special dikes or mobile barriers, IT solutions such as early warning systems or decision support tools, economic solutions such as insurance plans or land use reallocations, eco- compatible solutions such as green roofs. A show-case of all the innovations screened in BRIGAID is reported in the climateinnovationwindow.eu site.

The generation of clusters of innovations, as in the economic literature, can be based on similarity or on the value-chain approach: clusters may include different innovations addressing the same type of hazard, or different innovations addressing different hazards. As an example, the protection level of an urban area subjected to river floods can be increased by means of embankment reinforcements, creation of water storages, use of flood mobile barriers, insurance plans, early warning systems related to the riverine water level. However, the increase of the protection level can be achieved also by addressing the extreme climate conditions (i.e. rainfalls) that usually combine with and amplify the effects of the riverine flood, for instance by setting-up green roofs that reduce the effects of extreme rainfalls or early warning systems based on the rainfall precipitation rate.

Relevance of a cluster-based evaluation is based on the fact that the impact of a cluster may be more than the combined impacts of individual innovations (synergy effect). In some cases, however, the combination of innovations may have less impact than the sum of the impacts of the individual innovations (reduced impact effect).

1.2. How to assess a cluster of innovations?

The selection of the optimal cluster of innovations in a given area is based on the effectiveness of the cluster in reducing risk, where risk assessment includes the assessment of social, environmental and economic vulnerability assessment. The selection and the combination of the innovations in the cluster should consider the specific conditions at the site, including also the respect of existing laws and regulations, the social perception of the existing risk management and the potential acceptance of the new solutions.

The core of the methodology consists of the Source-Pathway-Receptor-Consequence method, which has been already widely adopted worldwide in flood risk assessment and in other (also multi-hazard) EC funded projects (a.o ClimSave, THESEUS, Risc-Kit). The method allows to get a system-view of the area under exam, highlighting the strong and weak points of the existing management. The SPRC promotes a participatory approach to risk assessment, where managers, communities, public authorities and scientists collaborate to assess the risk level and the areas where interventions should be prioritised.

Managers and scientists should then perform detailed modelling of the hydraulic conditions, and quantify environmental, social and economic effects to assess vulnerability and risk and provide an objective basis for the selection of the interventions. The quantification of risk can be performed by applying GIS-based Decision Support Systems (DSS) tools, through a scenario analysis that considers different climate, social, environmental and economic conditions at the site. Risk assessment is then ranked in different levels, based on threshold values that are site specific.

Based on the SPRC preliminary analysis and on the results of the hazard modelling, one or more adaptation solutions are proposed by experts and consultants, who also can suggest to group them in different clusters. The assessment of risk in presence of different clusters is then performed by new detailed hazard simulations and/or new applications of the DSS tools. The optimal cluster should be selected by comparing the results, i.e. the risk maps, obtained by the DSS tools.

In parallel to the assessment of risk, managers may require to have an insight of the role of different clusters in terms of economic development of a given site. The sectoral impact of each cluster can be estimated then by combining the sectoral impact of each innovation included in the cluster. The sectoral impact is qualitatively assessed by means of score tables derived from the application of the TIF methodology delivered in D5.2 and here recalled for convenience. The sectoral impact of the clusters may also contribute to the definition of the optimal cluster.

Fig. 1.1. shows the complementary methodologies adopted for the clusters' assessment.

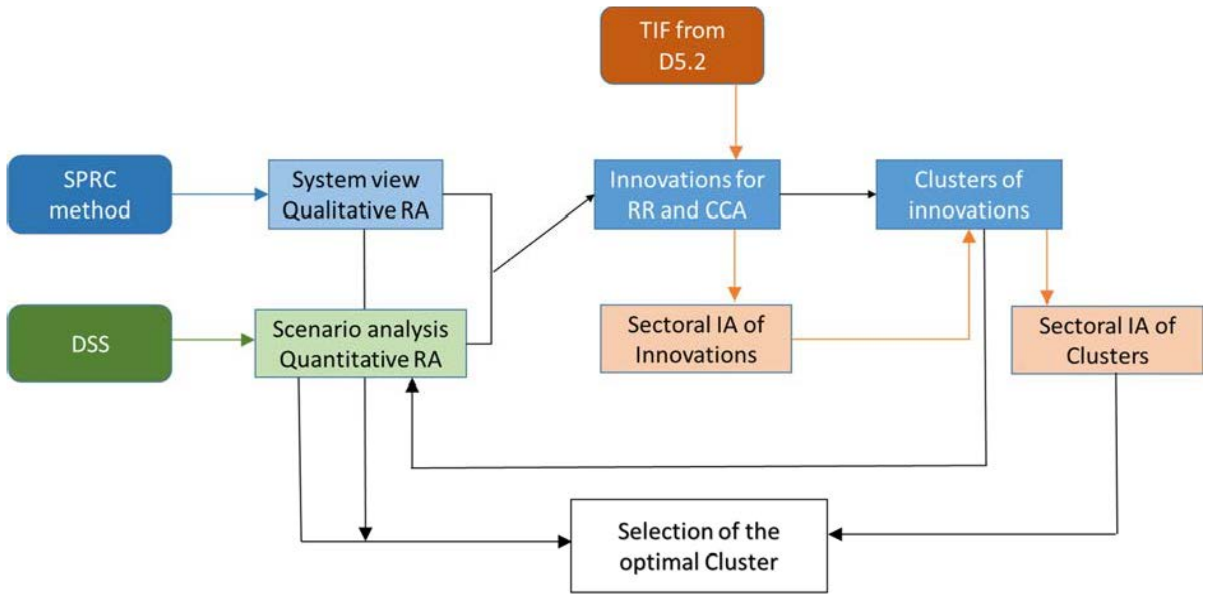

Fig. 1.1 Scheme of the complementary methods for the assessment of clusters: the qualitative risk assessment through the SPRC method to obtain the overview of the site, the quantitative risk assessment through the DSS tools, to perform the analysis of different risk scenarios depending on the management solutions, and the TIF tool to derive the sectoral impact assessment depending on the selected cluster of solutions. RR=risk reduction, RA=risk assessment, IA=impact assessment, CCA=climate change adaptation.

1.3. The deliverable contents

The aim of this document is to provide a framework for the analysis of clusters of innovations in terms of risk reduction and of their impacts on the society, on the economy and on the environment. The target users are consultants, decision makers, managers and local/regional/national authorities who have to plan adaptation measures to face floods, droughts, extreme weather taking into account climate change effects.

The document is divided into two main parts: the description of the methodological framework (Sections 2-6) and the applications in three case studies (Sections 7-9).

Section 2 describes the SPRC method. Section 3 is dedicated to the hydraulic, social and economic vulnerability assessment. The formulation of the integrated risk assessment based on the previous vulnerability assessments is addressed in Section 4.

Section 5 consists of the specific assessment of sectoral impacts, based on the delivered TIF in D5.2. The TIF is recalled for the assessment of the sectoral impact of each innovation composing the cluster, while specific criteria should be formulated to assess the sectoral impact of a cluster as a whole. It is basically suggested to use a linear combination of the sectoral impact of each innovation.

Decision support system tools have to be adopted to quantitatively assessment of the social, economic and environmental impacts of clusters of innovations. Section 6 gives an overview of existing decision support system tools for risk assessment and their critical issues. Specific attention is given to the DSS tool updated within BRIGAID to assess and manage risk under coastal and river flood and extreme rainfalls.

Sections 7, 8 and 9 show three example applications, in Belgium, in Italy and in Germany respectively. The applications include risk assessment by using the SPRC method and/or DSS, identification of adaptation solutions and of clusters of adaptations and related impacts.

Conclusions are finally drawn in Section 10.

2. The methodological framework

Risk assessment/risk management is one of the most important environmental policy developments of the past few decades; modern societies recognize that their activities both depend upon, and have consequences for, the environment and risk assessments can be used as a method for determining how and where to intervene for maximum benefit. To be effective, risk mitigation/management strategies therefore need to be developed with a multidisciplinary, long term (many decades) perspective to include factors such as climate change, urban development pressures, and habitat implications. This is challenging as this beyond typical financial, political and management decision timescales.

2.1. Nomenclature: Vulnerability, risk and resilience

Here we lay out a common set of definitions for key terms to facilitate their use and discussion through the document. This draws on earlier work such as the FLOODSite FP5 project (http://www.floodsite.net/) and on the THESEUS FP7 project (http://www.theseusproject.eu/).

The notion of *vulnerability* is the degree to which a system is susceptible to, and unable to cope with, adverse effects of the change agent, in this case floods. Flood vulnerability is a function of the character and magnitude of flooding and variation to which a system is exposed, the sensitivity and adaptive capacity of that system. A range of flood vulnerability indices have been developed to operationalize this concept (e.g., Balica et al., 2009). Vulnerability assessment has been conducted in a range of contexts with a view to understand and reduce this vulnerability, including to floods.

The notion of *risk* is a combination of probability and consequences, often expressed as an annual mean damage (or consequence), see Penning-Rowsell et al. (2013). Hence, risk can be expressed as a number, and the units of consequences may be related to flood victims and flood damage to homes, businesses and nature.

The notion of *resilience* is related to vulnerability and describes the systemic ability to experience the hazard with minimum damage and rapid recovery. It can be seen as a design approach that reduces the damage due to the hazard. For example, it could involve constructing a building in such a way that although floodwater may enter the building, its impact is minimized and recovery is rapid. Resilience operates at multiple scales from individual buildings, to communities, towns and cities. In this more aggregate sense, resilience can be provided by multiple measures that reduce damage and promote recovery, and hybrid approaches can be taken and need to be considered. This might include combinations of warnings, evacuation and emergency plans, land use planning, traditional hard and soft defences, building construction approaches, provision of insurance, etc.

2.2. The Source-Pathway-Receptor-Consequence model

2.2.1. Overview

In any integrated, multidisciplinary analysis it is essential to establish a common view of the issue being investigated particularly where a balanced and decision relevant assessment is required. In this way neglect or over-emphasis of aspects or issues is avoided. In order to develop such a view, a clear methodological approach, conceptual model and analytical framework are essential (Robinson, 2008b).

Any assessment should therefore start with establishing a comprehensive understanding of the current system about risk management. This allows a range of scientific disciplines to identify how and where their research fits within the 'big picture'. The conceptual model should be selected based on its suitability to support scientific investigation into the issue (amongst others: floods, droughts) that has been identified. It can also be useful as an explanatory tool with stakeholders in preliminary analysis and interviews (Robinson, 2008a). To illustrate the described principles, the text focuses on flood related risks to provide clear examples. Naturally, the approach is applicable to other vulnerabilities and impacts as well, such as droughts and extreme weather.

Essentially the conceptual model

- should be selected/designed in response to the specific aim of risk management
- should be accepted by all scientific disciplines with input into the risk assessment to ensure integration and transferability of inputs/outputs
- illustrates where/how management options are influential in the system
- is understandable by stakeholders to enable clear communication of management options
- works across different scales and levels of detail
- should require realistic resources (time, expertise, data) for operational use.

Ideally, various stakeholders can also reuse such conceptual models as part of a larger decision system. In such situations, the conceptual models are not only used solely for the risk or vulnerability assessment, but are embedded into the operational framework of the stakeholders.

A comprehensive way of visualising the process of flood risk estimation and all its components is the **Source – Pathway – Receptor –Consequence** (SPRC) conceptual model (Gouldby and Samuels, 2005). The model was first used in the environmental sciences to describe the propagation of a pollutant from a source, through a conducting pathway to a potential receptor (Holdgate, 1979). It was first adopted in coastal flooding in the UK by the Foresight: Future Flooding report (Evans et al., 2004). It has subsequently been used in several coastal flood risk studies (North Carolina Division of Emergency Management, 2009; FLOODsite Consortium, 2009; Burzel et al., 2010; Zanuttigh et al., 2014a) and is increasingly underpinning wider flood risk management. Based on conventional approaches to flood risk estimation, the SPRC model visualises flood risk estimation as a linear process involving a 'Source' of flooding, flood 'Pathways' and affected 'Receptors' associated with different 'Consequences' (Figure 2.1, Tab. 2.1).

The SPRC model recognizes the principle that the component parts of a system can best be understood in the context of relationships with each other (and with other systems), rather than in isolation. Consequently, it considers flood management within an overall system, highlighting where external drivers can be influential, and, importantly, where system vulnerability can be reduced or exacerbated. Fundamental to the approach is the defining of relationships between system components at a relevant scale to provide understanding and insight into the flood system under investigation. At its simplest, the concept is a linear representation of a flood event from the Source (of the flood waters) through the Pathway (route of the flood waters) to the Receptors (where the water culminates) and calculation of the effect of flood water on the Receptors (Consequences), see Table 2.1.

Table 2.1.Definitions and components of the SPRC model, applied to a flood risk assessment.

CATEGORY	DEFINITION	COMPONENTS
SOURCE	Where the flood waters originate	Sea—waves, surges, tides, mean sea level River—volume/flow Extreme precipitation (urban) —rainfall excess, conduit surcharging
PATHWAY	The route for the Source to reach the Receptor	Coastal floods - Various land uses seaward of any Receptor, including existing coastal management (e.g. built defenses, nourishment) and habitats. River – Natural or artificial flow paths, dikes and levees, etc. Urban environment – Surface flow, flows through the underground system
RECEPTOR	Land use and buildings/structures in the flood plain	Urban areas, infrastructure, farmland, habitats, etc.
CONSEQUENCE	Impact of flooding on the Receptor	Direct /indirect and tangible/intangible consequences for each Receptor (via various valuation methods)

The SPRC model presents a snapshot of the floodplain state (or within a context of urban flooding, local depressions in (semi-) sealed surfaces). This is, in turn, driven by boundary conditions operating at a range of spatial and time-scales, such as water levels (e.g. off-shore levels, waves, conduit levels, etc.), climate change effects, and human influences such as coastal zone or urban management decisions and actions. Therefore, the SPRC model is usually nested within broader approaches, such as the **Driver – Pressure – State – Impact – Response** (DPSIR) framework that conceptualises the influence of pressures and drivers external to the floodplain (e.g., Kristensen, 2004, Gregory et al., 2013, Lee, 2013, Zhang and Xue, 2013). The DPSIR assumes cause-effect relationships between interacting components of social, economic and environmental systems (Carr et al., 2007). By identifying where external factors influence the flood system, the DPSIR framework helps identification of where management interventions (acting as Drivers) influence the Consequences of a flood event. It also illustrates the circular nature of flood management, with an intervention affecting consequences which will influence society's response which, in turn, will determine future management interventions.

Fig 2.2 illustrates that the SPRC model can be divided into two components based on its nesting within the DPSIR. This figures illustrates this division for a flood analysis: a floodplain state description (SPR) and a description of the consequences to changes in this state (C). Flood risk assessments typically follow this division, using the SPR model to assess flood probabilities of elements within the floodplain and separate economic models to evaluate flood consequences. However, other vulnerabilities can also be assessed likewise.

The ‘Source’ component of the SPR model usually describes the sources of the event (e.g. flooding), such as waves, water levels or infiltration excess (direct surface runoff flows). The ‘Pathway’ component generally refers to all floodplain elements that influence flood propagation within the floodplain. The ‘Receptor’ component of the model is commonly used to describe the economic cost of a flood event estimated using existing observations and depth-damage relationships (Penning- Rowsell et al., 2013).

It is important to remember here that there may be several Pathways to the same Receptor and it is useful to identify these in order to fully appreciate potential risk or damages. For example, a house sited in a flood plain directly behind a dyke may appear to be adequately protected, but if a neighboring defense is of a lesser standard (a ‘weak link’) it may fail and the house still flood.

Building on the underlying systems approach of the model, mapping of the Receptors and their Pathways encourages the exploration of the wider environmental setting, physical functioning of the site and spatial variability within the system (Thorne et al., 2007). In this way, the SPRC model offers the opportunity to develop a more comprehensive representation of the flood system, acknowledging the complex network nature of the system (Narayan et al., 2012; 2014). The mapping also shows that individual elements may be classified as either a Receptor or Pathway depending on the analysis being undertaken and its relative position within the flood plain. It is evident that mapping Sources, Pathways and Receptors can be a challenging task, and system components cannot be treated individually in all cases. For instance, in an urban flood context, floods can originate in a part of the city that faces only mediocre rainfall intensities, but receives water from an upstream part of the sewer system through underground connections that is impacted more significantly by rainfall events. The dynamics in such underground (surcharged) sewer system are often highly complex and can lead to various outcomes. Therefore, the underground sewer system often has to be treated as a whole when defining Pathways.

Though the conventional conceptual model visualizes a linear system of Source, Pathway and Receptor, in practice, a typical risk assessment uses a range of diverse models and inputs to describe and analyse the state of the investigated system. Furthermore, the types and nature of models and inputs may differ depending on the scale and extent of detail of a particular assessment, the data and model availability, and relevant drivers. As an example, the key drivers affecting a coastal floodplain are: (1) climate change which can affect Sources such as sea level, storm frequency and intensity and rainfall patterns (increasing or decreasing the extreme water levels during a flood event)and in some cases a non-climate factor: subsidence); (2) sediment supply, which influences Pathways and ecological receptors, coastal geomorphology and ecosystems; and (3) socio-economic change, which can alter the type and extent of human receptors within the flood plain (e.g. Thorne et al., 2007). Key drivers responsible for extreme precipitation induced floods are to some extent similar, and include (1) meteorological conditions and climate change effects, such as rainfall intensities, durations and frequency; (2) land use characteristics, of which the infiltration rate is arguably most important (especially relevant in highly urbanized areas with sealed surface rates); (3) topography characteristics such as gradients; (4) the state and capacity of both subsurface and terrain sewer infrastructure, such as conduits, buffers and the emerging source control measures (e.g. infiltration basins, private rain water tanks); and (5) relevant boundary characteristics that impact the sewer system, such as riverine water levels that can impede spilling from overflow structures.

Once the relevant drivers have been determined in any flood plain, the relative importance of each driver can be evaluated based on expert judgment to assess potential impacts on future flood risk. This is based on a score for each driver impact according to its influence on flood risk (altering probability or consequences) under the given driver scenario and time slice (Evans et al., 2004; Narayan et al., 2014).

Fig 2.3 illustrates the possible range and diversity across scales and levels of detail of typical flood risk assessments – all of which use the linear SPR model described above to conceptualise the coastal floodplain. An applied example of the SPR model for urban floods (due to extreme precipitation) can be found in Section 7.

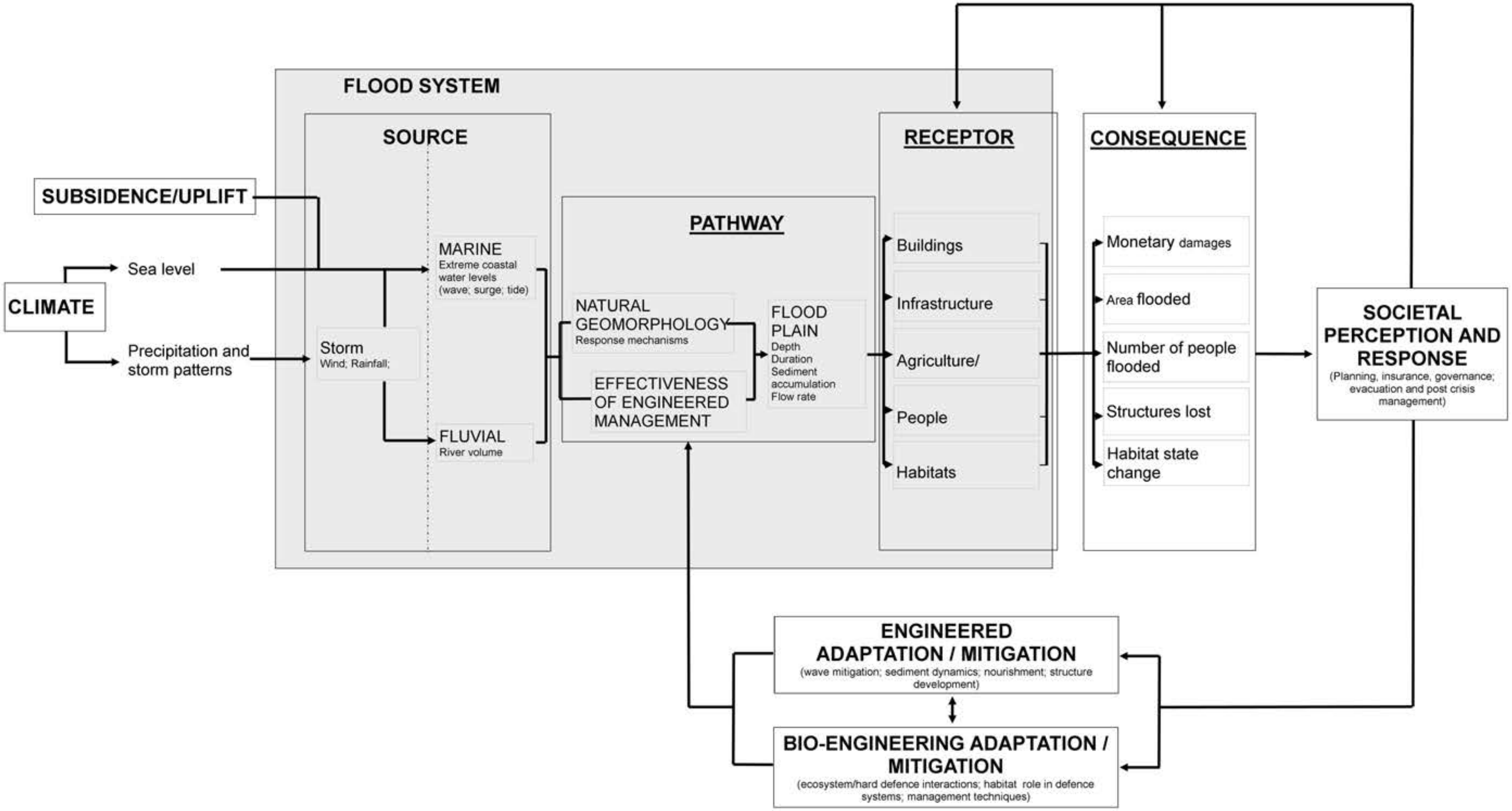

Figure 2.1 SPRC diagram showing where external Drivers can mitigate the Consequences of a flood event at the local scale in case of coastal and river floods. From Narayan et al. (2014).

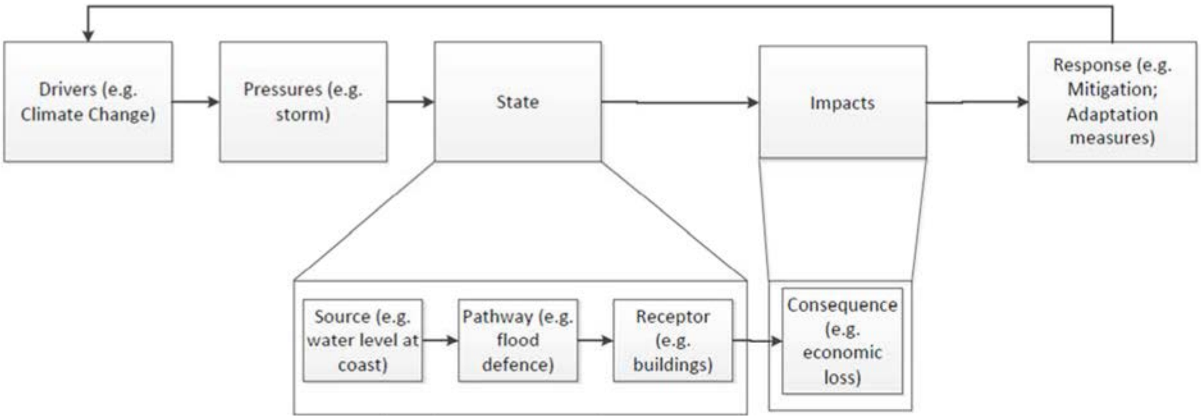

Figure 2.2. Nesting of the SPR-C model within the DSPIR framework. Example for coastal floods from Narayan et al. (2014).

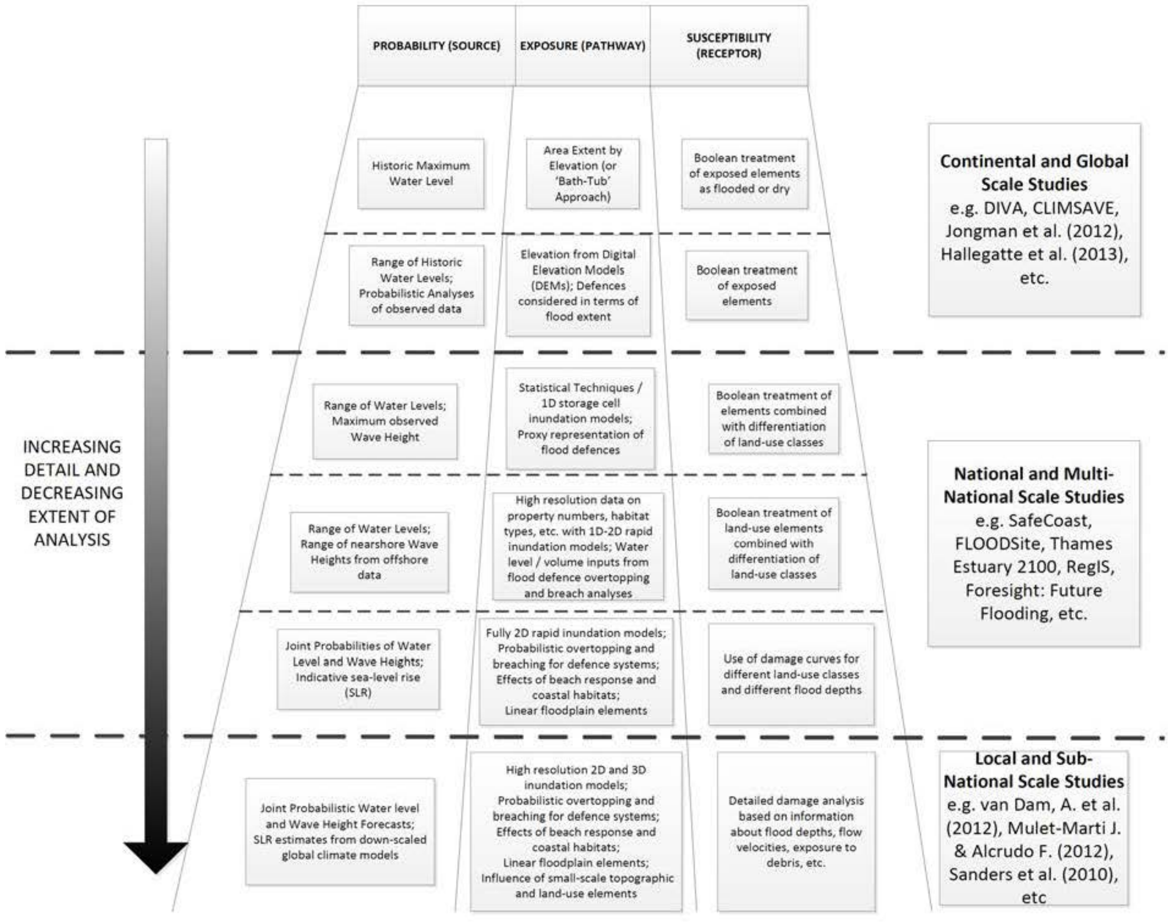

Figure 2.3 Types of flood risk studies in terms of the SPR model applied to coastal floods. From Narayan et al. (2014).

2.2.2. Defining the Sources

Best practice is to classify sources into different groups based on similar characteristics. These characteristics differ and depend on the hazards and risks that are investigated. A first example is given for a risk assessment of a coastal floodplain. Herein, sources are essentially classified into three groups according to flood duration: short-term (storm surge, wind waves, tides, run off due to downpours), seasonal (river high/low waters) and long-term processes (sea-level rise, local land surface vertical movement). Historical analysis (long and homogeneous time series of water levels or discharges) can be used to establish existing return periods for different extreme events. Extreme water levels from the sea are caused by a combination of several factors: (1) high astronomical tides due to the sun and the moon, (2) storm surges due to high winds and low atmospheric pressure, and (3) waves caused by local high winds or far travelled swell from oceanic fetches. Hence, tropical or extra-tropical storms can both produce extreme sea levels and cause flooding. Changes in any of these factors may alter the characteristics of a flood event. Historically, the long-term change in mean sea level has contributed to changing extreme sea levels, and globally this is increasing the frequency of high sea levels (Menéndez and Woodworth, 2010). Thus, it is important to include these various sources in the SPRC analysis as illustrated above.

For extreme precipitation induced floods, the highest rainfall intensities are the dominant source of floods, although antecedent conditions (i.e. rainfall in the hours and days prior to the most extreme intensities) and adjacent riverine water levels can also play a role. Antecedent rainfall events can fill up the sewer system partly or entirely, leading to reduced storage capacities. Water levels in nearby rivers can impede overflow spilling, and thus result in lower emptying capacities of the sewer system. All these processes are thus predominantly determined by short-term effects.

For riverine floods, both short-term and long-term processes play a role. High intensity rainfall events can lead to significant surface runoff flows (through infiltration excess), and act on the short- term. The infiltration excess itself is, however, also determined by processes that act over longer time spans, and depend on soil moisture conditions and ground water levels (and are thus, to some extent, also seasonally dependent). Riverine floods can also be driven by groundwater fluxes (base flows). Such systems are

2.2.3. Defining Pathways

Pathways are the routes and processes which are active during an event and run from a source to a receptor. Thus, without a pathway, an event cannot have any consequences. On many occasions, an individual pathway may have multiple receptors and individual receptors, thus multiple pathways. Pathways can include the components of the system (identified in the SPR mapping) that include with different defence failure mechanisms, such as overtopping versus breaching in case of floods, as they can lead to different receptors. Pathways can be also receptors: as an example, dikes affect the flood extent and they can stop flooding, fail or be degraded by the intensity of the Sources and act as a pathway. Similarly, coastal habitats, such as biogenic reefs and dunes, may be regarded as pathways as far as they offer some protection in terms of wave energy reduction or increased beach stability, and of course they are also receptors whose survival or modification depends on the Sources.

2.2.4. Defining Receptors

Receptors are usually defined based on the intrinsic value of the land affected by the hazard. In case of coastal floods, receptors can be defined by either what can be found on, the use of, or the value of the land which has the potential to flood. They are mainly, although not exclusively, found above the lowest water level for the site and can form part of either the human or natural system. It is vital to ensure that cross-sectoral and multidisciplinary receptors are included in the SPRC assessment. The initial information for the identification of potential Receptors can be represented through the land use, supplemented with more detailed habitat/environmental mapping and additional socio- economic information. An example of a broad-scale receptor classification is shown in Table 2.2. Consequences may be specific to the identified Receptor, e.g. for habitats - area lost, species change due to flood duration, or more general, e.g. for buildings/infrastructure - damages based on depth-damage curves, number of people flooded, number of houses flooded, etc.

Table 2.2 Example broad-scale classification of Receptors.

System	Receptor classification	Land use examples
Human	Buildings (residential)	Houses
	Buildings (non-residential)	Factories, storage facilities
	Infrastructure	Roads, hospitals, airport
	Agriculture	Arable land, grazing
	Mariculture	Mussel farming, fish farms, oyster beds
Natural	Natural element	Beach, spit, saltmarsh, mud flat
	Habitat	Dune, saltmarsh, kelp beds

2.2.5. Defining Consequences

The development of the SPR mapping encourages the identification of direct Consequences of an event related to the nature of the Receptor/s. To refer to the example of a coastal floodplain risk assessment, the mapping of the consequences of a flood event is usually done after quantifying the flood probability of the different parts of the floodplain, as described in Fig 2.2. The process – and probability – of flooding is driven by the physical state of the flood pathways. However, the consequence of a flood event is felt only by an element that functions as a receptor – even though this element may also function as a flood pathway. For instance, the flooding of a beach, apart from acting as a flood pathway, may result in tangible economic losses to the local tourist industry. Some floodplain elements may function primarily as receptors. For instance, critical infrastructure such as hospital buildings are elements for which the consequence of flooding is of immediate concern.

Consideration of the pathway effect of the building will depend on the detail and sophistication of the data and numerical models used for later analysis (see Fig 2.3). On the other hand, the flooding of infrastructure such as a pumping station will be of relevance both for flood propagation (as a pathway), as well as in terms of the direct economic costs of replacing damaged parts (receptor - consequence). A first overview of typical classes of receptors and their associated consequences for a flood event is given in Tab. 2.3. Once the physical characteristics of a flood event (i.e. flood extents, depths, probabilities) are mapped onto to the floodplain system description these can be combined with information on depth-damage curves and cost estimates for specific receptor types (Zanuttigh et al., 2014) to obtain the consequences of a flood event.

Table 2.3. Example of direct Consequences of flooding associated to Receptors.

Receptor	Example Direct Consequences
ALL	Area permanently flooded (land loss)
	Area temporarily flooded/displaced
(Critical) infrastructure	Physical flood damage
Buildings - residential	People temporarily flooded
	Building/content damage
Building – commercial/industrial	Area temporarily flooded
	Building/content damage
Habitat	Habitat state change
Agriculture	Flood damage to crops
	Change of agricultural practices (e.g. crops to pastoral)
Recreation	Flood damage to recreational facilities

2.2.6. Assessment of existing risk management

Analysis of present conditions, including existing defenses, policies, regulations and governance arrangements is an essential part of a risk assessment process (Penning-Rowsell et al., 2014). It provides the background against which any future management options will be taken and identifies those responsible for implementing such a strategy. Including those involved in policy development or decision-making also offers the opportunity to more fully integrate science into policy (De Vries et al., 2011).

Surveys can be used to characterise the risk governance in coastal flood plains based on five 'building blocks':

- the administrative organization of the system management (a system can virtually represent any natural or anthropogenic combination of processes, such as an urban area, agricultural lands, forests, coastal floodplains, etc.);
- the legal system;
- the financing system;
- the economy of intervention measures;

- the participation level of stakeholders.

Many sites have complex institutional structures for event and disaster management with responsibilities found at local, regional and national, as well as international levels. This information has to be collected in a systematic manner from local policy makers, managerial authorities and administrators. Presenting the conceptual model of the system is often a beneficial aid to these discussions. Experience within the THESEUS project (focusing on coastal floods) showed that institutional culture, traditions and capabilities are of great significance to (innovation in) risk management, and could be of at least the same importance as technical issues on risk assessment and reduction choices (Zanuttigh et al., 2014a).

Existing management structures, policies and defense design often reflect the relative importance and current understanding of disaster events and its consequences (Aven and Renn, 2010). Legal obligations, frequency of occurrence, economic value of the protected area, and previous experience with previous events are all influential.

Stakeholder interviews are probably the most appropriate methods to identify the current governance structures (De Vries et al., 2011). Such interviews could be supported with the help of a structured or semi-structured questionnaire, which should be sent in advance to the interviewees. An additional benefit of undertaking group interviews is that they can bring together, sometimes for the first time, stakeholders with management responsibilities in a risk prone zone. Possible feedback to participants of the resulting report is essential, particularly where there may be ethical issues or wider implications in the accumulation of the information.

The experience in the THESEUS study sites across Europe (Penning-Rowsell et al., 2014) showed that the institutional arrangements in many coastal situations are complicated, almost invariably multi- level, and potentially confusing for the public. Central government is almost always involved, because of the large investment required for engineering mitigation works to reduce risks from flooding and their involvement in spatial planning legislation at the coast. It is recognized that this investment and powers cannot simply come from the communities at risk, but need support from the general taxpayer and national or regional level legislators. Further, in most of the sites there is a provision for sustainable coastal zone management, within the existing legislation. However, not all laws and regulations are properly enforced.

2.2.7. Damage

Flood damage is defined as all the varieties of harm provoked by flooding. It includes all detrimental effects on people, their health and properties, on public and private infrastructure, ecological systems, cultural heritage and economic activities (Messner and Meyer, 2006). Understanding the nature of damages is important in assessing risks. For most people, the benefits of flood risk management is the avoided flood damage on property and economic activity as a result of schemes to reduce either the frequency or impact of flooding (Penning-Rowsell et al., 2013). However, the consequences of flooding for people are more complex. Following Smith and Ward (1998), we can classify flood losses into direct and indirect losses. Direct losses are caused by the physical contact of the flood water with humans, property or other objects and the location of the flood will indirectly affect networks and social activities, causing indirect losses (e.g. disruptions of traffic, trade and public services). Further, we can distinguish between immediate or long-term consequences and tangible or intangible consequences. Such consequences depend on the land uses found within the flood plain. Immediate impacts of flooding can include loss of human life, damage to property and infrastructure, and destruction of crops and livestock. Examples of long-term impacts include the interruption to communication networks and critical infrastructure (such as power plants, roads, hospitals, etc.) that can have significant impacts on social and economic activities. More difficult to assess are the intangible impacts – for example the psychological effects of loss of life, displacement and property damage can be long lasting (see Table 2.5). Methods of assessing these impacts are equally varied, ranging from quantitative (financial or economic) to more qualitative approaches.

Table 2.5. A typology of flood losses with examples. Source: Adapted from Merz et al (2010)

		Measurement	
		Tangible	**Intangible**
Forms of flood losses	**Direct**	Damage to private buildings and contents Destruction of infrastructure such as roads, railroads Erosion of agricultural soil, destruction of harvest Damage to livestock Evacuation and rescue measures Business interruption inside the flooded area Clean up costs	Loss of life; injuries; loss of memorabilia; Psychological distress, damage to cultural heritage; Negative effects on habitats/ecosystems
	Indirect	Disruption of public services outside the flooded area Induced production losses to companies outside the flooded area (e.g. suppliers of flooded companies) Cost of traffic disruption Loss of tax revenue due to migration of companies in the aftermath of floods.	Inconvenience of post-flood recovery Trauma Loss of trust in authorities.

A key concept in any loss or quantifiable damage estimation is the concept of damage functions or loss functions. They relate damage for a specific element at risk to the features of the event. These functions are similar to dose-response functions or fragility curves in other fields (Merz et al., 2010; Penning-Rowsell et al., 2013). Flood damage losses, for instance, are a function of the nature and extent of the flooding, including its duration, velocity and the contamination of the flood waters by sewage and other pollutants. It is important to ensure that for the purposes of flood risk management there is consistency in the assessment of damages: this often means that only the national economic losses caused by floods and coastal erosion are assessed, rather than the financial losses to individuals and organizations which are affected, severe though those may be.

Protecting property from damages is considered in investment decision making through approaches such as cost-benefit tests that, for example, the UK Treasury uses, and which are becoming more commonly applied throughout the world. Also, environments are often now protected—sometimes irrespective of cost—courtesy of national and European legislation (creating Ramsar sites, Special Protection Areas, Sites of Special Scientific Interest, etc.). Nevertheless, the 'social' effects of an damage need to be considered: those caused by the disruption of people and communities that do not or cannot carry a monetary price tag. Again, floods can be used as illustrative example herein. Floods can cause health impacts which are enduring, including the stress and trauma created months or years afterwards whenever floods threaten to reoccur. Loss of treasured possessions in floods can be 'heartbreaking', and much more significant than financial losses, which are now commonly recovered through government compensation schemes or household insurance policies. It sees these impacts as the net effect of the threat, the mediating influences (e.g. flood defenses) that moderate that threat for the affected population, and the support capacity in households, communities and indeed the nation that helps to promote resilience in that population and the capacity to recover from the threat, the event and its effects. In this respect, the health and mental health effects of flooding need to be considered, so that these can be accounted when evaluating policy options at the coast.

Natural disasters such as flooding, wildfires or heat stress can impact upon people's health in a number of ways (Tapsell et al., 2002); good health being defined as complete physical, mental and social well-being. Many impacts are associated with the trauma of flooding and living subsequently for long periods in damp and dirty conditions. The close proximity of people living in cramped conditions in their homes following flooding mean that some of these adverse health effects can be passed from person to person within the household, particularly where pre-existing health issues are present. Hence, the effects of flooding on people's health and general well-being can continue for many months after the actual flood event. People suffer from psychological health impacts from the stress of the flooding (Tapsell et al., 2002). Stress arises from the difference between the perceived demand the event places upon the individual and the resources the individual can draw upon to adapt to that demand. The severity of the impact represents the degree to which coping and support capacity are insufficient to cope with the challenge and costs of responding.

The conclusion is that the impacts of flooding on people are more extensive and complex than have hitherto been appreciated. Hence, assessments of the effect of flood risk reduction measures on these more intangible impacts are flawed and incomplete if only monetary losses are used within the necessary project-appraisal and option analysis methods.

2.3. Handling uncertainty

Uncertainty permeates the whole process of risk assessment and is often ignored. There are two main causes: (1) lack of knowledge either about relevant data, or about whether a particular effect will occur; and (2) as a result of the random nature of the events, which itself depends on natural circumstances and their timespan. These random events can include:

a. errors in the probabilities of events (sources): e.g. through the extrapolation of short time series;
b. precise extension of the hazard's effect: imprecision due to generalised models or because of difficulties in estimating failure probabilities of pathways;
c. type and location of elements at risk: inaccuracies because of generalisations in spatial resolution and categorisation of land use data;

d. value of elements at risk: values are often approximations or have to be disaggregated or have to cope with non-marketable elements such as valuable habitats;

e. susceptibility of elements at risk: damage functions are often derived from poor empirical data.

Hazard forecasting and risk assessment systems traditionally concentrated on separately modelling single phenomenon such as sea level, rainfall, waves, river discharges, flash flooding, wild fire, wind damage, etc. Each forecasting system comprises a linear flow of data and a combination of different models The weaknesses (or limitations) of these modelling systems include:

- the lack of inter-operability between model components,
- a tendency to consider only a single source of hazard;
- the lack of ensemble or data-assimilation techniques;
- the absence of tracking of estimation errors for uncertainty analysis;
- the need to constrain uncertainties and narrow prediction bounds with model refinement;
- that the assessment of the potential associated risk is often limited or even absent with respect to vulnerability and resilience; and
- that they assume historic /static data on the condition of pathways (defence systems, local changes in topography, ...).

Cascading forecast uncertainty in coupled models is an important step to improve the quality of hydrological forecasts (Cloke and Pappenberger, 2009). However, the best methodology to quantify the total predictive uncertainty is still debated (Beven et al., 2008), and may even be different depending on the type of hazard that is analyzed. Sources of uncertainty in the forecast chain are numerous and include: the meteorological forcing, corrections and downscaling procedure of the meteorological predictions, antecedent conditions of the system, observation networks, methods of data assimilation, possibility of infrastructure failure, but certainly also limitations of the model to fully represent processes (for example surface and sub-surface flow processes in the flood generation and routing; or soil moisture modelling in times of droughts). The importance of the individual components varies in time, depending on the dominant regimes, and in space, as each natural system is unique. It also depends on the interactions between the space-time scales of the predicted event, the main catchment characteristics (area and response time) and the resolution of the meteorological forcing data (Thirel et al., 2008). A full uncertainty analysis can track all sources of uncertainty and estimate both their relative importance in the system and the total uncertainty from the combination of each component (Pappenberger et al., 2005). The total magnitude of the uncertainty influences the quality of the predictions, the interpretation of model output forecasts, and ultimately its use in decision making (Ramos et al., 2010).

Many of the issues of projecting future change are addressed by presenting risk as a range of values rather than a single number. This provides an envelope within which the actual future is expected to occur – there are two main approaches; the use of scenarios and probabilistic approaches.

The use of scenarios in risk assessments recognises that the future is unknowable. For example, knowledge about future socio-economic developments is limited. In turn, this leads to uncertainties in future greenhouse gas emissions. Further, when subjected to the same emission scenario different climate models will show different responses reflecting both, imperfect knowledge of the underlying physical mechanisms and internal (natural) climate variability.

A number of different scenarios should be used which sample the underlying assumptions that appear plausible. Commonly an ensemble of climate change simulations obtained from different models and scenarios are used. Scenarios cannot be associated with a likelihood of occurrence and represent “plausible futures” rather than probable outcomes (Von Storch and Zwiers 2012). Hence, scenarios generally address questions of the type “What may happen if …?”. The benefit of using scenarios is that decision makers consider a range of views of what may unfold and understand broad sensitivities of the natural system. Hence, they can develop suitable policies/management. A focus on options that are robust to the range of existing uncertainty and flexible; that is they may be adopted in the course of time when expected changes manifest and uncertainty becomes smaller, raising the approach of defining and selecting adaptive pathways (Ranger et al., 2013; Tarrant and Sawyers, 2013). Hence, there can be benefits in considering scenarios that have a low chance of occurring (Randall and Ertel, 2005), to test for the long-term robustness and feasibility of different adaptation approaches over time and the range of scenarios.

In the context of historical changes and present conditions, probabilistic or statistical approaches can be used. For example, the definition of return periods and their uncertainties has become more common with the increase in data availability and computing power. However, this still depends on the availability of data. Extreme events pose a particular set of challenges for implementing probabilistic approaches because their relative infrequency makes it difficult to obtain adequate data for estimating the probabilities and this gets worse as return periods increase (Milly et al., 2002).

Communication of the uncertainty within a flood assessment is good scientific practice, maximizing credibility and minimizing misinterpretation, bias and different interpretations (Kloprogge et al., 2007). Ineffective communication of scientific research to decision makers and the public has often proved a barrier to uptake of knowledge by stakeholders. Uncertainty information concerning probabilities is particularly prone to biases, as the concepts themselves are not easy to understand; risk experts separate the probability and magnitude components of a risk, but for non-scientific audiences the perception of risk is often directly linked to consequences and specifically to consequence experienced by the users involved in the assessment. This can lead to an under- appreciation of low-probability high-impact events (Kloprogge et al., 2007).

2.4. Capturing future changes

Timing and timescales are important cross-cutting themes that need more attention when dealing with the identification and management of extreme climate and weather events, disasters, and adaptation strategies. The first key issue when dealing with timing and timescales is the fact that different hazards and their recurrence intervals might fundamentally change with time. This implies that the identification and assessment of risk, exposure, and vulnerability also needs to address multiple time scales. At present most of the climate change scenarios focus on climatic change up to the year 2100, while projections of vulnerability often just use present socio-economic data.

However, a key challenge for enhancing knowledge of exposure and vulnerability as key determinants of risk requires improved data and methods to project and identify directions and different development pathways in demographic, socioeconomic, and political trends that can illustrate potential increases or decreases in vulnerability with the same time horizon as the changes in the climate system related to physical-biogeochemical projections (Birkmann et al., 2010). This is challenging as future socio-economic conditions are more uncertain than biophysical conditions, and for example, a maximum of 25/30 year time frames are normal in government. Furthermore, the time dependency of risk analysis, particularly if the analysis is conducted at a specific point in time, has been shown to be critical (e.g., Setiadi, 2011). These types of issues should also be considered, but the details of how and to what degree will vary from study to study.

As the SPRC model describes the system at a single moment in time, the conceptual system needs to sit within a wider analytical framework which allows for time and external and internal changes as a result of different Drivers. Including Drivers is essential when looking at the evolution of the any natural system (and risk) over time and require clarity early in the risk assessment (Millner, 2012).

This effectively addresses the uncertainties faced when looking at future situations and can range from uncertainties inherent in the modelling process (including scientific understanding of the system) to the range of possible socio-economic futures and projections of climate change which can affect the hazard's effect and thus impact. Participatory approaches including stakeholder engagement are good practice, maximizing credibility and minimizing misinterpretation, bias and differences by readers and users (Kloprogge et al., 2007).

Many of the challenges of communicating possible change are addressed by presenting risk as a range of values rather than a single number. Scenarios (storylines) are often used to illustrate different plausible relationships between cause and outcome illustrating how current and alternative development paths might affect the future (Nakićenović et al., 2000, Moss et al., 2010, Nicholls et al., 2012). Hence, scenarios can have multiple dimensions depending on the question being posed. In addition to considering the Drivers in isolation, one approach is to use a range of scenarios which vary the underlying assumptions: at the minimum, estimations can reflect where everything works to expectations – a best case scenario – and where nothing does – a worst case scenario; the difference between the best-case and worst-case value can then be used as a measure of the range of risk. There can also be benefits to considering scenarios that have a low probability of occurring (Randall and Ertel, 2005, Nicholls et al., 2014).

How individual parameters within the scenario are represented also needs to be decided (see Table 2.6). For the quantitative components of the system, such as water levels, temperature, wind speeds but also anthropogenic projections such as the number of people, future projections commonly draw on global or national level data and are down-scaled using statistical methods. For example, with the increase in data availability and computing power, methods such as standard deviation and probabilities have become more common, particularly for the translation of climate model outputs for detailed quantitative modelling. For some parameters, however, the use of such data to represent local changes could raise the question of plausibility as a different pattern of change could be experienced: for example a city may increase in population despite regional or country projections of population decline.

For long-term risk assessments, potential changes in population, land uses, economic and asset value should be considered. Specific knowledge may be available at local level and the short term (e.g., development plans) but over longer periods appropriate socio-economic scenarios need to be created. In particular, population, Gross Domestic Product (GDP), and other scenarios relevant at the scale of the study sites are required. These localised scenarios need to represent coherent, internally consistent, and plausible description of possible trajectories of future conditions based on self- consistent storylines or images of the future. They also need to agree with relevant stakeholders for credibility purposes. The high level of indeterminacy of these factors should be conveyed to local and national stakeholders: these scenarios must be presented as food for thought and action, rather than robust projections of the future.

These social and economic scenarios will also need to consider cross-scale interactions (Turner et al., 2003a, b). However, the practical application and analysis of these interacting influences on vulnerability from different spatial scales is a major challenge and, in most cases, not sufficiently understood. Furthermore, vulnerability analysis, particularly linked to the identification of institutional vulnerability, must consider the various functional scales of climate change, natural hazards, vulnerability, and administrative systems. In most cases, current disaster management instruments and measures of urban or spatial planning as well as (water) management tools operate on different functional scales compared to climate change. For example, policy setting and management of climate change and of disaster risk reduction are usually the responsibility of different institutions or departments, thus it is a challenge to develop a coherent and integrated strategy (Birkmann and von Teichman, 2010). Consequently, functional and spatial scale mismatches might even be part of institutional vulnerabilities that limit the ability of governance system to adequately respond to hazards and changes induced by climate change. This illustrates the potential complexity of this aspect of risk assessment and the need for clarity on the questions being asked.

For the more qualitative aspects of the system and hazard impacts, such as public perception and human behavior, deciding how (or even whether) to incorporate them is a challenge for assessments largely based on quantitative modelling. This represents a key research challenge.

Table 2.6 Examples of representative scenarios and data for the different aspects of a flood system.

Data type	Data source	Social aspects	Ecological aspects	Hydrological aspects
Qualitative	Global	SRES or SSP scenarios		SRES or RCP scenarios
(Semi) Qualitative		Human typologies	Vulnerability/ resilience assessment (expert opinion)	
Quantitative	Global - national	Down-scaled existing population and GDP projections	Designated areas	Water levels and discharge modeled from global climate models (long-term)
	Local	Local data on population and GDP, census data, landuse maps, habitat maps, development plans, buildings database	Changes in specific indicator parameters (e.g. species diversity, salinity, area)	Projections based on 30+ years of historical data -short-term only (10 year)

3. Vulnerability assessment

3.1. Hydraulic vulnerability

Flood studies are an important first step towards understanding and managing flood behaviour, whether for a large rural catchment, a highly developed urban area or for individual property and infrastructure development. Flood modelling is carried out to identify the source of potential flooding, the more critical flood pathways, the extent and duration of a flood event, their frequency of occurrence and the effects of proposed mitigation and protection measures.

Flood modelling can be performed through a plethora of different approaches, ranging from simple (empirical) methods to full 3D simulations. Naturally, the more detailed the flood modelling approach, the higher the computation times will be. Given the rapid advances in computational technology and power, full hydrodynamic have become the standard tool of operation for most water managers throughout Europe. Flood modelling is thus usually carried out with 1D (sewer and rivers) and 2D (coastal zones and floodplains) approaches, which typically include full solutions of the 1D or 2D shallow water equations. Examples of (commercial) software packages that are based on such solutions are MATO (Posada et al., 2007), InfoWorks ICM, TUFLOW, Mike 21, TELEMAC, LISFLOOD-FP and Delf-FLS (e.g. Neelz and Pender, 2009). The computational time ranges from hours to days for typical storm durations. Simpler 1D methods (Wadey, 2013) such as Mike 11, HEC-RAS, Infoworks RS (Neelz and Pender, 2009), with computation time in the order of minutes to hours, represent the flooding process under the assumption that the floodplain flow is equal to the channel flow.

For many real-time applications, such computation times are still too large. Especially (large scale) optimization problems, such as determining optimal control settings of hydraulic infrastructures like gated weirs, require simulation times that are several order of magnitudes smaller. Indeed, given the complexity of flood dynamics and the multitude of possible control settings, such optimization problems cannot be solved analytically. Typically, such optimization problems are solved using a brute force technique, in which numerous different control settings are simulated and post- processed to determine the optimal ones (e.g. Vermuyten et al., 2018). The same is valid for long term simulations, which are needed for various impact and scenario analyses. Although computational power evolves rapidly, these improvements will not deliver the required speed gain in the next decades. Thus, alternative flood modelling techniques that solve simplified versions of shallow water equations or even rely on entirely different hydraulic equations remain popular. The DSS SCAN, a BRIGAID innovation and used in this report to assess the impact of green roofs on floods in the city of Antwerp (see Section 7) is an example of such modelling approach. It lumps (uncertain) processes on a larger to limit the number of calculation nodes and thus computation time, enabling rapid scenario analyses and long term simulations. In particular, SCAN simulates underground flows through the conduits and assesses the flood volumes. These flood volumes are then translated into flood extent maps through depth spreading algorithms (see below).

Where a broad scale assessment of extents and depths of flooding is required, even more simple GIS-based flood inundation or flood spreading models (Poulter and Halpin, 2008; Brown, 2006) can be an alternative cost-effective solution. These models do not solve hydraulic equations but perform flood mapping through the spreading of water levels or volumes across a Digital Elevation Model (DEM) by using several techniques (Zerger et al., 2002; Chen et al., 2009; Wang et al., 2010; Gouldby et al. 2008). The computational times range from seconds to a few minutes, depending on modifications introduced in the algorithms, therefore these approaches can be easily implemented in Decision Support Systems. However to provide the user with sufficient accuracy they require high resolution topographic data and are less suited to application in flat areas. The SCAN application to the city of Antwerp (see Section 7) also employs a depth spreading algorithm to translate simulated flood volumes into flood extent maps.

Some complex dynamics require, however, the most accurate simulation models. For example, the accurate representation of the complex dynamics of sea-river interaction and/or beach reshaping and run-up requires 3D solution of the 3D Reynolds Averaged Navier Stokes equations. This in turn necessitates of an approximate numerical technique such as finite differences, finite elements or finite volumes. A number of codes are available for local predictions of three-dimensional velocity fields in main channels and floodplains, such as MATO-3D (Posada, et al., 2008), and FLUENT. However, these approaches are computationally expensive (run time of several days) and thus far have only been applied to channels of a limited domain size and regular geometry (Woodhead, 2007).

Thus, the employed modelling technique (solving 1D/2D shallow water equations, using “conceptual” or even empirical approaches, or the most detailed 3D shallow water equations) strongly depends on the system that is being investigated and the application. One must always search a balance between model detail and the level of uncertainty on the model parameters and the inputs. For instance, using highly detailed 3D solutions of the shallow water equations for riverine flood simulations is not wise, as the uncertainty on the inputs (e.g. rainfall, but also friction terms, …) is much greater than the additional accuracy gained by 3D solutions compared to using 1D of 2D simulations. Also, complex models, thus comprising more parameters, do not always result in more accurate simulation results. Indeed, models can be overparameterized, or the parameter uncertainty can weigh on the accuracy. However, as stated, some applications or systems require these complex models, such as for modelling sea-river interactions. Hence, assessing flood vulnerabilities always require a profound knowledge on the different modelling techniques and the system that is being investigated.

3.2. Environmental vulnerability

Impacts of floods are evaluated in relation to community and habitat vulnerability and also resilience to flooding, erosion and damage associated with storm events. Vulnerability is considered to arise from the system’s inherent properties, which determine resistance and resilience. An ecosystem can be defined as resistant if it has a high ability to withstand disturbance events. Resilience is the time the ecosystem needs to recover to the state before the disturbance event took place: a rapid recovery time leads to a high resilience and vice versa. As such, the most vulnerable ecosystems are ones in which both resistance and resilience is low, the persistence of such systems is highly unlikely, especially under unfavourable scenarios of climate change.

The types of habitat/ features to be analysed include: habitats, protected sites, rare species and species protected under the Habitats Directive (European Commission, 1992), locations where economically important species are harvested/farmed, habitat features that have particular importance to the local ecosystem.

The habitats (and key species) affected by flooding and erosion are classified as Receptors within the SPRC methodology (Narayan et al., 2014). Hence, they may change in response to changes in the Sources as follows:

i. *Short-term processes* (storm surge, wind driven waves, tides, high intensity rainfall events, riverine water levels, etc.);
ii. *Long-term processes* (sea level rise, vertical land movements – uplift/subsidence, changing rainfall extremes and frequencies, land use changes (e.g. increased the ratio of sealed surfaces), etc.).

These processes have different effects on habitats. *Short-term processes* are temporary process where after inundation floodwater will subsequently retreat (see Hoggart et al, 2014 for a discussion on the impact of salt water flooding to terrestrial areas). This imposes the need for identification of several possibilities for effects on and the recovery of habitats and species in respect to inundation duration. In contrast, for inundation due to *Long-term processes* (e.g. sea level rise) it is assumed that the water will not retreat. While losing terrestrial habitat areas (as, for instance, a consequence of sea level rise), it is important to recognise that aquatic habitats may be gained or expand resulting in no overall change in total area, but a change in the relative extent of different habitat types. If habitats have the ability to "retreat" (the affected terrestrial habitats can move landward), these newly occupied territories may be considered as additional coastal habitat. Alternatively, where there is no possibility for habitat retreat because of natural or anthropogenic barriers (coastal squeeze), intertidal habitats such as saltmarshes are expected to decline.

Vulnerability of habitats is dependent on:

i. Which part of a particular habitat area will be a subject to the unfavourable impact and which species will be affected;
ii. The degree of sensitivity of habitats/key species to unfavourable impact/hazard;

To assess the vulnerability of ecosystems to changes in stresses and to disturbances an index was adopted within the THESEUS project (Zanuttigh et al., 2014a; www.theseusproject.eu). This provides a rapid and standardised method for characterising vulnerability (applied in the project across coastal systems) and identifies issues that may need to be addressed in order to reduce vulnerability. By looking at combinations of factors, ecosystem vulnerability can be assessed. Such factors are the inherent ecosystem characteristics, the natural drivers that act upon the ecosystems, human use of the ecosystem, and the effects of climate change.

The proposed Environment Vulnerability Index (*EVI*) is similar to that used in Gornitz *et al*. (1994) and many subsequent studies (e.g., Thieler and Hammar-Klose, 1999; Boruff et al., 2005) to assess coastal vulnerability. The *EVI* is calculated as the square root of the product of the ranked variables divided by the total number of variables. The *EVI* ranked variables respond to the secondary Sources for particular habitats:

$$EVI = \sqrt{(A_1 \times A_2 \dots \dots \times A_n)}/n \quad (6)$$

where A_1, A_2, …, A_n are different receptor habitats/species, identified for the discrete area in question and n is the number of different receptor habitats/species. Each habitat is given a score of 0, 1, 2 or 3 following Table 3.1. Thresholds beyond which the index increases to a higher value are determined by the specific EVI for each habitat and the attributes of the site.

Table 3.1: Definitions of the Environment Vulnerability Index (EVI).

	Negligible	Transient effect (no long term change anticipated)	Moderate effect	Permanent effect/change
EVI Index	0	1	2	3
Habitat/ Key species	Negligible impact to habitats / species	Changes within the range of Receptor's natural seasonal variation and full recovery is likely within a season	Changes are beyond Receptor's natural seasonal variation. Partial recovery is possible within several seasons, but full recovery is likely to require human intervention	changes are so drastic that natural recovery of receptor is very unlikely without human intervention
	Negligible	Transient effect (no long term change anticipated)	Moderate effect	Permanent effect/change

The assessment of *EVI* uses the following steps:

1. *Define Sources:* Different primary/secondary Sources are examined with respect to their potential to cause habitat degradation.
2. *Identify and map habitat types,* based on the available data in the area.
3. *Identify Consequences of the Source on the habitat Receptor.* For instance, storm surge (Source) affecting sandy dunes (habitat) will cause erosion and inundation.
4. *Calculate the area affected.* The approach for calculating the areas of the habitats affected will be different according to the Source. Use of a GIS platform permits delineation and calculation of the inundated habitat. Construction of these maps requires both habitat maps and a Digital Terrain Model.
5. *Calculate the EVI.* Environment vulnerability for each habitat is calculated following Eq. 6. The degree to which each habitat is affected by the Source using a categorical method for each habitat: a score

from 0-3 is given based on the definitions given in table 3.1. Four categories are proposed for Short-term and seasonal processes (categories 0, 1 and 2); for Long-term processes it is assumed that habitats will be permanently affected (category3).

Tab. 3.2 shows an example of the *EVI* for *Sabellaria Reefs* as it was elaborated within THESEUS by the ecological team. The *EVI* depends on the increased wave action, both in terms of intensity and frequency, and on sediment depth and duration. The maximum value of the *EVI* has to be assumed after computing the values of the *EVI* from the two separated tables. The result from each table is derived based on simplified functions relating the vulnerability to sedimentation and agitation and on threshold values of sedimentation and agitation.

Tab. 3.2 Example of the EVI table for Sabellaria reefs (for coastal flooding).

Sedimentation			
Quantity of sedimentation	Light	Medium	Heavy
Duration of sediment	<1cm	1-10cm	>10cm
Daily	+	1	1
Springs	1	2	2
once month	1	2	2
once year	2	2	SB
Every 10 years	SB	SB	SB
every 100 years	SB	SB	SB
Wave action			
Intensity of Storms	Slight	Moderate	Heavy
Frequency of increased wave action	10% increase	50% increase	100% increase
Daily	1	2	3
Springs	1	2	2
once month	0	1	1
once year	0	0	0
Every 10 years	0	0	0
every 100 years	0	0	0

3.3. Social vulnerability

The social context of floods is a critical dimension of any system-based analysis of floods. All human groups are not equal when facing floods, and within coastal communities parts of the population may be more vulnerable to floods and their consequences. A review of social vulnerability analysis to floods indicates that the following key dimensions must be taken into account: demographics (age, population density, migratory status), wealth (absolute and its distribution), health status, and mobility. McElwee (2010), Baum et al. (2008) and Coninx and Bachus (2007) provide detailed examples for Vietnam, the Gold Coast (Australia) and climate change, respectively. Social vulnerability is a complex phenomenon and no single measure comprehensively includes all aspects of vulnerability (Adger et al., 2005). Factors such as those listed above can all be considered, but vulnerability is site-specific and some relationships between social characteristics and vulnerability are unlikely to be linear or readily transferable. While there seems to be a consensus on the dimensions to be taken into account, their local articulation varies because of local variation in governance, cultures and perceptions, and this requires evaluation in any assessment.

A review of governance structures and perceptions should thus take place at the beginning of any flood risk assessment and the stakeholders contacted should be encouraged to participate throughout the assessment process. Information is generally collected from stakeholders using qualitative methodologies; individual interviews, semi-structured interviews and focus groups.

These are time consuming processes to apply with distinct benefits and limitations (Table 3.2). Ultimately, a focus on the participation of local communities and authorities has two major benefits:

- optimal use is made of the know-how and skills of local communities, taking into account their wishes and needs;
- the involvement and shared responsibility of local parties in coastal risk assessment will guarantee a sound community basis for the development of management plans.

Recently, the Social Vulnerability Index has been suggested as a comparative spatial assessment of human-induced vulnerability to environmental hazards (Cutter et al., 2003; Wisner et al., 2004). This index is based on a large set of measurable variables that can be grouped into main common factors such as: population structure, gender, income, socio-economic status, and renters (www.csc.noaa.gov/slr). Analysis and mapping of social vulnerability should also consider identifying critical facilities or resources to help prioritize potential hazard mitigation.

In THESEUS Decision Support System (Zanuttigh et al., 2014b), social vulnerability is modeled considering two main aspects: (1) the damages to critical facilities (CFs); and (2) the expected number of fatalities. It is worthy to remark that flood damages to society include also psychological consequences that are mainly qualitative in nature and are hard to translate in linear functions with quantitative outputs for practical and ethical reasons (Tapsell, 2011).

CFs are defined as “the primary physical structures, technical facilities and systems which are socially, economically or operationally essential to the functioning of a society or community, both in routine circumstances and in the extreme circumstances of an emergency” (UNISDR, 2009). On the one hand, the notion has been adopted recently in disaster management, and is related to the creation of GIS maps on Community Vulnerability (a.o. DEFRA, 2005; FEMA, 2007); on the other hand, CFs have been applied in the development of priority lists for the effective reactivation of buildings after disasters and applied emergency management (e.g., Hillsborough County –Florida, 2009).

The impact of the flooding process on CFs is estimated following these steps.

3.3.1. Ranking of Critical Facilities

In the Theseus Project, a rank was derived based on the function of buildings in relation to social vulnerability (Hillsborough County –Florida, 2009). Considerations were made both in terms of building use in emergency management, building role in ordinary activities and community aggregation, and the building's symbolic function. The range was defined as Approximated Social Value (ASV), with values from 1 (low) to 5 (high), Tab. 3.3. The final output is an overall view of possible intangible damages in the range 0 to 100. Even if it maintains high levels of uncertainty, it is one of the first attempts to provide to end users the possible effects of floods on the community and individuals. The ASV also provides a re-activation list in reverse order, as the highest values are supposed to receive priority in emergency interventions for reducing social damages. In the perspective of land use planning, the adoption of such an approach should lead to the relocation of high scoring buildings to safer areas or encourage measures to increase the building's resilience capacity. Similarly, higher scores indicate where efforts for higher education and training of personnel could be concentrated and where emergency measures such as mobile barriers should be deployed with maximum effectiveness.

Table 3.2 Benefits and limitations of qualitative assessment methods

Techniques	Structured interviews; Focus groups; Survey, Questionnaire
Benefits	Engaging stakeholders in the flood management process Provides depth, detail and context for more quantitative approaches Ensures identification and focus on relevant issues for stakeholders Identifies people's individual experiences building up a picture of the diversity of stakeholder's views and why these exist Attempts to avoid pre-judgments, identifies trends and emergent themes Can be cyclical with analysis informing subsequent data collection and further analysis Focus groups promote openness by allowing different views to be expressed
Limitations	Identification of relevant individuals Time consuming; available time may dictate number of participants, length of interviews and analysis Not easy to generalize or systematically compare a small number of interviews Highly dependent on skills of the interviewer
Techniques	Structured interviews; Focus groups; Survey, Questionnaire

3.3.2. Estimation of physical damage for structures

The damage scale is estimated based on flood depth and duration. Following the method by Schwarz and Maiwald (2008), the damage grade is related to the flood depth (De) through a non-linear function. Intuitively, the effects on society and structures are inversely proportional to flood Duration (D) (excluding flash flood phenomena). Long duration floods, even if relatively limited in space, produce greater impacts on social functions: a bridge blocked for an hour might be a nusance, while for a week it could compromise trade routes or tourism activity. Therefore the following scenarios (corresponding to different scores) should be considered: i) Short D (Hours), ii) Medium D (Day/days), Long D (Week/weeks).

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3.3.3. Definition of touristic impact

The geographic features that determine the vulnerability of social response are related both to the physical structures and to the situation where the action is settled (Cutter, 1996). In many coastal areas, one of the most relevant variable affecting the ordinary social pattern should be considered the presence of tourism. Its presence can determine furthermore the scale of flooding impact. It can be presumed that not all the tourist have previous experiences in flooding, and that if a flood could happen when a large number of tourist in place critical infrastructures could have clearly higher pressure and warning messages should face more problems in their dissemination. The tourist presence should be represented through a value reflecting seasonality S; this factor will act as a final scale multiplier, where low season (1) could denote normality, and high season (2) will imply that the effects will be exacerbated.

The Collateral Social Damages CSD are finally estimated as:

$CSD = \Sigma_I \; ASV_i \cdot De \cdot D \cdot S$

The value of CSD should be related to a common scale to allow exportability to other case studies and comparison of the results.

For tangible social damages, we derived a function of life losses and injuries (NI) fromPenning- Roswell et al. (2005)

$NI= (H*AV)/(Pa+ID)$

where H is the hazard rate, AV is the Area Vulnerability, Pa is the sensitive population (age<14years and >65 years) and ID is the number of sick and disabled people.

The value of H is computed in each cell of the domain as $H=NI \cdot y \cdot v \cdot DF$

where N is the number of people involved in the flood, y is the flood depth, v is the flood velocity, DF is the debris factor equal to 1 for the Mediterranean and 2 for the Ocean.

The Area Vulnerability AV is derived as:

$AV = W+ Fo+ Na$

where W denotes the Warning, Fo is the speed of onset of flooding and Na is the Nature of the flooded Area, see Tab. 3.4.

The type Na can be derived from statistical demographic data or schematised based on Penning- Roswell et al. (2005). If statistical areas are available, their main use should be identified and risk levels from 1 (low) to 3 (high) should be attributed, see Tab. 2.7. As social patterns determine the risk levels of special attributes, three main scenarios were identified: day, night and touristic period. Higher risk was attributed to residential areas when people are generally at home sleeping (night), while zones identified for schools and education are vulnerable when children are in classes (day). Finally, tourist resorts are most susceptible during holidays (touristic period).

The percentage of the Population Aged (Pa) can be derived from Demographic data or referred to national middle average. The final value of Pa should be conformed to a common value of 50 as: Npa: X50= Pa:50, X100 = nPa *(100/Pa). The percentage of Infirm/disabled/ long-term sick (ID) can be set based on perception or on the national average.

Values for the factors are synthesised in Tab. 3.3. In general, this function provides and overall count of people that could be subject to death or injuries. As too many external variables such as local lifestyle, wealth or public health services influence the final output of life losses, and the uncertainties are high, it may be decided not to distinguish between these two aspects.

Table 3.3 Ranking values and factors required to estimate the Collateral Social Damages. To be continued.

	Associated Social Vulnerability factors
ASV	Definition
5	Critical structures that if involved could compromise the emergency action, the coordination chain, public safety and public health in the long term. For example, Hospital and emergency facilities. Depending on local features, main military facilities, power plants and institutions can be included in this category
4	Facilities that provide significant public services and should be activated within 24 hours. For example, there can be included Nurseries, Major water and sewer facilities, Fire and police stations, Schools and park facilities used to support critical purposes.
3	Facilities that provide important public services but should be sequent to critical facilities ranked 4 and 5 points. Main centers of aggregation, education or prayer that are important for symbolic belonging to the community. Some particular place that links those features to economics can be included too.
2	Facilities that provide public services but that are less critical for the community. Common storages, sport centres can be included depending on the context. Literature on social capital can be taken also as reference.
1	Places which value are mainly symbolical, but can influence anyway the overall amount of social damages. For example, particular community areas of meditation and prayer.
	Depth induced damage
Factor De	Depth range from Schwarz and Maiwald (2008) – has to be adapted to the site
1	0.1-0.5 m
2	0.6-1.5 m
3	1.6-2.5 m
4	2.6-5 m
5	>5 m
	Duration induced damage
Factor D	Flood duration
1	Hour/s
2	Day/s
3	Week/s
	Seasonality
Factor S	Definition
1	Low seasonality
2	High seasonality
	Collateral social damage scale

Table 3.3 Ranking values and factors required to estimate the Collateral Social Damages. Continued.

Score	Definition
0	No collateral social damage.
1-10	Possible malfunctions in citizen's ordinary life are possible but can be prevented. The damage is limited and could be managed with experimented procedures and stakeholders activation. The situation could require more details about which critical facilities involved, and planning of alternative solutions.
11-20	Malfunctions in citizens' life are expected. The damage is still limited but diffused (or high and very concentrated), and requires higher mobilization for the rehabilitation process.
21-30	Social damages are concrete and visible. A major involvement of local relief and reprise resources is expected. The presence of external help is suitable and should be activated in advance in order to avoid higher losses.
31-50	Massive social damages in ordinary period or medium involvement of critical infrastructure in high touristic period. Massive damages could be managed with timing alert and planning, but the presence of external help is absolutely needed. Long times for re-activation of services and community reprise should be prevented.
51-100	Exceptional damages, calamity. The situation could have terrible social damages and should be mediated with external help and cooperation at the highest level possible. Very long times for re-activation of services and community reprise should be prevented.

Table 3.4 Ranking values and factors required to estimate Life losses and injuries.

W	Not present	Present, not implemented	Present, well working
	3	2	1
So	Slow flooding (many hours)	Gradual flooding (an hour or so)	Rapid flooding
	1	2	3
ID	Low Presence	Medium Presence	High Presence
	10%	25%	50%
Na	Touristic Season	Day	Night
Residential Area	2	1	3
Tourist area	3	2	1
Manufacturing	2	3	2
Common or religious area	2	3	1
Education Area	1	3	1
City Centre	3	3	3
Parking and Green	1	1	1

3.4. Economic vulnerability

In the economic vulnerability analysis, major sectors of economy and the primary centres of activity in those sectors have to be identified. These economic centers are areas where hazard risks could have major impacts on the local economy and therefore would be ideal locations for targeting certain hazard mitigation strategies.

The Economic Vulnerability Index EcVI can be calculated (Guillamont, 2009), based on a composition of the following seven indicators: 1) population size, 2) remoteness, 3) merchandise export concentration, 4) share of agriculture, forestry and fisheries in gross domestic product, 5) homelessness owing to natural disasters, 6) instability of agricultural production, and 7) instability of exports of goods and services. However, within a Multi-Criteria Analysis, where social and economic impacts must be distinguished and separately weighted, this index turned out to be inadequate, since it combines social and economic indicators. Instead, if one could refer to detailed data on economic activities in Gross Domestic Product terms, a consistent approach can be based on incomes for each economic land use: e.g., hotels are evaluated in terms of annual GDP, houses are evaluated in terms of annual rents, beaches are evaluated in terms of annual willingness to pay to preserve it.

The overall economic consequences of flood in terms of flood depth and flood duration can be estimated by applying the following formula:

$$vij \bullet bj \bullet Fd + vij \bullet aj \sqrt{Fy}$$

where ij are the values of land uses in euro/m^2/year from census statistic data; Fd is flood duration and Fy is flood depth; aj are proportionality constants as functions of Fy that are normalised for each land use j at the maximum value of Fy for a given extreme event (in THESEUS project, the 2050 scenario for a storm return period Tr=100 years), assuming different reference percentage of damage depending on the use (for instance, 50% damage for buildings/homes/hotels, 25% damage for harbors); bj are proportionality constants as functions of Fd that express the expected period to restore economic activities as a factor of duration, depend on the land use (for instance, a value of 30 is set for hotels and of 20 for private services) and are normalized to annual incomes with the days/year. Note that flood velocity is assumed to be irrelevant.

Alternatively, a consistent approach can be based on market values of infrastructures. Note that it is theoretically possible to move from an income approach to an infrastructure approach under a standard set of assumptions about market competition.

4. Integrated risk assessment

In the overall vulnerability analysis, multi-disciplinary approaches are often needed, with the involvement of different experts, coming from different areas with distinct knowledge and experience, and using different judgment and evaluation methods (e.g., qualitative and quantitative forms; certain and uncertain assessments), and with the consideration of various and at least partially conflicting objectives (e.g., economic, social and ecological aspects) (Li et al., 2010). Multi- Criteria Multi-Expert Decision Making is a methodology to deal with the inherent complexity and uncertainty as well as the vague knowledge arising from the participation of many experts in the decision making process (Yan et al., 2011). It is a response to the inability of people to analyse multiple streams of unalike information in a structured way: preferential information is modelled by weighting factors (i.e. inter-criteria comparisons) and value functions (i.e. intra-criteria preferences) (Chen et al., 2011). It is here suggested to rely on this methodology, by properly weighting the three impacts (i.e. ecology, society, economy) according to stakeholders' preferences and by properly normalizing all values estimated by experts. The demonstration of this methodology is given in the Decision Support System developed by BRIGAID, see Section 8.

5. Sectoral impact assessment

5.1. Introduction

Section 5 consists of the assessment of sectoral impacts, based on the previous D5.2 deliverable. The delivered TIF is recalled for the expert assessment, which addresses each innovation proposed by BRIGAID. The expert judgments have to be combined by considering one or more criteria that should be identified and agreed by the project consortium. It should be noted that D5.2 is targeted to innovators, while this D5.3 is targeted to policy makers and consultants.

The DSS developed within the project sticks to the social, economic and environmental impact assessment without entering the details of each sector. The inclusion of the sectoral assessment in the DSS would require i) to establish general indicators of the regional/national/European sectoral impacts; ii) to define simple relations among the key governing parameters of each sector and the sectoral development itself; and iii) the collection of economic data for each sector at high resolution in study sites, and (iv) eventually the set-up of interviews and focus groups for the assessment of their dynamic development. While the definition of appropriate indicators is doable, the data collection effort would be unfeasible as well as the quantification of the dynamic relation of the indicators with the dynamics of hydraulic forcings, society and economics.

5.2. The assessment for each innovation

Climate Adaptation Innovations are designed to directly offset the effects of climate change in socio-economic sectors like agriculture, energy, forestry, health, infrastructure or tourism. However, they may also have (unintended or unforeseen) co-benefits or trade-offs in others. All impacts must be compared with the present situation (i.e., reference situation) and to the business as usual approach over the short and long-term.

Direct impacts are those caused by the preparation, construction, or operation of an innovation at a particular location. Indirect impacts are those that occur away from the location of the innovation (in space or in time) as a consequence of the implementation or operation of an innovation. Some impacts may be reversible with additional efforts when the innovation would be removed, while other impacts may be permanent.

It is important to note that the effect of climate change and the local, regional, and national impact(s) of an innovation on the different socio-economic sectors will be highly dependent on the implementation of the innovation at a specific geographic location. Its impact will also depend on the duration and severity of a hazard event together with the exposure, vulnerability and resilience of the socio-economic sector(s) and their components.

5.2.1. Agriculture

If an innovation needs area that is currently used for agricultural production, then its implementation may lead to resistance among farmers, and implementation could lead to an obligation to compensate the affected landowners.

If your innovation could improve local agricultural production conditions e.g. by increasing freshwater availability, improving the groundwater table, preventing damage by temporal flooding, or increasing the soil quality, then your innovation will probably meet support from farmers.

If your innovation could lead to an increase in the variety of agricultural products that could be produced, then this may result in interest of farmers or consumers for your innovation. However, when new products do require new expertise or additional investments, such interest may be very modest, or result in a demand for agricultural innovation.

If your innovation results in increased yield, e.g. by improving local production conditions, or improving harvest conditions or methods, then your innovation probably will meet support from local farmers.

5.2.2. Energy

If your innovation generates energy (e.g. a device that harvest wave energy) or sources for energy production (e.g. biofuel), or offers space for energy production (e.g. wind turbines or solar panels), then it probably meet support from the energy sector, the government, and the general public.

Research has shown that climate change may affect power generation by decreasing water availability and increasing ambient air and water temperature, which reduces the efficiency in cooling. If your innovation improves cooling water conditions for energy plants, then it will probably meet support from the energy sector and the government.

If your innovation improves the efficiency of energy production, then it will probably meet support from the energy sector and the government.

The energy sector is the largest contributor to global GHG emissions. If the innovation results in less greenhouse gas emission by the energy sector than in the current situation, or forms a sink for carbon dioxide, then it probably will be meets societal support and support from the energy sector.

5.2.3. Forestry

If an innovation needs area that is currently used for wood production, then its implementation may lead to concern from the forestry sector, and implementation could lead to an obligation to compensate the affected wood producers.

If your innovation would lead to improved resilience of a forest against climate change (e.g. by improving surface water management conditions, improving the groundwater table, preventing damage by temporal flooding, or increasing the soil quality) then your innovation probably result in support from the forestry sector.

If your innovation cost area that is currently in use for non-wood productions such as cork, fruit, hone, mushrooms, pastures, game, or fish, then it will meet concern from forest owners and users, and implementation could lead to an obligation to compensate the affected non-wood producers.

If your innovation would result in improved production conditions for non-wood products such as cork, fruit, hone, mushrooms, pastures, game, or fish, then your innovation probably result in low resistance or even in support from forest owners and users.

5.2.4. Health

If your innovation could decrease the potential numbers of fatalities of climate change related hazards (e.g. by reducing the risk of drowning during a flood, by a cooling effect during heat waves, by improving air and or water quality during heat waves), then it will probably be supported by the health sector, the government, and the general public.

If your innovation could reduce the impact of hazards on the physical health of affected people (e.g. by reducing the impacts of floods, by a cooling effect during heat waves, by improving air and or water quality during heat waves), then it will it will probably be supported by the health sector and the general public.

Climate change related hazard may result in stressful conditions for human beings, such as a high night temperature during heat waves (which may impact sleep). If your innovation could reduce the impact of climate related hazards (e.g. by reducing the urban heat effect due to the cooling effect of vegetation, the urban wind pattern, or water bodies) on the mental/psycho-social health of affected people, then it will it will probably not meet resistance by the health sector or the general public.

If your innovation emits or release chemicals or products that are harmful, then this may result in resistance, and it is recommended to adjust the design in order to prevent or reduce the emittance of these chemicals.

5.2.5. Infrastructure

If the innovation improves the quality of the built environment (e.g. by a urban design that deliberately uses trees to provide shade, or green roofs or walls to cool buildings or to store rainwater, or to develop green water retention areas), then it will probably meet less resistance, or even support from local residents or the local government.

If the innovation needs area that is currently in use for urban development, then it will probably meet resistance from the infrastructural sector, and implementation could lead to the appointment of another area for urban development, or an obligation to compensate the affected stakeholders.

If the innovation does increase existing transportation capacity or create new transportation possibilities (e.g. roads, railways or energy transportation networks integrated in flood defences), then it is likely to meet less resistance, and even receive support from the transportation sector and the government.

If the innovation results in a higher reliability of the existing transportation systems (e.g. by reducing the time that a road or railway is flooded, or by reducing the potential damage by erosion due to flooding to roads and railways), then it will probably meet few resistance, or even support from the general public and the transportation sector.

If an innovation results in a decrease in the power, water or waste management infrastructure, then it may not be accepted, and the innovator is advised to adjust the design.

If an innovation results in a less reliable infrastructure, then the innovator is advised to adjust the design.

5.2.6. Tourism

If an innovation needs area that is currently used for recreational activities, then it will probably meet resistance, while an innovation that results in more recreational area (e.g. a green water retention area, or water square in the urban area), will probably meet support.

If an innovation improves the recreational attractiveness of an area, e.g. by creating nature area or walking paths, then it will probably not lead to public resistance, and could create opportunities to strengthen or to develop the tourist sector.

If an innovation would lead to an extended tourist season (e.g. by offering new recreation possibilities outside the normal tourist season) then it will probably generate support among the general public and the tourist sector.

5.3. The assessment for a cluster

The assessment of the sectoral impact of each innovation, following D5.2, has been reported in Sub- section 5.2. This method is the only available method so far that can support end users in the estimation of the sectoral impact of proposed adaptation measures. The combination of the tables with scores (+/-/0) completed for each innovation can be used for a general qualitative assessment of the sectoral impact of the cluster as a whole. The combination of these tables may benefit by expert opinion, eventually by discussion in focus groups including the same persons involved in the SPRC application at the site.

The overall impact of a cluster of innovations cannot be simply quantified as the linear sum of the sectoral impact of each innovation, as the combinations will interact at local, regional and national scale. Put simply the combined cluster of innovations may more than the sum of their parts. Therefore, the sectoral impact for a cluster should not be merely given by a linear combination with equal weights assigned to the scores of each innovation selected to be in the cluster. The use of equal weights would not allow taking into account on one hand its effectiveness in terms of local performance and affected areas/activities/people and on the other hand its social and economic impact at a wider, i.e. regional and national, scale.

The weights to be assigned to each innovation in the cluster should in principle be such to represent

i) the effectiveness in risk reduction of each innovation in the cluster with respect to the cluster in case of the same storm, i.e. the same reference situation;

ii) the present condition and the development of each sector at local, regional and national scale;

iii) the cross-sectoral connections, and the interactions among these.

The extension of the sectoral impact assessment from a single innovation to a cluster of innovations is in principle possible by setting up an adequate criterion for weighting the sectoral impact of each innovation in a given cluster. However, the definition of such a criterion is extremely complex. It is therefore suggested

- to perform the full assessment of risk reduction produced by different clusters of innovations by using a Decision Support System, see Section 6. The available Decision Support systems allow to represent consequences of specific scenarios and to assess social, economic and environmental impacts. These tools, however, cannot provide the users with quantitative indications at the level of each sector, since this would require a number of indicators and data to develop original functions describing the dynamics of each sector;
- to assess the sectoral impact of each innovation and combine the outcomes of each table eventually discussing within a focus group of end users and experts, who also actively participated in the set-up of the SPRC in the site.

5.4. Overview of BRIGAID innovations

The Climate Innovation Window gives an overview of the 119 innovations currently associated with BRIGAID. Most of these innovations are designed to deal with multi-hazards (36) or intend to reduce the risk of droughts (29), heavy precipitation (21), and river floods (20); others address wildfires hazard (7), heatwaves (4), and coastal floods (2). The map of innovations (Figure 5.1) illustrates the location where each innovation has been developed and the related number produced so far for each country. Of these innovations, twenty-six have been selected by BRIGAID for testing, while two have completed such phase.

The innovations cover several functionalities (Figure 5.2): water availability, quality and safety, disaster management, agriculture and energy purposes, forest conservation, protection and improvement of urban areas including the implementation of nature-based solutions. In most cases they have multiple impacts on one or more sectors. This properties represents an advantage for the finalities of the adaptation strategies and for end-users.

We analysed which are the topics most frequently addressed by the 119 innovations and which innovations have multiple impacts. Results indicate that innovations on disaster and ICT are the most frequent (39), followed by innovations related urban areas (35), water safety (22) and agriculture (22).

Twenty-one innovations (group 1) are supposed to be beneficial to three different sectors, and thirteen innovations (group 2) are supposed to be beneficial to two sectors. In the group 1, the most frequent innovations are related to disaster and ICT, forests and natural-based solutions, agriculture, and water availability/quality. In the group 2, the most frequent innovations are related to disaster and ICT, and urban areas".

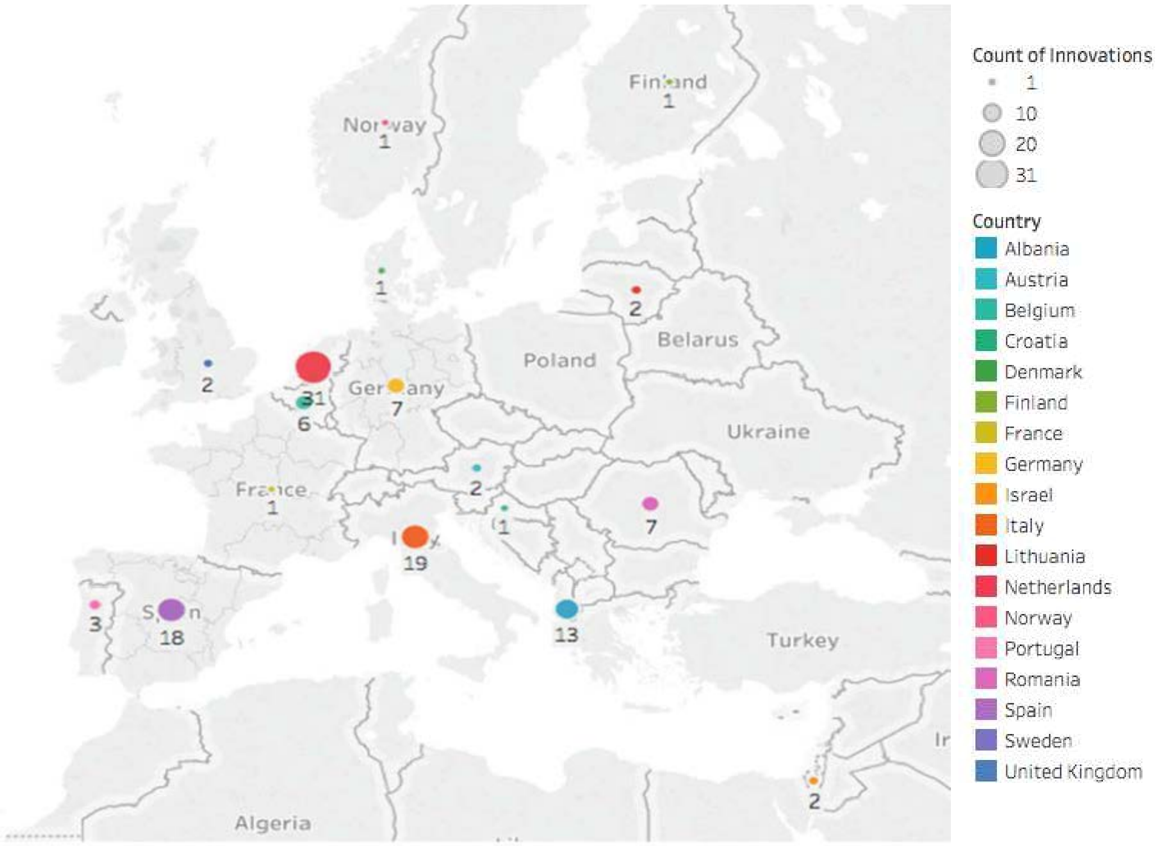


Figure 5.1. Map of innovations according to their number and location of development, currently included in Climate Innovation Window (N=119).

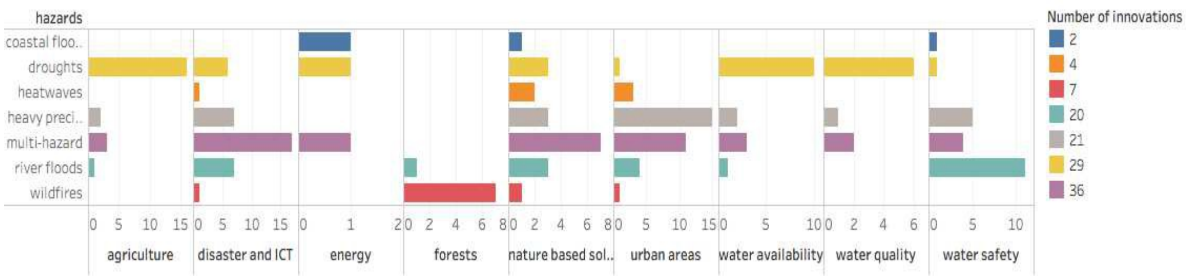


Figure 5.2. Innovations according to the specific hazard and the topic (sectoral impact), currently included in Climate Innovation Window (N=119).

6. Decision Support tools

6.1. Motivation

Policy makers and managers require tools for the rapid assessment of disaster risk, for the prioritisation of areas where interventions are urgently required, for the understanding of the effectiveness of the available mitigation and adaptation options, and finally for the selection of the best combination of measures that can promote safety and sustainability in a changing climate.

Moreover, improving the adaptive capacity of individuals, groups or organizations requires communicating present and possible trends in risk, building awareness of potential impacts and their implications. To these purposes, the use of Decision Support Systems (DSSs) is becoming more and more widespread in preliminary investigations of risk or as non-technical measures to promote disaster preparedness.

6.2. What is a DSS?

A DSS is an exploratory tool that allows to assess the conditions of a system under a variety of scenarios and the consequences of different adaptation and mitigation measures. A DSS will generally integrate the relevant environmental models, database and assessment tools - coupled within a Graphic User Interface (GUI). Spatial problems such as flood and erosion risk require a Geographical Information System (GIS) approach which can capture, manipulate, process and display spatial or geo-referenced data facilitating spatial data integration, analysis and visualisation. GIS tools are used either as data managers (i.e. as a spatial geo-database tool) or as an end in itself (i.e. media to communicate information to decision makers).

The key to successful risk management is to use mitigation techniques that are appropriate for the local situation. This is best achieved if all alternatives are reviewed to identify most efficient individual or suite of options for consideration by stakeholders and decision makers. Different mitigation options change the consequences of the hazards in different ways; in case of floods, engineering based solutions generally change the amount or the extent of flood, while planning can change the nature of the flooded area and therefore the consequences.

The development of DSSs is an important part of selecting and assessing mitigation options. Generally, they are unable to determine the 'best' option or provide detailed option applicability or placement. They can, however, identify, examine and explore mitigation options by evaluating their relative efficiency, equity and sustainability in determining risk levels and potential consequences. This is particularly important when selecting mitigation strategies under uncertain future conditions.

6.3. A short review of DSS for risk assessment

As an example, the review is here limited to coastal flooding. The use of GIS for coastal zone management has expanded rapidly during the past decade (Wright and Bartlett, 2000; Bartlett and Smith, 2004; Wright et al., 2011; Sheppard, 2012). Similar DSSs can be configured for other vulnerabilities, such as droughts, pluvial and fluvial floods, heat stress, wind speeds, etc.

Based on a review of a range of existing DSSs which deal with coastal areas (Table 9.1), the main objectives of these tools are the analysis of vulnerability, impacts and risks, and the identification and evaluation of related management options, in order to support robust decisions for sustainable management. Specifically, the objectives of the examined DSS tools address three major issues (with examples in brackets from Table 6.1):

- the assessment of vulnerability to natural hazards and climate change (DIVA, RegIS, CVAT, DESYCO, KRIM, Coastal Simulator, THESEUS);
- the evaluation of present and potential climate change impacts and risks on coastal zones and linked ecosystems, in order to predict how coastal regions will respond to climate change (RegIS, CVAT, Coastal Simulator, THESEUS);
- the evaluation or analysis of management options for the optimal use of coastal resources and ecosystems through the identification of feasible measures and adequate coordination of all relevant users/stakeholders (COSMO, WADBOS, SIMCLIM, RAMCO, THESEUS).

It is worthy to mention the effort of the European Commission delivering a web-platform to promote Climate Adaptation by means of sharing information, best practices, assessment methodologies and adaptation solutions. The resulting tool provides guidance, i.e. it is not a software tool for running specific scenarios at a given area (http://climate- adapt.eea.europa.eu/knowledge/tools/adaptation-support-tool).

6.4. THESEUS DSS

Some details about the recently developed THESEUS DSS (www.theseusproject.eu, Zanuttigh et al., 2014a) are given here as an example of how a high-resolution GIS-based DSS for coastal risk assessment and management works.

The THESEUS DSS is based on the following pillars:

- It provides seamless integration across disciplines: physics, engineering, ecology, social sciences and economy.
- It considers intermediate spatial scales (10- 100 km) and short-, medium- and long-term time spans (1-10-100 years).
- It allows diverse combinations of mitigation options such as engineering defences (i.e. barriers, wave farms, etc.), ecologically-based solutions (i.e. biogenic reefs, sea-grasses, etc.) and socio-economic mitigations (i.e. insurance, change of land use, etc.).
- It supports decision-making based on a balance between deterministic models and expert judgement.

The 'structural' scheme of the DSS is presented in Fig. 6.1. It is worth noting that this DSS is only desktop based. The DSS input database for each site has to include a Digital Terrain model (Fig. 6.2) – as detailed as possible; hydraulic structures and infrastructures position, geometry; map of land-use including critical facilities; list and/or map of geo-referenced social and economic indicators, such as: age, gender, unemployment rate, education level, health status, etc; geo-referenced maps of habitat types and species including: rare species, rare habitats, commercially important marine habitats, habitats relevant for coastal protection.

Tab. 6.1 Review of existing exploratory tools that can be used for supporting decisions applied to coastal areas. These GIS-based tools perform scenario construction and analysis. To be continued.

Name	Year	Ref	Processes	Functionalities
COSMO	1992	Feenstra et al. (1998)	Sea-level rise	Problem characterization (e.g. water quality, coastal erosion,) Impact evaluation of different development and protection plans Multi-Criteria Decision Analysis Ecosystem-based
Coastal Simulator	2000-	Mokrech et al. (2009) Dawson et al. (2009)	Storm surge Flooding. Coastal Erosion Sea-level rise Socio-economic scenarios	Environmental status evaluation Risk analysis Management strategies identification and evaluation Uncertainty analysis Integrated risk assessment
CVAT	1999-	Flax et al. (2002)	Multi-hazard Extreme events Storm surge	Hazard analysis Social, economic and environmental vulnerability indicators Mitigation options analysis Risk analysis at regional scale
DESYCO	2005-2010	Torresan et al. (2010)	Sea-level rise. Storm surge Flooding. Coastal erosion. Water quality	Impacts and vulnerability analysis Adaptation options definition Multi- Criteria Decision Analysis Regional Risk Assessment

Tab. 6.1 Review of existing exploratory tools that can be used for supporting decisions applied to coastal areas. These GIS-based tools perform scenario construction and analysis. To be continued.

DIVA	1999-	Vafeidis et al. (2008) Hinkel & Klein (2009)	Sea-level rise Coastal erosion Storm surge Flooding Wetland loss and change Salinisation	Environmental status evaluation Impact analysis Adaptation options evaluation Cost-benefit analysis
KRIM	2001-2004	Schirmer et al. (2003)	Sea-level rise Extreme events Coastal erosion	Environmental status evaluation Adaptation measures evaluation Information for nontechnical users Risk analysis
RegIS	2003-2010	Holman et al. (2008)	Coastal and river flooding Wetland loss and change Sea-level rise Emission scenarios Socio-economic scenarios	Implementation of DPSIR conceptual model Management measures evaluation Impact analysis Integrated risk assessment Information for nontechnical users
RAMCO	1996-1999	De Kok et al. (2004) http://www.riks.nl/resources/papers/RamCo2.pdf	Socio-economic scenarios Coastal and river flooding Policy options Impact of human activities Integrated management	Environmental status evaluation Management measures evaluation.

Tab. 6.1 Review of existing exploratory tools that can be used for supporting decisions applied to coastal areas. These GIS-based tools perform scenario construction and analysis. Continued.

SimCLIM	2005-	Warrick et al. (2009)	Sea-level rise Coastal flooding Coastal erosion	Environmental status evaluation Impact and vulnerability evaluation Adaptation strategies evaluation Cost/benefit analysis
WADBOS	1996-2002	Van Buuren et al. (2002)	Socio-economic scenarios Policy options Impact of human activities Integrated management	Socio-economic, hydrological, environmental, ecological data Socio-economic, ecological, landscape models Management measures identification and evaluation
CLIMSAVE	2010-2013	Harrison et al., (2013)	Emission scenarios Agriculture Forests Water Resources Coastal and river flooding Urban development	Implementation of DPSIR conceptual model Impact analysis Adaptation strategies
THESEUS	2010-2013	Zanuttigh et al. (2014a)	Sea-level rise Coastal flooding Coastal erosion Socio-economic scenarios	Hydraulic, social, economic, ecological vulnerability Combination of engineering, social, economic and ecologically based mitigation options Multi-criteria analysis High resolution risk assessment

THESEUS DSS is based on scenarios analysis (Fig. 6.3 shows the scenario analysis interface) and specifically includes:

- climate and environmental scenarios, which can be a pre-defined set of conditions derived by scientists (wave height, storm surge, sea level rise, etc.) for short, mid and long term or a set of conditions based on the kind of scenario the user wishes to explore, ordinary or extreme;
- economic and social scenarios, essentially based on expected changes or trends of the population and on the gross domestic product;
- environmental scenarios, provisionally limited to subsidence; in a future research, the scenarios of the habitat modifications likely to occur based on changes of temperature, social and economic development, etc. may be included.

The DSS needs the definition by the site manager of the following elements (lines, points) that are relevant for modeling the hydraulic processes.

- Waves: boundary conditions have to be prescribed at locations where scenarios are given by the scientists.
- Shoreline and sea-bank line: these lines represent the water/beach boundary needed to estimate beach retreat, and the water/land boundary from which flooding starts, respectively.
- Water sources: one or more punctual sources for each coastal segment, depending on the minimal resolution adopted for describing the area, where flooding will be predicted.

Mitigation measures are represented both as changes of pathways and of receptors, and include (Fig. 6.4 shows the mitigation selection interface):

- engineering mitigations, such as wave farms, barriers, floating breakwaters, sea walls, etc., that affect wave transfer from offshore to shore; these mitigations can directly be drawn by the user (Fig. 6.5) or uploaded through a shapefile;
- ecologically based mitigations, such as management or construction of dunes, reinforcement of salt-marshes, creation of biogenic reefs; these mitigations can be represented as a change of the habitat map and where applicable also as a change of bottom elevation;
- economic and social mitigations such as evacuation plans, land use change (for instance managed realignment), insurance premium; the user can interact by modifying the insurance premium value, the percentage of evacuated people or the destination of a given area.

The physical processes include wave transformation from offshore till the shoreline, beach erosion, wave runup on the beach and overtopping over the sea-bank, and finally flooding. The 'flooded DEM' consists of maps of flood depth, duration and velocity of flood propagation, see an example in Fig. 6.6.

THESEUS scientists developed appropriate 'damage functions' to link economic, social and ecological data to hydraulic parameters (beach retreat, flood depth, duration, velocity) and produce 'damage' maps (actually impact maps since the monetary scale is used only for the economic consequences).

The overall risk related to the examined combination of scenarios and mitigations is assessed by means of the multicriteria analysis, which integrates the engineering, social, economic and environmental impacts into the spatial distribution of a semi-quantitative risk indicator; see the map in Fig. 6.7.

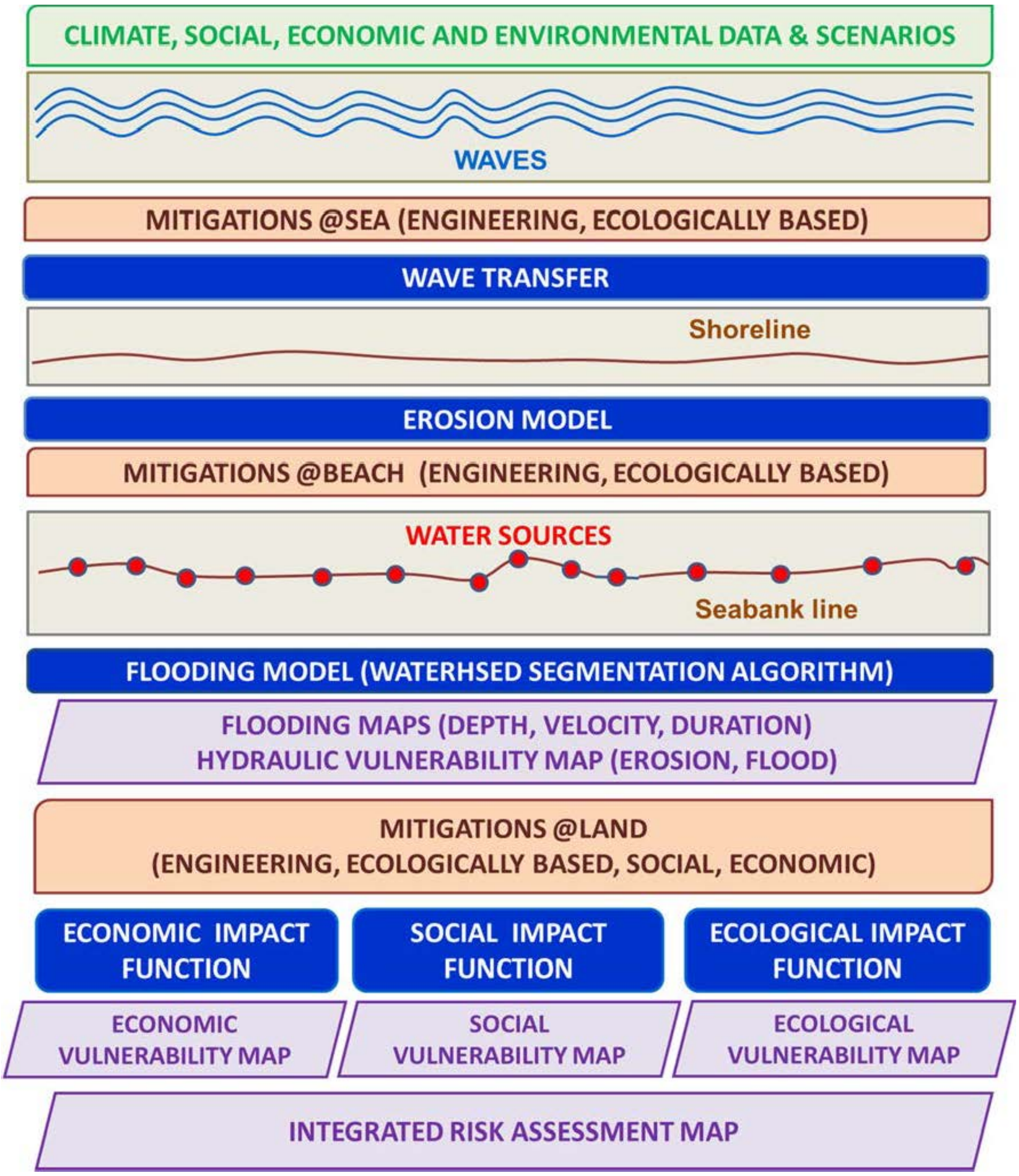


Fig. 6. 1 Key elements and the flow of the information within THESEUS DSS. A sharp rectangle indicates the input data required to run the model; a rectangle with 2 sharp and 2 rounded corners denotes the input data where the users can interact; a rounded rectangle the functions defined by the scientists; with a parallelogram the output of the DSS. From Zanuttigh et al. (2014a).

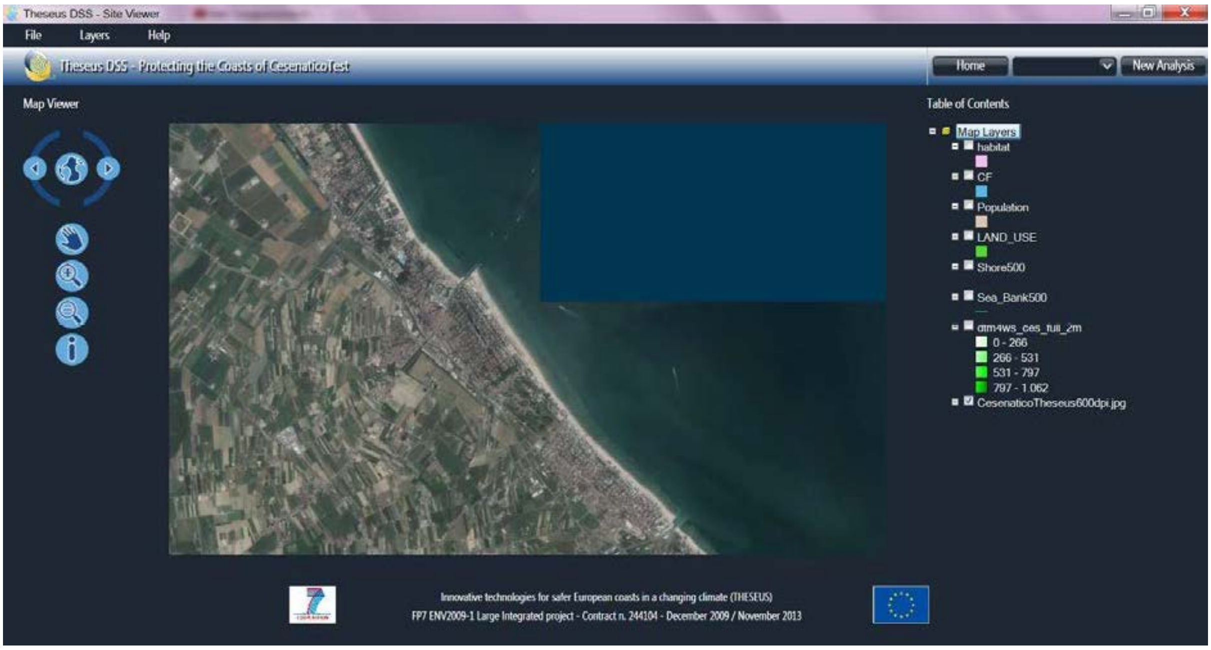


Figure 6.2. The viewer at the start-up.

Figure 6.3 Scenarios screen.

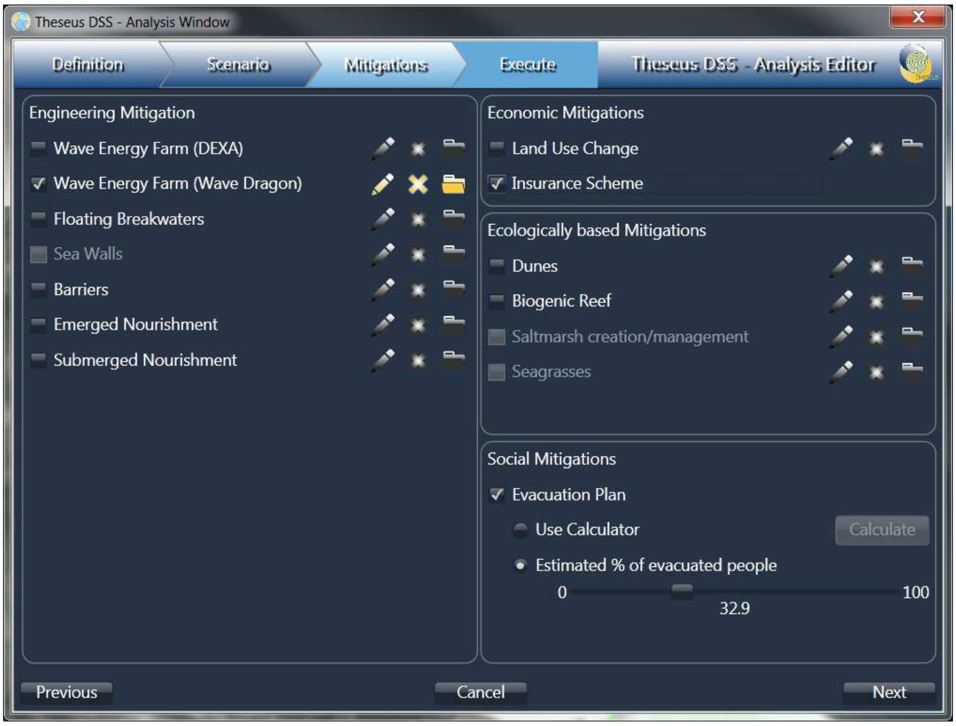


Figure 6.4 Mitigation screen.

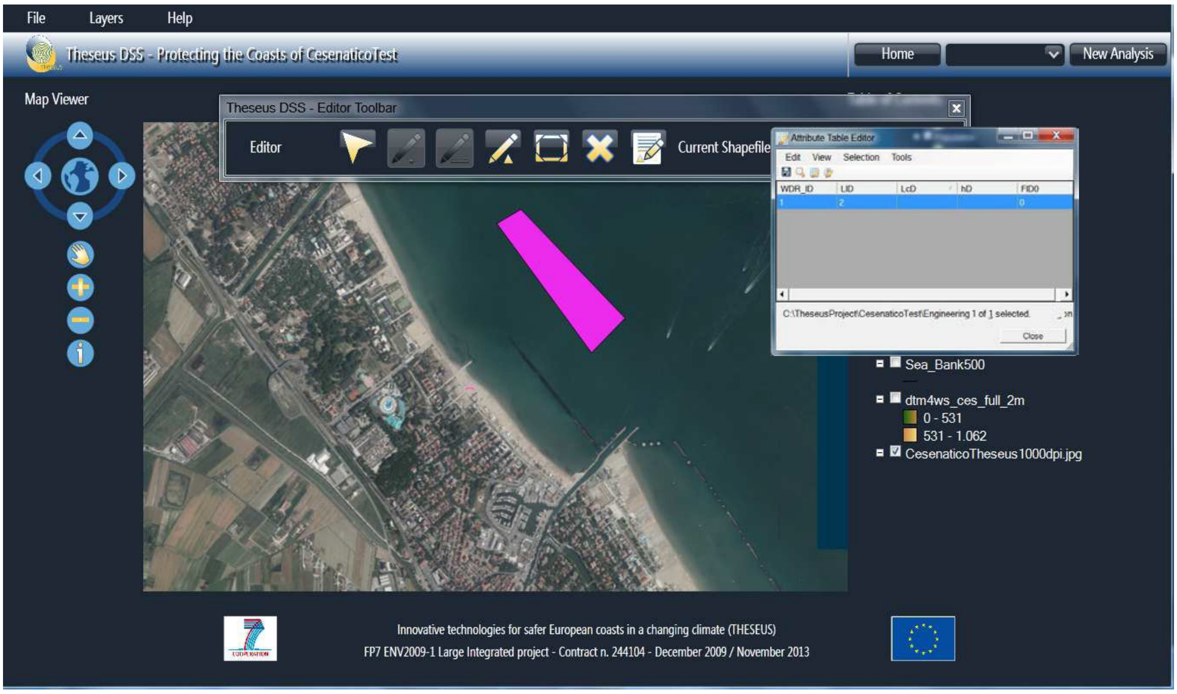


Figure 6.5 Editing a mitigation option in front of Cesenatico.

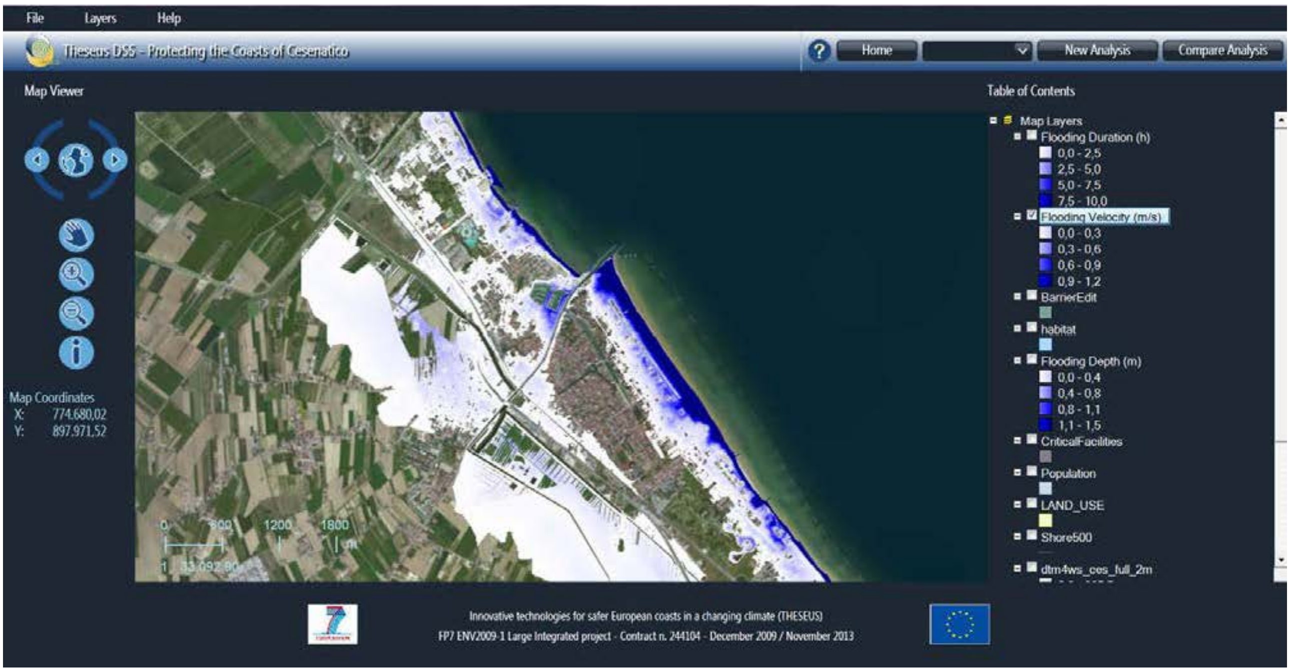


Figure 6.6 Example map of flooding velocities derived from the modified watershed segmentation algorithm. Long term (2080) scenario with return period (combined wave and storm surge statistics) Tr=100 years.

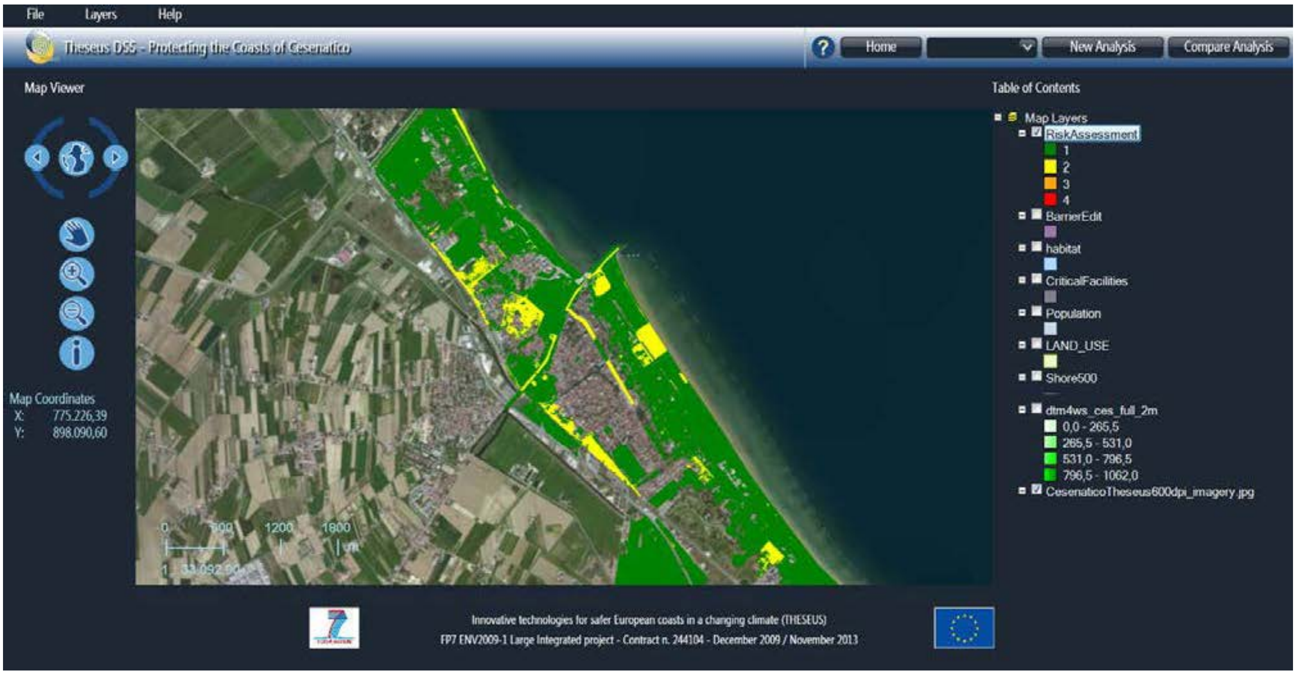


Figure 6.7 Example of integrated risk map, scale from 1 to 4 (from low to very high impact). Long term (2080) scenario with return period (combined wave and storm surge statistics) Tr=100 years.

6.5. The DSS developed within BRIGAID: the COASTS tool

The DSS developed by UNIBO within the BRIGAID project, the COASTS tool, is based on a significant revision of THESEUS DSS, leading to three overarching improvements.

The first improvement was the migration of the DSS from a desktop-based to a web-based platform by using the Geocortex environment provided by VertiGIS, an ESRI platinum partner to allow a wider dissemination of the concepts supported by the DSS and of the decision making process among managers, consultants, researchers and students.

The second major revision was the replacement of the flooding model with a more physically based model, based on a simplified version of the shallow water equation (Hunter et. al. 2007) integrated in a 2D quadtree mesh. The flooding model solves the equations described in Bates et al. (2010) coupled with an adaptive integration domain adapted to the new mesh type.

The third major improvement was the coupling of the 2D overland flow with the 1D channel discharge (rectangular and trapezoidal sections) and the rain runoff , so that the DSS can reproduce not only coastal flood but also river flood and extreme rainfall events fulfilling the multi-hazard perspective adopted by BRIGAID.

Figures 6.8 and 6.9 show as an example two new results derived directly from the second and third major improvements. Figure 6.8 shows the dynamic evolution of a coastal flood. The panels to the left and to the right correspond to the flooding after one hour and two hours of storm respectively. Figure 6.9 shows the flooding induced by an extreme rainfall. The panels to the left and to the right refer to 1 hour and 8 hours after the 6 hours rainfall event.

Figure 6.8. Example of flooding in time with the new 2D model in Cesenatico (FC, Italy).

Figure 6.9. Example of flooding due to an heavy rain in the watershed of Cesenatico (FC, Italy).

A further improvement of the DSS consisted in the presentation of the results not only in terms of maps but also as quantitative indicators to allow an easier comparison among different scenarios, such as: the percentage of the flooded area with respect to the total area under investigation; the percentage of the flooded area characterized by flood depth greater than 0.5 m, 1 m, 1.5 m and 2.0 m with respect to the total area and time. Similarly velocity maps are produced and a set of indicators are calculated for different threshold velocity and respect to time: The percentage of CFs interested by a loss greater than or equal to 20%, with respect to the total number of CFs; the percentage of the flooded area characterized by land value losses greater than or equal to 30% of the total value loss.

Finally, in order to overcome the complexity of the framework developed in THESEUS, where several code pieces written a complied by using several languages (such as CSharp, Matlab, Python, C++, etc.) were assembled into one tool, and in favour of a better, all the scripts previously coded where been re-coded in Python in order to simplify the architecture of the DSS. In fact the python shell can be easily included and used in several tools and also natively in the *Geocortex* framework.

Overall, the new tool has running time for each scenario much lower than the original tool: about 5-8 minutes against 30-45 minutes for the same conditions. The user experience has also significantly improved.

6.6. Practical and conceptual challenges

Besides the intrinsic problem of integrating different disciplines with different views and languages, the preparation of a DSS has to face practical and conceptual challenges:

The conceptual approach and the simplified modeling assumptions that are at the basis of the DSS may be considered too simplistic by coastal managers and stakeholders to trust the reliability of the results.

However, the relatively fast running time allows the user to examine many different scenarios so that he/she can identify how and how far the DSS results compare with the historical data and/or the memory in the sites. Moreover, the inherent uncertainty of the results (common to any type of sophisticated model) can be overcome aiming at a sensitivity analysis of the results, i.e. at comparing results of different scenarios considering that all the results are affected by the same simplifying assumptions.

In many cases, the topographic, social, economic and ecological high spatial resolution data that are required for running the DSS may be not available. Even when available these data may be owned by different authorities (municipalities, regional governments, ministry) and scattered and hard to obtain, due to miscommunication among the owners and confidentiality issues.

Results based on a single scenario run may lead to erroneous decisions. It is therefore important to warn the users that the best methodological approach consists of running multiple storm scenarios for each selected time slice and by post-processing the results of these scenarios to get the sources-consequences function. Specifically, the social, economic, hydraulic and ecological vulnerability maps obtained for each storm should be multiplied by the probability of occurrence of the corresponding storm and then added to get the average vulnerability maps. Relevant parameters/indicators should be identified and compared to better quantify the effects rather than by the qualitative impression given by the maps (Zanuttigh et al., 2014b).

In conclusion, it should not be forgotten that the DSS is essentially a tool to be used in a preliminary assessment phase. It is not meant to substitute the detailed design process. Hence, the DSS is designed to be part of a multi-layer approach for risk management.

7. Antwerp case: climate adaptation planning through the innovation HydroVentiv and alternative solutions

7.1. Introduction

The district of Sint-Andries in the heart of the city of Antwerp is one of BRIGAID's living labs, where innovations can be tested in operational settings. The impact of such (cluster of) innovation(s) on hazards and consequences needs to be quantified. This Section describes the application of the newly developed SCAN tool to quantify the impact of an innovation and compares it against alternative solutions. More specifically, the impact of the innovation "HydroVentiv" (new type of green roof) of the company Vegetal on urban floods is quantified, and compared against the impact of other SuDS (permeable pavement with a buffer capacity). It is essential that the developed impact quantification tool can also include today's (water management) solutions to tackle similar hazards. Only through such a comparative approach, innovations can truly be tested, improved and promoted successfully. Therefore, the city of Antwerp and sewer management company Aquafin were also included in a participatory traject to define the scenario's of alternative solutions. Hence, their practical considerations, experience and ideas on innovative urban water management are also included in the comparison to ensure realistic results were obtained.

The HydroVentiv green roof was installed in autumn 2017 as a first-cycle innovation in BRIGAID on the roof of Beweging.net in the district Sint-Andries (Antwerp, Belgium). Different green roof configurations were built, and a monitoring campaign was started (see also Figure 7.1). Details and pictures of the installation, as well as the first monitoring results were included in report "BRIGAID – 700699 – Climate change indicators". Also, several movies were created during the installation procedure, including interviews with stakeholders such as staff of the city of Antwerp. This movie was shown at the BRIGAID conference in Venice (9th November 2017). In this section, the SCAN tool is applied by the BRIGAID team for upscaling the HydroVentiv green roof to the level of the city. This allows the team to quantify its effect when the green roof would be applied at numerous roofs through the city (see Figure 7.2).

The SCAN tool itself is also an innovation which is tested within BRIGAID. SCAN is designed to support decision making, such as spatial planning, climate impact analyses and adaptation, etc. Also, it can be incorporated in a broader Decision Support System (DSS) to drive various applications, such as real time optimization problems, warning systems, etc. SCAN is a tool that (currently) focuses on urban and riverine water management, and is under development in company Sumaqua. For this application, the KU Leuven partner used the SCAN tool. More information about SCAN is provided in a next subsection. Note that is section solely focuses on urban flood risks, but the SCAN approach was designed so it can easily be extended to include, for instance, urban heat stress. Likewise, equations can be implemented in SCAN to quantify consequences.

Besides the measurement results of the HydroVentiv green roof monitoring campaign, additional data and models were used to set up and simulate the SCAN model. Meteorological data from neighbouring rain gauges (Melsele and Wilrijk) were used, together with composite storms (for the Uccle and Antwerp climate), and perturbed for climate change. The latter allows to quantify the effect of climate change on floods in the city of Antwerp, and to investigate if the innovation can have a significant impact on climate change effects. Hydrodynamic InfoWorks ICM models were available from the sewer management company Aquafin to calibrate the SCAN model. Validation data of emergency response units (fire fighters and Civil Protection) were gathered. This validation data indicates where and when calls were made to the emergency response units regarding floods, and thus give an approximate indication of historical urban flood problems. Finally, vulnerability data (such as the locations of hospitals, crèches, schools, retirement homes) can be collected through Flanders' Geopunt portal.

Figure 7.1. Antwerp test site of the HydroVentiv green roof (picture taken on 14 February 2018).

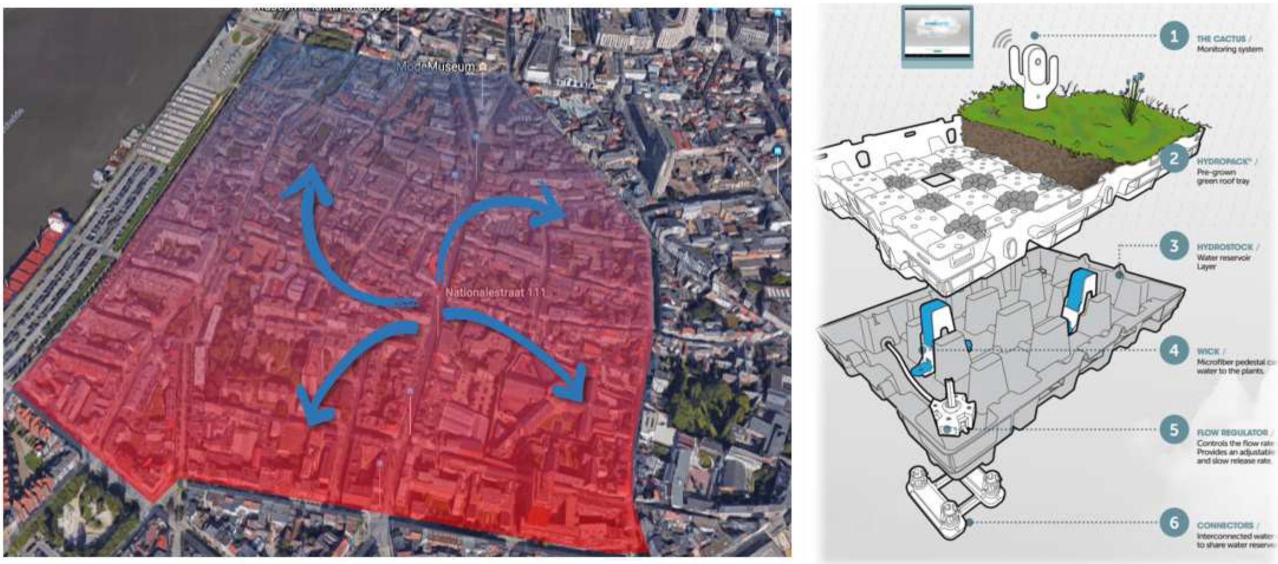


Figure 7.2. Upscaling and quantification of the innovation HydroVentiv (green roof, right) in the city of Antwerp through the SCAN tool.

7.2. SPRC approach

The Source-Pathway-Receptor-Consequence (SPRC) approach was followed to quantify urban flood hazard on the city of Antwerp. The conceptual SPRC approach is described in detail in Section 2 of this report, which has been used numerous times in environmental sciences, also to quantify flood hazards (see Section 2 for a list of references). Herein, the SPRC approach visualises the flood risk as a linear process involving a "Source" of flooding (e.g. a heavy precipitation event with surcharging sewer pipes or limited surface runoff/infiltration capacity), one or more "Pathways" (which can be either through the underground network of sewer pipes, or the above ground topography such as streets), one or more "Receptors" (e.g. a crossroads, house, infrastructure, street where ponding/flooding accumulates) and related "Consequences". This process is also visualized in Figure 7.3. Naturally, the SPRC approach is driven by boundary conditions. For the case of Antwerp, this is, amongst others, rainfall, evapotranspiration (although only marginally), the level of the neighbouring Scheldt River in which is spilled, the underground sewer system and capacity itself, pumping stations, hydraulic infrastructure (such as sluices, weirs and overflows), the topography and digital elevation, surface roughness, etc.

The SPRC approach can also be embedded in a higher level Driver-Pressure-State-Impact-Response (DPSIR) framework which more explicitly accounts for the influence of drivers and pressures external to the system being investigated. For the case of urban flooding in Antwerp, this can refer to urban water management decision making, such as a broader adaptation planning to tackle the impacts of climate change. Indeed, different adaptation strategies can be assessed in DPSIR, in which each time a SPRC approach is followed to quantify the consequences for one of those adaptation strategies. This DPSIR analysis is not performed for the Antwerp case, as it is not the goal of this SCAN's application. However, the applied framework surely enables uptake in such DPSIR approach.

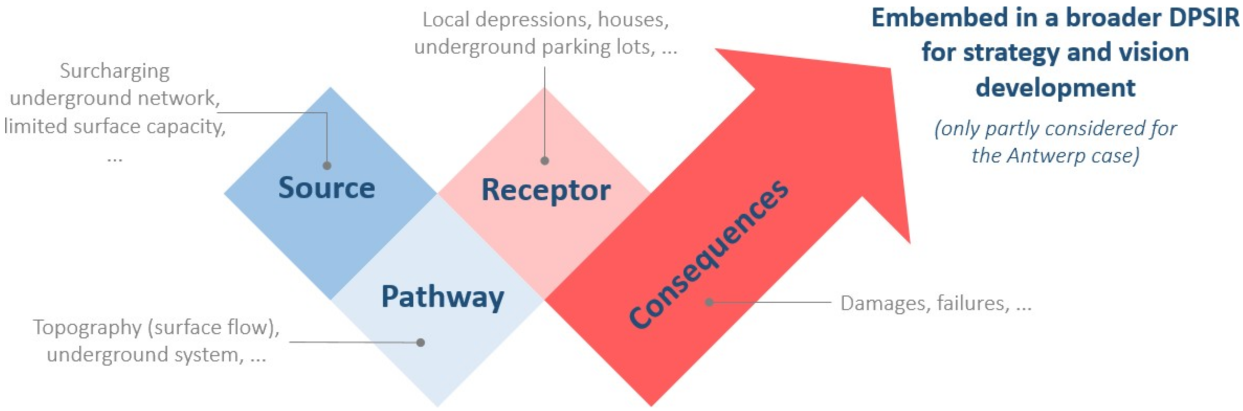


Figure 7.3. Followed SPRC approach to characterize urban floods for the city of Antwerp. SCAN is applied to quantify this process, including innovations.

In the application of the SPRC approach for urban (solely pluvial) floods in Antwerp, one could consider the related indicators described in BRIGAID report "BRIGAID – 700699 – Climate change indicators". These indicators include the Simple Daily Intensity Index (SDII) and precipitation from very wet days (R95p). When assessing climate change, indicators such as the relative changes in return periods can be used, such as RX1day. These indicators are also used by the IPCC AR5 report. However, in the context of urban floods, such indicators refer to the threshold when pluvial floods are going to emerge, and what their probable extent will be (if such threshold is "calibrated" to historical pluvial events with a known flood extent), but do not account for changes itself in the urban system. Indeed, after analyzing long term records of pluvial floods and its main drivers (being precipitation, but also water levels of receiving rivers), one can establish thresholds of these drivers that will lead to a certain pluvial flood. If the urban system changes, such as because of the uptake of innovations, these thresholds might change. A simple approach using indicators thus does not suffice to quantify the impact of innovations.

Therefore, the SPRC approach must include explicit modelling of the processes underlying urban floods. Hereto, multiple approaches are plausible. One could rely on "classical" hydrodynamic modelling. For operational management of urban water systems, such hydrodynamic models (e.g. InfoWorks ICM, SWMM, 3di, ...) often already exist. This is also the case for Antwerp, for which sewer company Aquafin created InfoWorks ICM models (1D-1D) of the city of Antwerp. These models were made available for this BRIGAID study. An advantage of these hydrodynamic models is the level of detail. However, one should note that a higher level of model detail does not necessarily lead to enhanced model accuracy. The parameters and assumptions underlying a hydrodynamic model are far more important, and are often not well calibrated. Hydrodynamic models also suffer from major disadvantages in the context of quantifying the impact of (clusters of) innovation(s) and operational urban water management. Firstly, given their prolonged calculation times, simulating a range of different scenarios is very time consuming. And yet, to quantify the impact of innovations, a large number of scenario runs can be necessary to cover all possible implementations (e.g. the precise lay-out of the green roof, the locations of implementation, different boundary conditions, etc.). Secondly, due to their rigid model structure, it can be difficult or even impossible to model (thus implement) innovations. Indeed, some innovations can require model equations that are not coded in the hydrodynamic software. Thirdly, hydrodynamic models solely focus on urban floods. Other (although related) processes are not accounted for. Green roofs for instance, mitigate urban floods, but are also useful to tackle heat stress problems. Finally, some consequences can be difficult to quantify, such as long term effects. Green roofs have an impact on biodiversity, but such (positive) consequences can only be quantified through long term simulations.

To overcome the limitations of these hydrodynamic models, Sumaqua currently develops the SCAN framework. This SCAN framework is applied by KU Leuven for this analysis. SCAN is a conceptual modelling framework that aggregates processes on a higher level. This allows the modeller to focus on the dominant and most relevant processes. The framework is highly flexible, so it can easily be extended with additional model structures. Hence, innovations, that require any equations, can also be included. Different processes, such as city heat stress, could also be implemented (by including additional model structures in SCAN). In addition, the SCAN framework can be embedded in an IT system to drive other applications, and thus function as a DSS. One of SCAN's main advantages is its simulation speed. Due to the model conceptualisation, it can easily simulate time series of multiple years in just a few seconds. This enables applications that require a vast range of different scenarios, and long term simulations. Such simulations result in unique insights, that cannot be gained through hydrodynamic modelling at this moment. The reader is referred to the next paragraph for a more elaborate discussion on SCAN.

This application does not quantify consequences explicitly, as it is not the goal of this analysis. Instead, it relies on indicators, such as the extent of floods and flood volumes as a proxy for the flood consequences. One should note though that, if more detailed information such as damage curves become available, these can also be included in the analyses. Naturally, vulnerabilities (and risks) can also be visualized and quantified by creating overlays with valuable or vulnerable infrastructures, such as retirement homes, schools, crèches, low-income districts, etc.

7.3. SCAN framework and model

SCAN is an innovative hybrid modelling platform that is currently under development. The platform focuses on the integrated water system (urban hydrology and drainage systems, riverine hydrology and hydraulics, floodplains, buffers, etc.), but can easily be extended to include other processes, such as city heat stress and ecovariable modelling up to socio-economic impacts. The SCAN model can form the core of an advanced and versatile decision support system (DSS) for the cities that can be used for various applications, including strategic planning, climate adaptation planning, communication and awareness creation through visualizations of scenarios, and emergency planning, up to smart applications such as early warning systems and intelligent control.

SCAN combines 3 innovative aspects, being:

- Its' model core consists of a unique hybrid combination of conventional model structures and big data analytics (such as machine learning). See Figure 7.5 for an overview of the included model structures.
- SCAN has a hyper fast simulation engine, able to simulate input time series of multiple years in a few seconds.

• The SCAN platform has an open architecture, and can thus be integrated in virtually any environment. Vice versa, other third-party modules (such as radar – rain gauge merging algorithms, but also cross-sectoral KPI's) can also be integrated in SCAN.

SCAN focuses on the integrated water system, from small scale elements (e.g. private rain water tanks) up to floodplains and urban drainage systems of entire cities (see Figure 7.4). It has an open architecture, enabling other modules to be linked to SCAN, even in a simulation environment (time-step based coupling). Given this open architecture, SCAN itself can also be integrated in various (operational and cloud) IT environments.

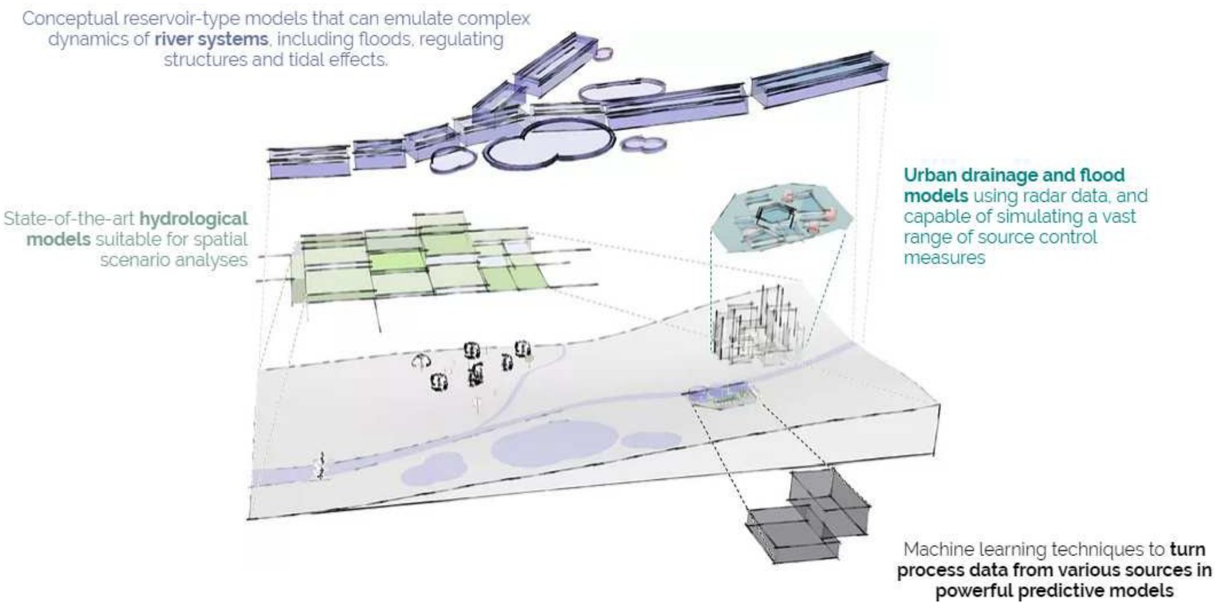


Figure 7.4. SCAN model framework (focusing on water systems, but expandable to other processes).

What is unique about SCAN is its hybrid combination of conventional model structures and advanced data-driven techniques. Conventional structures refer to elements also found in "classic" modelling approaches, such as equations that explicitly describe controllable hydraulic infrastructures, dikes and levees and the equation of conservation of mass. By expanding and enforcing these structures with big data analytics (machine learning techniques), the methodology becomes more versatile and powerful. Indeed, big data technologies can be leveraged to gain new insights into the function of the system (e.g. during long term monitoring campaigns), or to improve model predictions. Figure 7.5 shows the different model structures that are included within SCAN.

SCAN's advanced and hyper-fast simulation environment is under development at Sumaqua. The majority of the simulation core is published in international peer reviewed journals (e.g. Wolfs et al., 2015; Wolfs and Willems, 2017). This simulation engine can simulate the effect of decades of time series (such as rainfall, evaporation, temperature) in a few seconds. Despite rapid computational advances, a need for such fast simulation remains and even increases due to the growing numbers of data in terms of availability. For instance, applications that require a large number of simulations require fast engines, such as uncertainty analyses (e.g. ensemble simulations) and optimization problems (which simulate a number of different strategies). Also, applications requiring long term simulations need such simulation cores with limited calculation times (such as trend analyses).

In addition, SCAN enables the user to create tailored models that are designed to an application and situation. Irrelevant processes, such as for instance the precise flow vortices around hydraulic structures, and highly uncertain processes can easily be neglected or aggregated to a higher level. Thus, such processes are incorporated in less detail. Likewise, if data is missing, the level of detail of the SCAN model can be adjusted to match the data that is available. Overparameterisations, which happen frequently in classical modelling, can be obviated. Hence, the model can be tailored to the application that one has in mind and the data that is available, by only focusing at the most dominant and relevant processes. This also results in practical models, that only focus on the relevant processes, and form an operational toolkit for water managers. Figure 7.6 shows such application of SCAN on part of the city of Ghent. In this example, processes were aggregated extensively, while maintaining a high model accuracy for the desired application. The coloured polygons on the right delineate the conceptual reservoirs of the SCAN model.

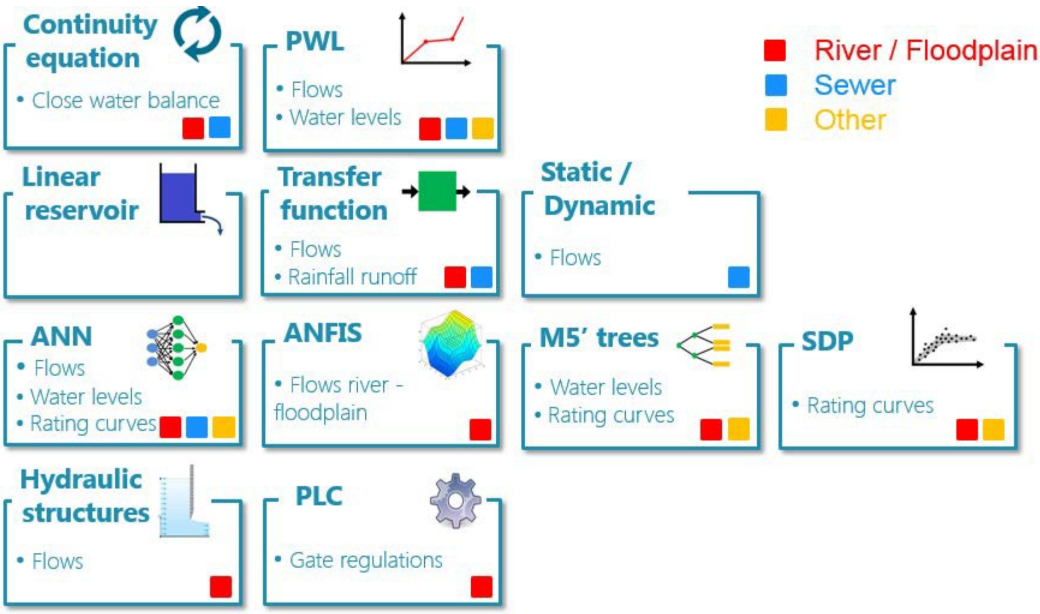


Figure 7.5. Overview of included model structures in SCAN.

The SCAN model of Antwerp focuses on the (mainly) historical center of the city, which is delineated by the ringway and the Scheldt river (see also Figure 7.7). As in Figure 7.6, the underground system is divided in multiple "storage cells". In each of these cells, the water balance is closed explicitly, and in- and outgoing flows are calculated. These flows mainly consist of rainfall runoff (i.e. incoming flows). Between the different storage cells, fluxes or discharge links are located. The number of discharge links between two cells varies, depending on the flow dynamics. These flow links are calibrated. The urban subcatchments determining the incoming flow are simply copied from the InfoWorks ICM model, using the same equations as in the hydrodynamic model itself. These are thought to give the most suitable representation available of the topography and rainfall runoff, although it is probably also the largest source of uncertainty in the entire model set up. Indeed, the sub-catchments are only a rough and highly aggregated representation of reality. As insufficient real measurement data is available to set up the SCAN model, the simulation results of the InfoWorks ICM model were used as virtual sensor data to calibrate the fluxes between the storage cells and the Combined Sewer Overflows (CSOs). Thus, the SCAN model is configured based on simulation results of a detailed InfoWorks ICM model. The InfoWorks ICM model is considered to be the best available representation of the urban drainage system. In a next phase, a validation is performed based on data from emergency units, indicating where floods occurred in the past.

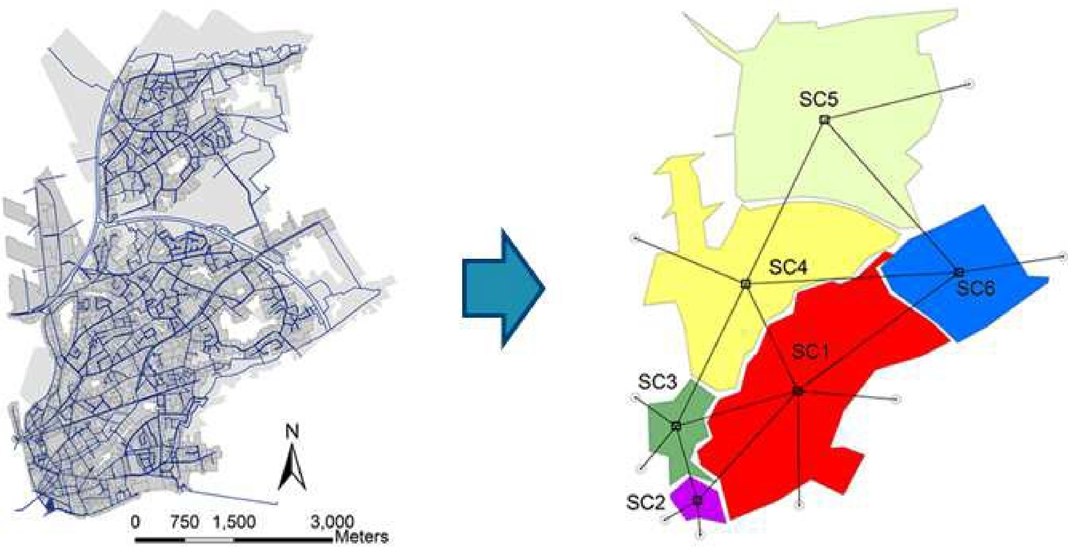


Figure 7.6. Application of SCAN to the city of Ghent (Belgium) for quantification of combined sewer overflows.

Figure 7.7 shows the extent of the SCAN model. It covers the entire urban drainage system within the ringway. The original InfoWorks ICM models cover a broader extent beyond the ringway. This area was discarded in the SCAN model. The green area is further divided in multiple storage cells. The urban drainage system in the centre of Antwerp can be split in two parts: the left part (most historical site) closest to the Scheldt River, and the right part next to the district of Deurne. There are surprisingly few connections between both parts of the sewer system.

Figure 7.8 shows the division of the left part of the sewer system (and topography) or the Antwerp historical centre into four sub-catchments. Thus, this represents the layout of the SCAN model of that part of the sewer system. Given this specific delineation, the number of discharge links from one to another SC was very limited: there is, for instance, not a single link between SC2 and SC4, only 1 between SC1 and SC4, up to 10 between SC2 and SC3. Processes are aggregated within each SC.

Figure 7.9 shows the shows a schematic overview of the main drainage directions in the considered part of the city of Antwerp. Note that the SCAN model is able to simulate those processes accurately, and actually tries to simplify the model to the level of such dominating processess. This simplification results in faster and more flexible models (both in terms of adding new components to test innovations and to integrate the model in an operational IT environment in a later stage) that are also easier to manage and understand by engineerings and decision makers.

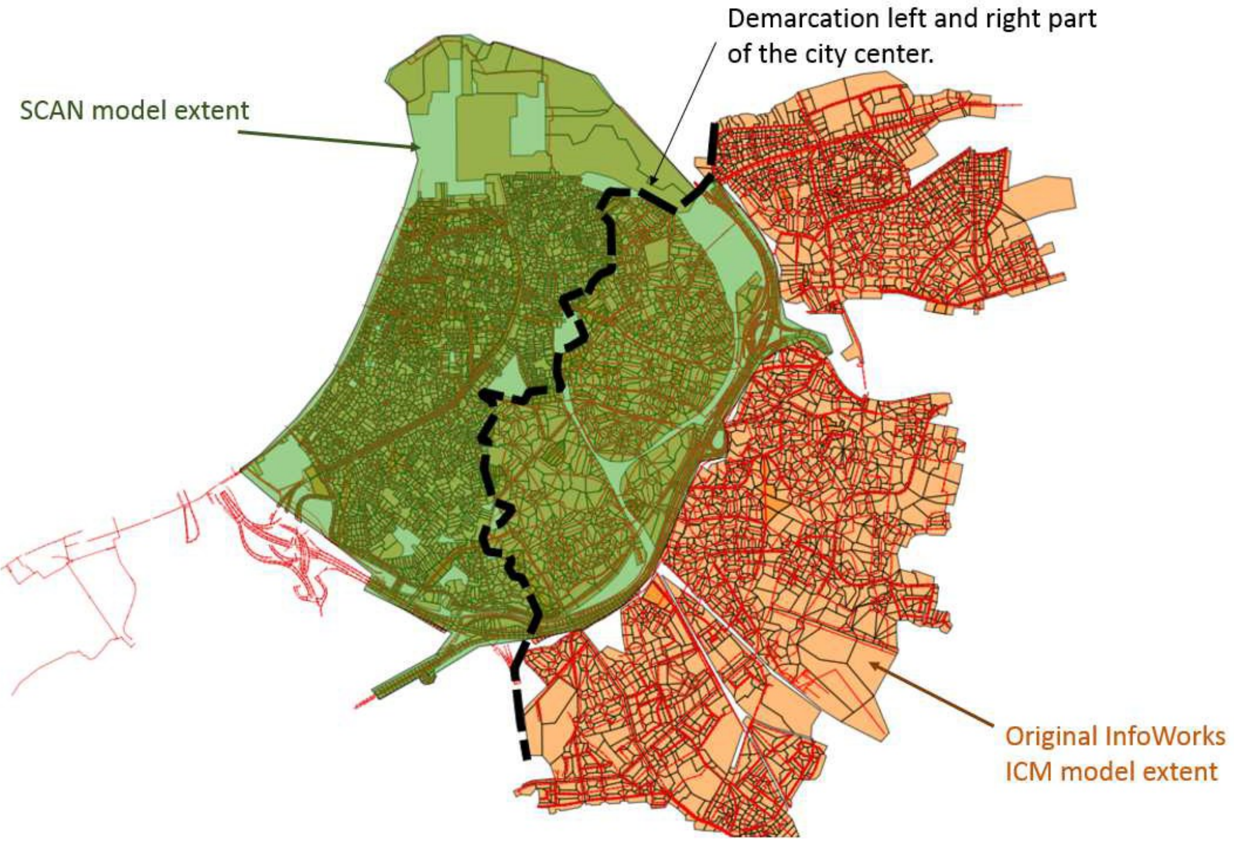


Figure 7.7. SCAN model extent (green) versus the available InfoWorks ICM models (red).

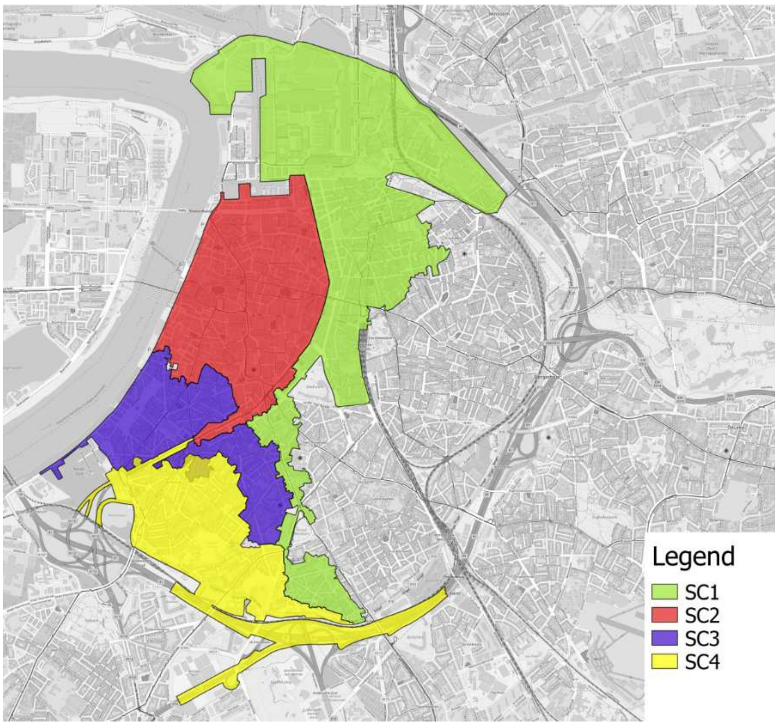
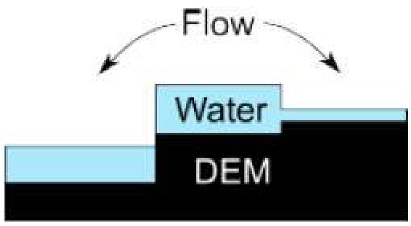


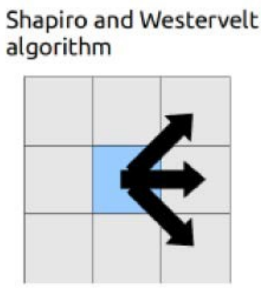
Figure 7.8. Division of the left part of the Antwerp sewer system into 4 “subcatchments” (SC).

Figure 7.9: Schematic overview of the drainage directions and main flow pipes in Antwerp (source: Riolink; sewer manager of the city of Antwerp).

SCAN was initially designed to focus on the underground system, but recent developments allowed the modeller to also focus on floods and flood extents. These developments were added, as visualisation of results is crucial in decision making and creating awareness. Thus, SCAN simulated underground volumes and discharges for each cell (and flux), and also simulate flood volumes. The reader is referred to Bermúdez et al. (2018) for a detailed description on how these flood volumes are simulated in the model. For the application of SCAN within BRIGAID, two additional visualisation procedures were developed. The first is based on heat maps, while the second incorporate the 2D depth spreading algorithm to translate flood volumes into flood extents. Depending on the precise desired representation of the results and available simulation time, an approach can be selected. The heat maps do not calculate nor show flood extents, but rather indicate which areas are most flood prone. Hereto, the flood volumes are converted into points, weighted based on the flood volume itself. For instance, a volume of 100 m³ will get 10 times more weight than a volume of 10 m³, and thus be represented by 10 times more points. Next, an equally spaced raster is created over the area of interest. For each raster cell, the number of flood points is calculated in a certain radius. By varying this radius and the colour scales, a fluent heat map is created, indicating the areas that are most flood prone. Also, such map inherently deals with the associated uncertainty of the model simplification. Indeed, these heat maps do not show a crisp delineation of the flood extents, but give a more robust representation of the flood vulnerability. In contrary, the second visualisation technique does calculate the precise flood extents. Hereto, a 2D depth spreading algorithm was linked to SCAN. The Wetland DEM Ponding Model (WDPM) of the Centre of Hydrology of the Canadian university of Saskatchewan was employed. This algorithm is based on the theory described in Shapiro and Westerveld (1992) and programmed in C++. Figure 7.**10** shows the basic principles of the algorithm. At the moment, these calculations and visualisation is performed in QGIS (thus outside SCAN), but can easily be linked to SCAN directly. Note that there is a huge difference in calculation times between one approach and another within SCAN. The SCAN model itself takes much less than a second to simulate a 2-day event. The heat map creation takes a similar amount of time, and is thus negligible. The 2D depth spreading algorithm, however, takes approximately 4 to 6 hours (depending on the flood volume that needs to be spread) before calculation is complete. Hence, these calculations should only be performed for those floods for which detailed maps are desired.



(a) Schematic representation of the algorithm.



(b) Principle of depth spreading in a

raster for flood extent calculations.

Figure 7.10. Principles of the applied depth spreading algorithm (2D visualisation) linked to SCAN to calculate flood extents.

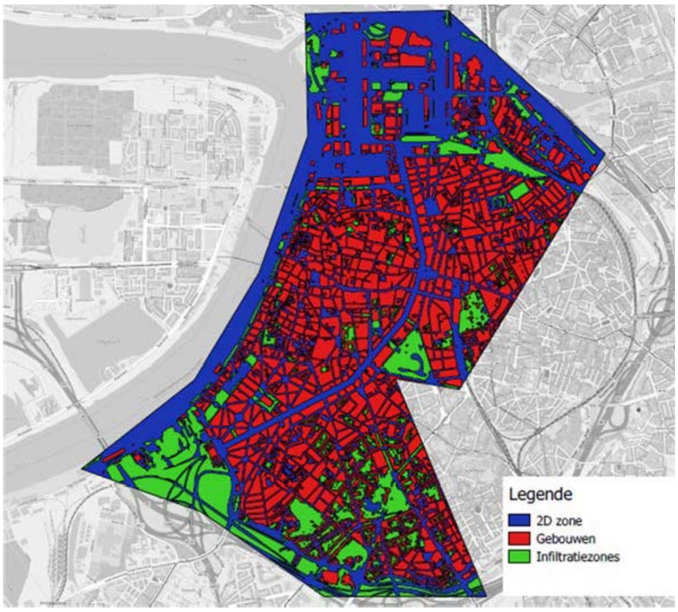


Figure 7.11. Overview of the most important components of the 2D mesh used to create flood maps: 2D zones (non-buildings, impermeable), buildings (impermeable) and infiltration zones (permeable; e.g. grass lands).

7.4. Methodology: test innovation and alternatives in a climate adaptation context

This analysis is focused on quantifying the impact of the HydroVentiv green roof, and comparing the innovation with alternative solutions. The analysis is carried out in the context of urban adaptation planning to mitigate climate change. Hereby, a realistic context is created in which innovations such as the green roof can effectively play an important role as adaptation measure. The creation of adaptation plans and strategies is an iterative procedure (see also Figure 7.12). First, the climate states are quantified for current and future climate. The future climate states include for instance rainfall for a specific time horizon (e.g. 2050 or 2100) and in a certain scenario (in Flanders, 4 scenarios are being used in practice that cover a range of global climate model outputs following different RCP pathways). Next, the effects of these states are simulated, such as urban flooding, city heat stress, etc. After quantification of the effects, the consequences can be calculated (e.g. number of persons affected by floods, etc.). Based on this analysis, adaptation measures can be implemented to mitigate those adverse effects and consequences. Naturally, these adaptation measures affect the extent of the climate effect (such as the amount of flooding), and thus also the consequences. This iterative procedure can be repeated until an adequate plan is created, that also accounts with practical considerations (such as timing, budget and other constraints).

The BRIGAID analysis does not follow this iterative path, but completes the cycle only once. As adaptation measure, the HydroVentiv innovation is implemented, together with an alternative solution (permeable pavement). The next paragraph describes the climate states, effects and impacts under current and future climate. A subsequent paragraph describes the implementation of the innovation and alternative solutions in SCAN, and compares their impact on urban floods in the centre of Antwerp.

The SCAN approach and climate adaptation planning presented in this case study, was also transferred to another city (Bruges) and an industrial context (Brussels Airport Company). More information on these deployments can be found in Section 7.7.

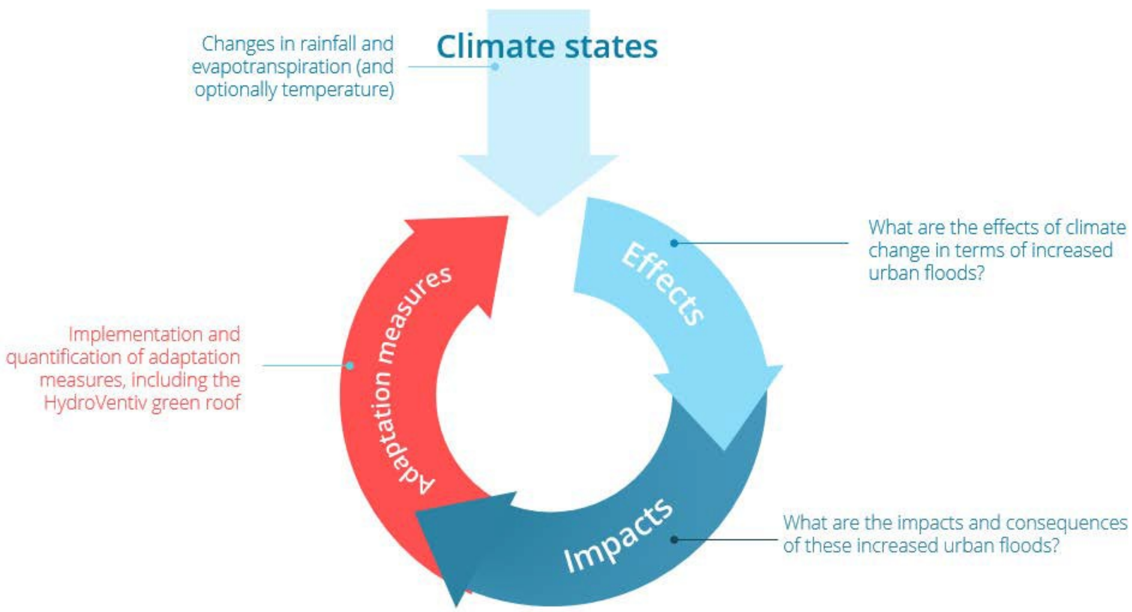


Figure 7.12. Assessment of the innovation (and alternative solutions) in a context of climate adaptation planning for the city of Antwerp.

7.5. Analysis of flood hazard in Antwerp for current and future climate without adaptation or innovations

Both the current and future climate states (rainfall, evaporation, temperature, wind speed, etc.) were available for the city of Antwerp from another study. This report does not elaborate on those data. The reader is referred to van Lipzig and Willems (2015) for more information on the climate scenarios and data. Instead, these data were simulated in the SCAN model. The results are briefly described below.

First, the historical storm of 30 May 2016 was simulated to validate the model to real data. This storm caused widespread floods in the study area, and led to massive damages. The emergency units of the city of Antwerp provided their call-logs for this storm. This log includes all calls (and origin of the call) that were made related to urban floods for this particular event. In additional, photos of the floods were collected from news papers, social media and amateur photographers to further validate flood extents. Figure 7.13 shows the simulation results in the Brederodewijk (in the Southern part of the city of Antwerp). It is clear that there is a close match between the simulation results and the locations where calls were made to theemergency response units. The darker the red color, the more calls were made in a 100 meter radius. On the right, one can see a picture of the flood (source: Gazet van Antwerpen).

For the future climate, the composite storms of different return periods perturbed to the year 2050 were simulated under the "high summer" climate scenario. Figure 7.14 visualizes the urban floods under current and future climate. As water managers and decision makers prefer to have a proper indication of the flood extents, the 2D GIS spreading algorithm was applied after simulations to generate such maps. There is a clear difference in flood extents for the future climate compared to the current weather conditions. This drastic increase of urban floods necessitates an adequate and targeted climate adaptation plan, in which the HydroVentiv green roof could play a role.

Finally, Figure 7.15 shows a heat map as alternative representation of the results, which indicates the change in return periods of urban floods due to climate change (current versus climate in 2050 using the "mid" climate change scenario). Note that a different climate change scenario was run compared to Figure 7.14, and thus the results also differ (although only marginally). A green color indicates that the return period of floods does not change significantly, while red colors indicate a great change in return periods. The precise shift in return periods cannot be extracted from the map, as this information is lost during the map generation process. Indeed, the color and thus value of the heat map also depends on the number of floods in the neighbourhood, and the weighting scheme that is applied during map generation. Instead, the goal of this map is to clearly communicate the areas which are most flood prone, also to a non-expert audience. The advantage of such map is that the map generation itself takes much less time than creating the 2D flood extents. Indeed, no time consuming volume depth spreading is needed for the map creation.

From this brief analysis, it is concluded (1) that the configured model is able to provide realistic results of urban floods, (2) the results of SCAN can clearly be visualized in different ways and (3) climate change will likely have a significant impact on urban floods in the city of Antwerp (although not in the district where the HydroVentiv green roof is installed).

Before implementing the innovations, a detailed analysis was performed to identify the most critical locations leading to floods. This fits within the SPRC approach proposed in this report, in which the **sources and pathways are identified**. **Fout! Verwijzingsbron niet gevonden.** zooms in into a critical location. One can clearly identify the "sources" of urban floods. The model simulates hereto surcharged manholes. From these manholes, water is spilled onto the street, which is then led by the topography of the street to other locations. The street acts as the flood "pathway". Finally, the water impacts a parking, which is the “receptor” in the SPRC approach. From this, one can calculate the “consequences”, such as the damage of vehicles due to flooding. For the latter, standard damage curves are used.

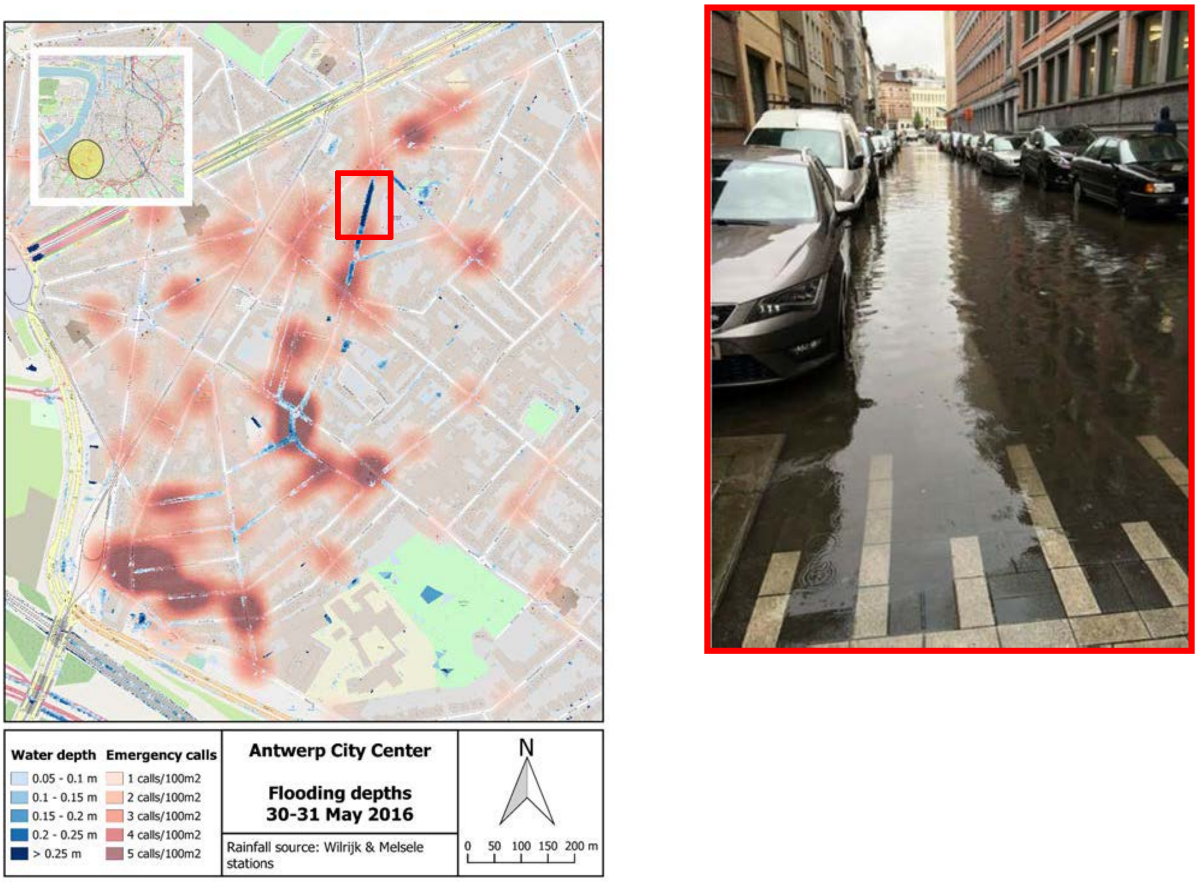


Figure 7.13. Simulated urban floods (blue) and calls to the emergency units (red) for the historical storm of May 2016 in the Brederode district.

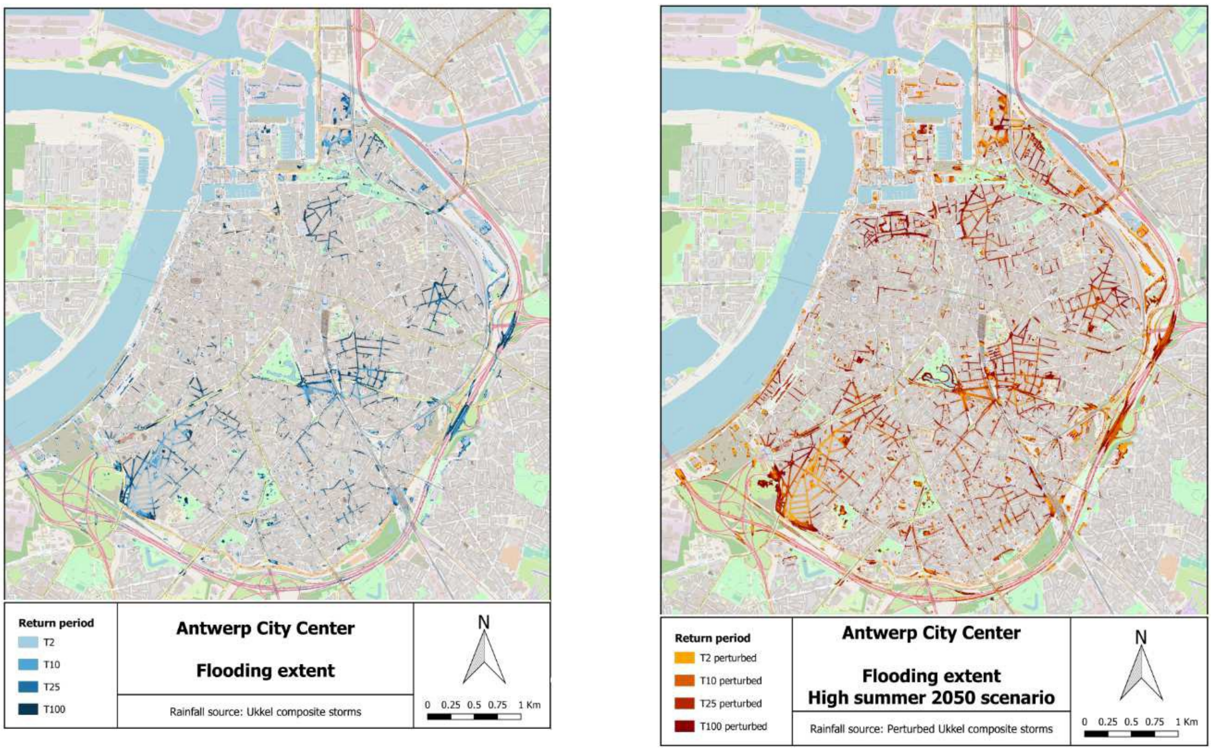


Figure 7.14. Simulation results of urban floods under current climate (left) and future climate (2050, “high summer” climate scenario; right).

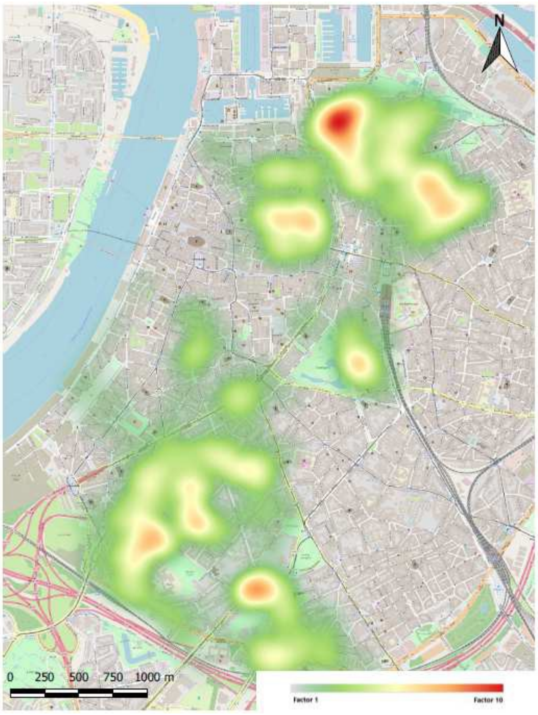


Figure 7.15. Example of a heat map showing the relative increase in vulnerability to urban floods due to climate change (based on simulation of the future climate change – “mid” scenario – 2050).

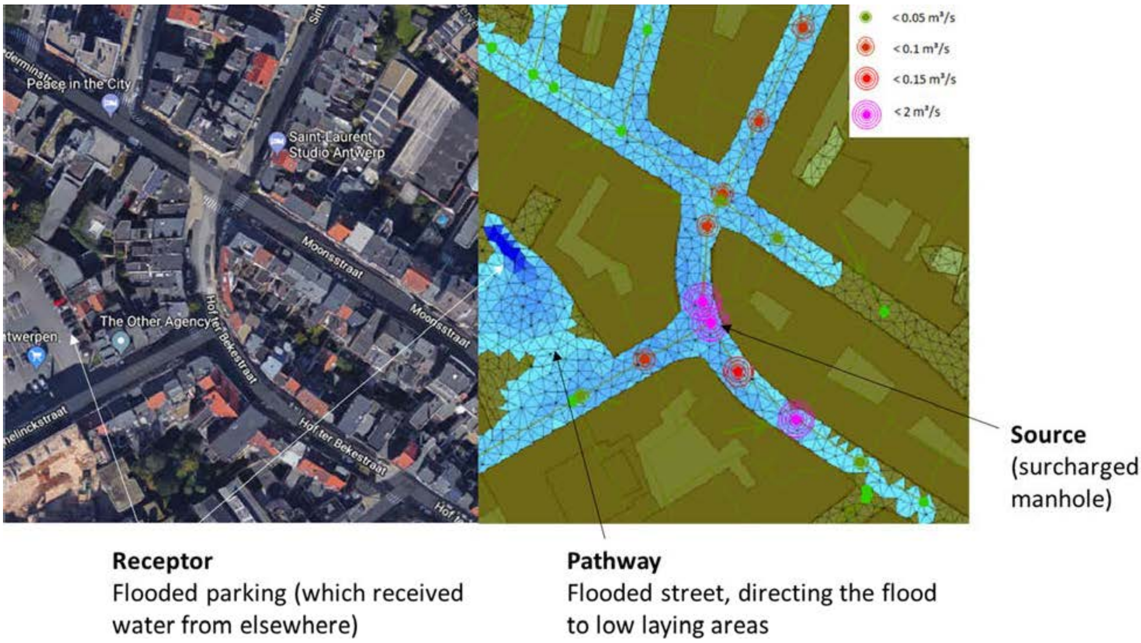


Figure 7.16. Identification of sources and pathways.

7.6. Impact assessment of innovations in SCAN

This paragraph describes the implementation of the HydroVentiv green roof and alternative adaptation measures in SCAN. Due to the flexibility of SCAN, any model structure can easily be included. Thus, every innovation can be tested with SCAN that has an impact on urban floods. As described in §7.3, other hazards such as city heat stress could also be included in SCAN (but require additional model structures, and are thus not considered explicitly in this analysis). To demonstrate this functionality, a novel type of green roofs was implemented in SCAN, based on a measurement campaign on green roofs in Antwerp that was set up for the BRIGAID project.

Two types of innovations were implemented within SCAN, to test their impact on urban floods within the city of Antwerp: (1) various types of green roofs, and (2) other source control measures. The source control measures are implemented as permeable pavement (thus disconnected from the sewer system), but can also be applied in reality through small scale buffers. The impact (and implementation) of these source control measures within SCAN is highly similar. Therefore, the source control measures are only implemented through permeable pavement.

7.6.1. Green roof model structure identification and calibration

Green roofs can have various designs. To ensure that various types of green roofs can be tested thoroughly, a proper model structure and parameters were identified first. Hereto, a measurement campaign was set up, as described in more detail in Section 7.1.

The HydroVentiv green roof's layers are shown in Figure 7.2. It consists of a lower tray which can retain water. Its capacity depends in reality on the builder's choice, and can vary from a few centimetres up to 12 centimetre. On top of this tray, there is a thin drainage layer which forms the connection between the storage tray and the substrate layer above. Additional wigs can enhance capillary rise, so water can be transported faster and easier from this water tray to the vegetation.

The characteristics of the different layers are synthesised here:

	DUO1	DUO2(HVV)	DUO3(OASIS)
Vegetation	Sedum	*Sedum* and grasses	*Sedum* and grasses
Soil depth (mm)	60	60	200
Buffer layer type	Drainage mat	Plastic tray	Plastic tray
Capacity buffer layer (mm)	Approx. 10	37	37
Outflow/Overflow	Free outlet	Limited outlet (regulator) and overflow	Overflow

First, the results of the measurement campaign were analysed to get some insights into the functioning of green roofs. Figure 7.17 shows the drainage from the green roofs to the sewer system during the period April-June 2018. During this period, approximately 100 mm of rainfall was recorded. The bare roof (aluminium construction with almost zero inclination) yielded approximately 82 mm of runoff. This is slightly less than the rainfall, which is caused due to the "wetting" of the material and ponding. The green roofs were able to absorb significantly more rainfall: DUO1 resulted in a runoff of 20 mm, while the green roofs with thicker substrate and a buffer layer only yielded 8 and 11 mm of runoff. Surprisingly, the roof with the thickest substrate and no constant drainage of the buffer (DUO3) generated a slightly larger runoff. Although this difference actually falls within the uncertainty bounds of the measurement devices, this difference can also be explained by the rooting depths of the DUO3 which were less than DUO2 after installation. This hinders the uptake of water from the buffer layer, resulting in fewer evaporation eventually.

Figure 7.19 shows the recorded rainfall and water levels in DUO2 (HVV) and DUO3 (OASIS). A significant difference in buffer layers between DUO2 and DUO3 is the droplet device of DUO2: as soon as the water level exceeds 12.5 mm, the water in the buffer is drained constantly up to this level. This ensures that there is, in most circumstances, enough capacity to capture incoming storms. DUO3 does not have an outflow in the buffer layer. Thus, that buffer can only be emptied through evaporation of the vegetation. The water level within each buffer is measured through an ultrasonic level device. From this figure, one can conclude that the water buffer of OASIS enables the green roof to survive a dry period of approximately 4 weeks. The buffer in the HVV roof is, of course, emptied much quicker due to the droplet device, and is thus not able to bridge such dry periods.

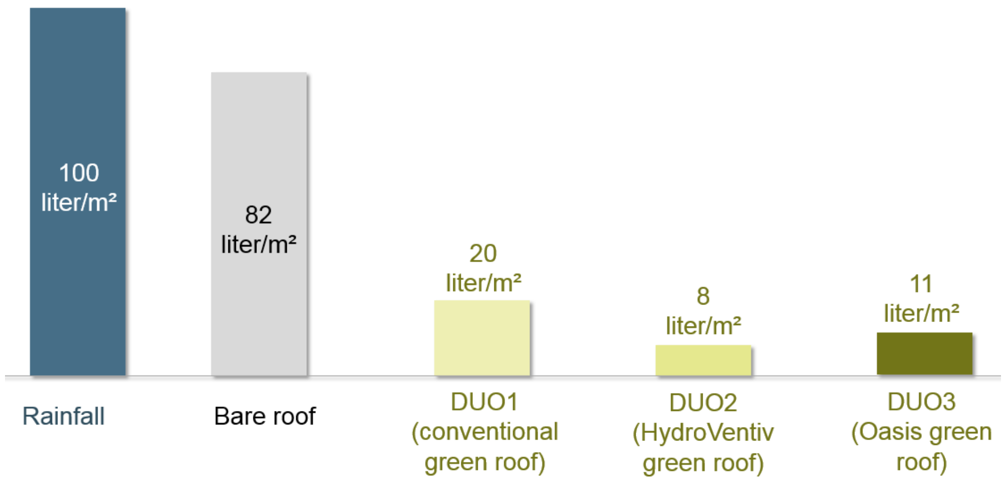


Figure 7.17. Runoff to the sewer system during the period April - June 2018.

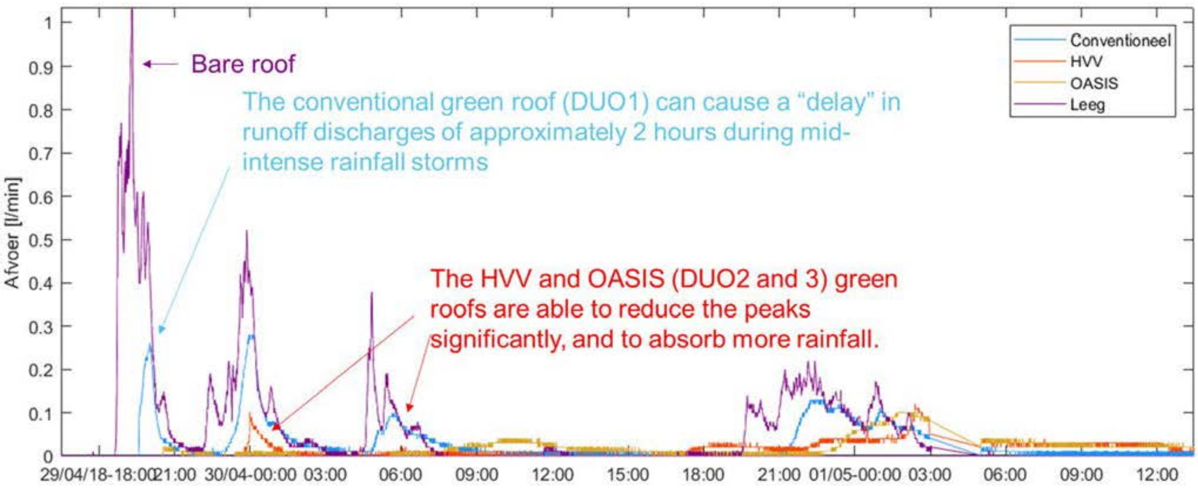


Figure 7.18. Recorded runoff of the different green roofs during a mid-intense rainfall event in April 2018.

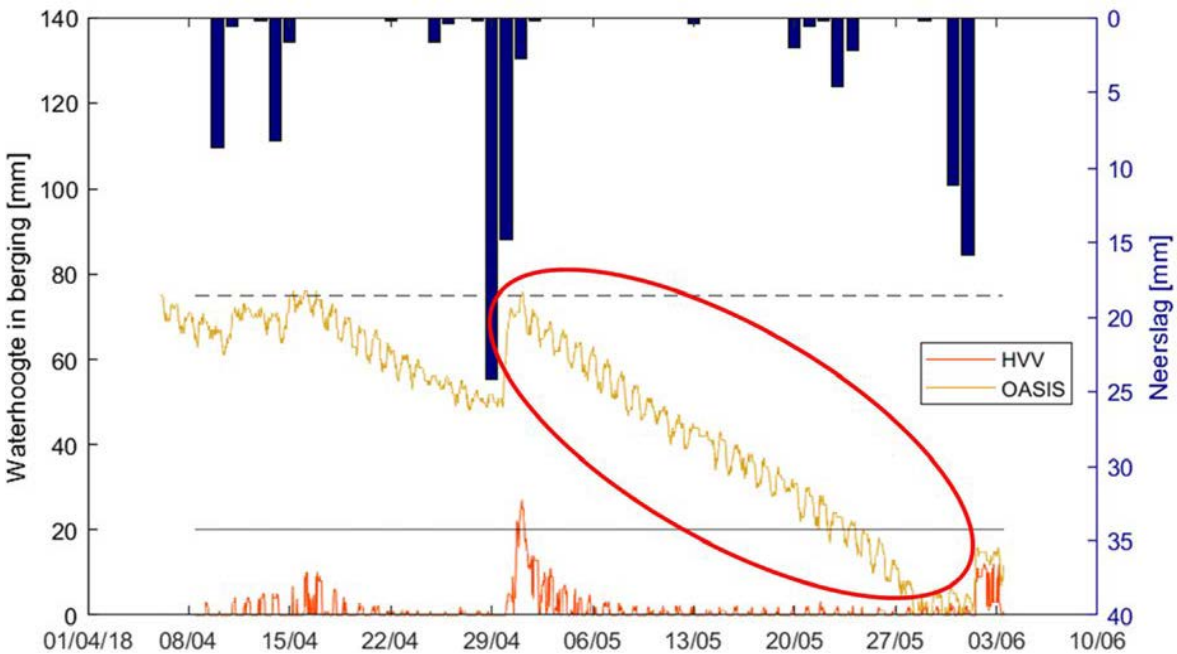


Figure 7.19. Measured water level and rainfall during the period April - June 2018.

Figure 7.18 shows the recorded runoff from the green roofs (and bare roof) to the sewer system during a rainfall event in April 2018. It is clear from these measurements that the conventional green roof can reduce and delay the runoff towards the sewer system, although green roofs with thicker substrate and a buffer layer have a far greater impact. Note that the intensity of this particular storm was not extreme, and the runoff strongly depends on the storm intensity and its antecedent conditions. To investigate the dynamics of the green roofs further, a model is derived (see below) that represents green roof and coupled to the sewer system. This allows to quantify the impact of this innovation on urban floods.

To simulate the impact of green roofs, a model structure and parameters are needed that can accurately describe its dynamics. Different model implementations can be found in literature which are often created after prolonged monitoring campaigns. Palla et al. (2008) and Locatelli et al. (2014) describe similar implementations based on three buckets. Figure 7.20 represents the model by Locatelli et al. (2014). This implementation contains a surface storage layer, a detention storage layer and subsurface storage element.

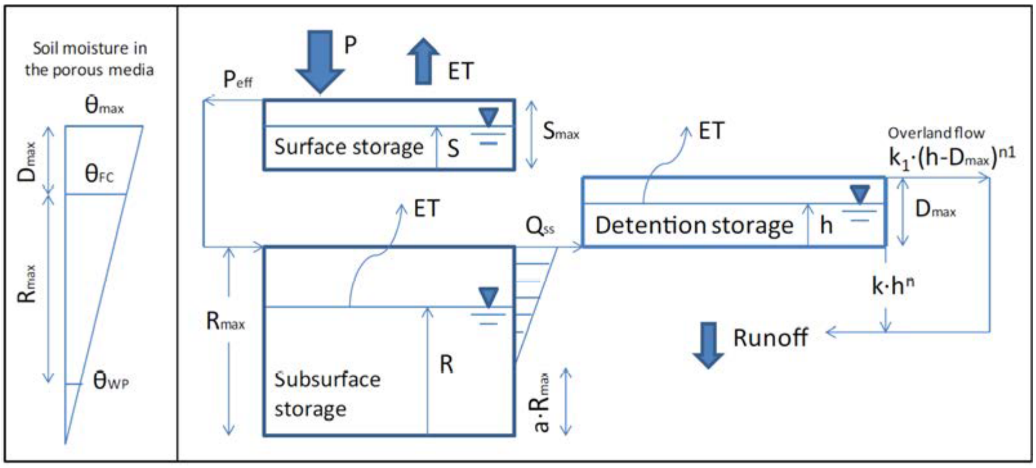


Figure 7.20. Green roof model implementation of Locatelli et al. for urban drainage applications.

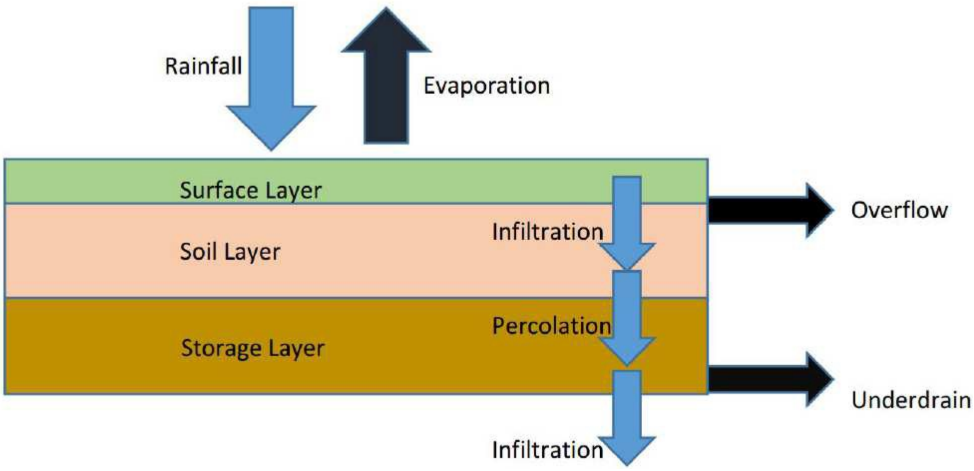


Figure 7.21. SWMM implementation of the green roof.

A novel model structure was created, which is however based on the model setups of Kasmin et al. (2010) and Locatelli et al. (2014). Some fine tuning was done to the model structure to be able to cover a broader range of different green roof setups, and based on the measurement campaign of the HydroVentiv green roof in Antwerp. The main model concepts of Kasmin et al. (2010) and Locatelli et al. (2014) were preserved, resulting in a 3-layer model:

$$\phi_1 \frac{\partial d_1}{\partial t} = i + q_0 - e_1 - f_1 - q_1 \qquad \text{Surface layer}$$

$$D_2 \frac{\partial \theta_2}{\partial t} = f_1 - e_2 - f_2 \qquad \text{Soil layer}$$

$$\phi_3 \frac{\partial d_3}{\partial t} = f_2 - e_3 - f_3 - q_3 \qquad \text{Drainage layer}$$

With d_i the depth, ϑ_i the soil moisture, f_i a flux rate (infiltration/percolation/exfiltration), q_i a dischage, e_i an evaporation rate, D_i a depth or thickness and φ_i of the corresponding layer, and *i* the rainfall rate. More information on these parameters can be found in (EPA, 2016).

The final model structure was obtained based on analysis of the measurement campaign organized on the green roof in Antwerp. The measurement campaign was also used to calibrate the model parameters, for each of the 3 configurations (DUO1, 2 and 3). Table 7.1 shows the different physically based parameters that were calibrated to the measurement campaign in Antwerp. As the three setups use the same type of substrate, common parameters were derived to mimic the water dynamics of the substrate layer. Note that this table does not show all parameters of the green model structure. The structure is also characterized by different empirical factors, which are not included in this report.

In a next phase, a 1-year time series of rainfall and evapotranspiration was simulated for each configuration using the identified model structure and accompanying parameters. This analysis allows to investigate the **mass balance** of each green roof configuration, and thus to assess how much water will evaporate or drain to the sewer system. The former can also act as indicator of city heat stress reduction, but was not considered as such in this analysis. Indeed, the purpose of this analysis is mainly to quantify the impact of green roofs (and other innovations) on urban water management. It shows, however, that expansions to other domains are easily feasible.

Figure 7.24 shows the mass balances of this 1-year period that were acquired through simulations with the green roof models and parameters. From these results, it is clear that DUO1 generates the largest runoff towards the sewer system. This is also logical, as is does not have a buffer layer to store water, and confirms the previous results. Thus, during short rainfall storms in dry periods, water that cannot be captured by the substrate layer is virtually immediately drained to the sewer system through its "overflow". The second configuration, DUO2, does not lead to overflows, but generates more "outflow". This outflow is generated through the droplet-system that is included in the green roof: as soon as the water level reaches 12 mm in the buffer basin, the buffer is emptied gradually through this filter. Note that the flow rate is not included in this figure, but is essential information to assess its impacts on the urban water system. This aspect is, however, taken explicitly into account in the flood assessment analysis discussed below. Finally, DUO3 has similar characteristics, although the thick substrate layer and buffer layer are able to absorb much more water than DUO1. Again, these results are in line with the expectations.

Table 7.1. Physically related parameters of DUO1, DUO2 and DUO3 calibrated based on the measurement campaign in Antwerp.

	DUO1 (conventional green roof)	DUO2 (HydroVentiv)	DUO3 (OASIS)
Surface layer			
Max. infiltration rate [mm/h]	78	42	42
Maximum surface storage [mm]	1	1.98	2.74
Substrate (soil) layer			
Thickness [mm]	60	80	200
Δθ (difference between the saturated and residual soil moisture content) [-]	0.5	0.5	0.5
Θ_FC (field capacity) [-]	0.2979	0.2979	0.2979
LAI (leaf area index) [-]	1	1	1
Crop factor [-]	0.97	0.90	0.90
Enable capillary rise [y/n]	No	Yes	Yes
Max. capillary rise flow [mm/dag]	-	4.35	4.35
Buffer (drainage) layer			
Max. capacity [mm]	-	80	80
Lin. Reservoir constant [10 minutes]	-	70	-
Drain start [mm]	-	12.5	-

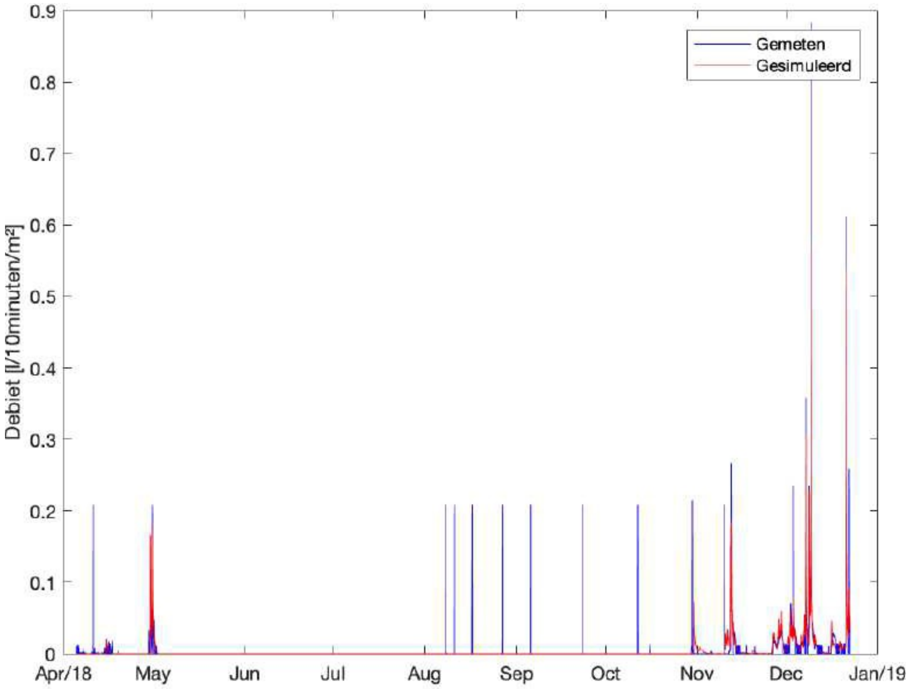


Figure 7.22: Calibration result DUO3: simulated and measured runoff of the green roof.

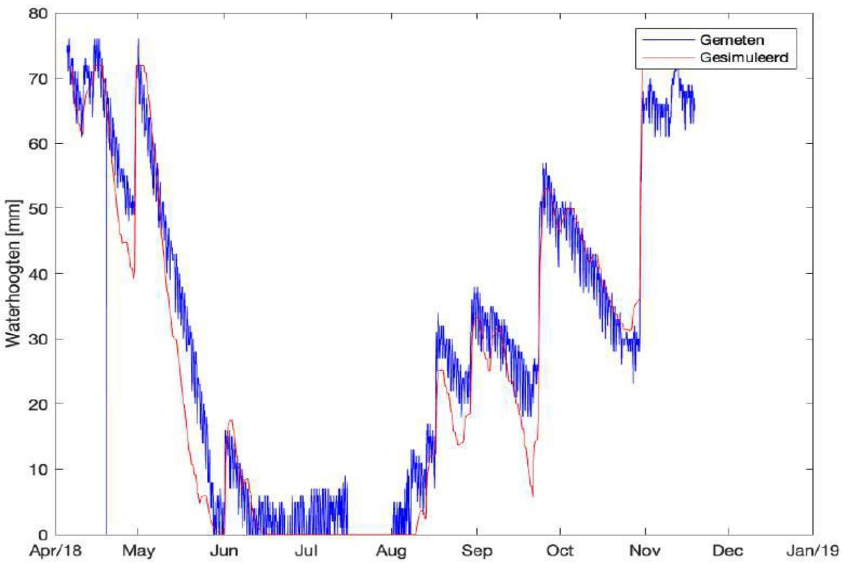


Figure 7.23. Calibration result DUO2: simulated and measured water level in the buffer layer of the green roof.

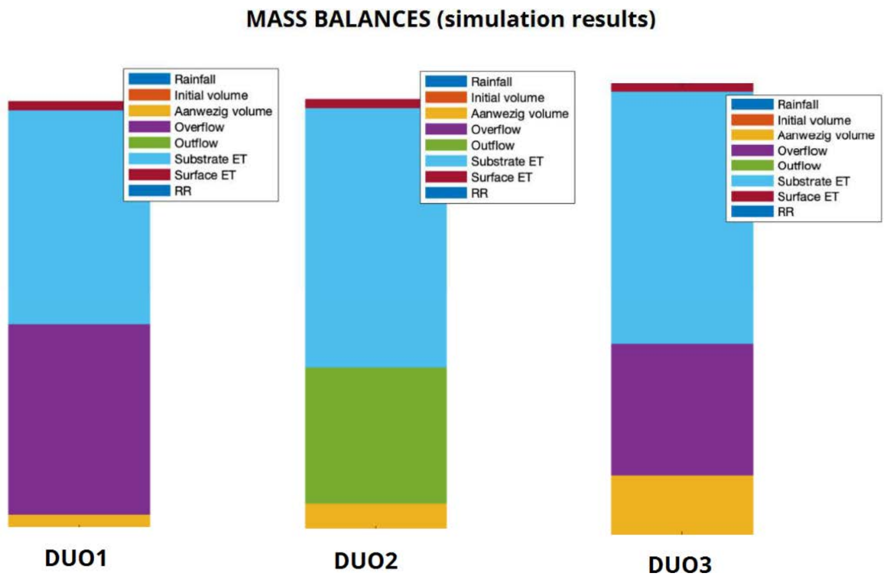


Figure 7.24. Simulated mass balances of the three green roof configurations.

7.6.2. Implementation of clusters of innovations in SCAN

After the model structure was identified and calibrated for a single green roof, the green roofs were implemented on a large scale within SCAN. Hereto, the locations where green roofs could be installed were selected. This was done through a GIS “potential green roof map”. The city of Antwerp has such map available, but closer inspection of this map by the BRIGAID team unveiled that many locations that could also host green roofs were not included in this map. Therefore, an algorithm was developed to create a new potential green roof map. This algorithm accounts for the buildings (through the “GRB map”, a reference GIS file created by the Flemish Government and made available through the website GeoPunt.be). Buildings with a roof with an inclination of less than 15% were identified by the algorithm. Next, areas smaller than 50 m² were removed. This resulted in a new map, which is shown in Figure 7.25. Naturally, this map just yields a first indication of potential installation sites of green roofs, and needs further refining. The original map identified 166.312 m² where green roofs can be installed, versus 934.597 m² in the newly created potential green roof map. Different types of green roofs are implemented in SCAN, which can also be included in different spatial spreads.

A second adaptation measure was included to enable comparison. This adaptation measure consists of reopening the surface, and creating permeable surfaces for parking lots (next to roads) and green zones throughout the city. The SCAN implementation of such measure is much simpler, and simply incorporates a (local) reduction of the effective contributing area, or the addition of ponding buffers with infiltration. To identify the locations were these measures can be realized, a similar algorithm was developed as for the green roofs. The algorithm selected locations within the study area of which the city of Antwerp is owner (for practical reasons), that consist of maximum one driveway in each direction (creating such permeable surfaces next to busy roads is undesirable for practical reasons) and of a low management category. However, experiments showed that these criteria identified nearly all roads in the historical center of

Antwerp. Therefore, the Brederode district was selected as study area, in which the outcome of the algorithm was manually refined. This district was highly flood prone (see also Figure 7.13). In this district, 24.730 m² of parking lots next to roads was identified that can be made permeable, across a total length of 12.37 km. In the same district, the potential green roof map includes an area of 54.903 m². Thus, the potential green roof area in the Brederode district is more than twice the identified area that could be made permeable.

Figure 7.25. Potential green roof map for Antwerp creating through the newly developed algorithm, indicating where green roofs can be installed.

Also, green zones were implemented across the city, although the potential locations were such green zones could be implemented were rather limited due to practical reasons. These green zones were included in the scan model at the following sites: "Colruyt" shopping mall, "Cashwell", Balansstraat, Zuidervelodroom, Haantjeslei, Vlooienmarkt, "CVO provinciaal instituut PIVA", "Den Bell" en "AVA". Their implementation within SCAN is highly similar. Therefore, the results of these green zones are presented simultaneously with the "permeable pavement" results.

Finally, different strategic scenarios were considered in which each scenario included a different extent of measures: 12.5%, 25%, 50%, 75% and 100% of the identified areas for green roof or permeable pavement implementation were considered.

Figure 7.26. Implementation of a cluster of innovations: green zones (shown in blue), permeable pavement (orange) and green roofs (green). These innovations can be simulated individually or simultaneously in SCAN.

Figure 7.27. Identified roads in the flood prone Brederode district to implement permeable pavement.

7.6.3. Results

These scenarios were simulated (separately) in the SCAN model for the historical storms of 27/28 July 2013, and 30 May 2016. Both storms resulted in floods as witnessed by the validation data made available from the Antwerp fire brigade. Each time, 48 hours were simulated. Two different SCAN model sets were simulated: one with green roofs implemented across the entire city of Antwerp, and a second model including both green roofs and permeable pavement, but only in the Brederode district.

Table 7.2 shows the simulation results of the storm of 27/28 July 2013 with green roofs implemented across the city, while Table 7.3 shows the results for the storm of 30 May 2016. The reported flood extent is considered as a proxy for flood damage, as more precise damage functions were not available for this study. The results show that the green roofs can have a significant impact on the flood extent: if all roofs that can host a green roof are effectively equipped with such (i.e. 93.5 hectares), the flood extent can be reduced with almost 30% (5.80 hectares). The fewer green roofs can be installed, the lesser the impact is of course. If only 12.5% of all potential roofs are equipped with a green roof, the flood extent is still reduced by approximately 3 to 4%. Note that the overflow volumes are hardly affected by the green roof. They cannot retain the water long enough to significantly reduce the CSO spillings.

Next, the Brederode district is being analyzed in particular. For this site, an alternative solution (permeable pavement) is also considered.

Table 7.4 shows the results of the storm of 27/28 July 2013 and Table 7.5 those for 30 May 2016 when only measures are implemented within the Brederodewijk. Thus, for this area, both the permeable pavement and green roofs were implemented. The reported flood extents again cover the entire city of Antwerp. Naturally, one can conclude that the overall impact is relatively low: if all potential roofs within the Brederodewijk are effectively covered with green roofs (i.e. 5.49 hectares), the flood extent across Antwerp is reduced by approximately 7.9% to 11% for both storms. If all potential parkings are transformed into permeable pavement (i.e. 2.47 hectares), the flood extent is reduced by 3.8% to 4.8%. Of course, these numbers are relatively low, as the flood extent is still considered across the entire city. More importantly though, one can conclude that the effectiveness per m² of green roof or permeable parkings is very similar. Thus, both adaptation measures can directly be compared in terms of costs (installation, maintenance), robustness, ownership, additional benefits such as city heat stress mitigation, biodiversity, … A full analysis of all benefits and consequences is not performed, as it is not the goal of this study. This study is solely focused on providing a means or tool to test the effectiveness of innovation within a real setting.

Finally, SCAN is used to simulate a long term time series of rainfall (and evapotranspiration). Through such long term simulations and post-processing of the results, one can assess the impact of various climate adaptation measures statistically, and account correctly for antecedent conditions. Such antecedent conditions are very important for many adaptation measures: indeed, part of their capacity can already be taken due to previous storms. When long term rainfall series are simulated continuously, one accounts inherently for such previous storms. SCAN enables to do such long terms simulations ultra fast: simulating 100 years of input takes less than 0.01 second for the entire model of Antwerp, including the implemented innovations. This also enables the user to optimize the design of climate adaptation measures through iterative simulations.

Table 7.2. Summary of the simulation results of SCAN for different strategic scenarios for the storm of 27/28 July 2013 with implementation of green roofs across Antwerp.

	Maximum flood extent [ha]	Reduction of flooded area [%]	Net flood volume [m³]	Overflow (CSO) volume [m³]
Current state	8.12	0	1281	160723
Green roofs				
100%	5.80	28.57	818	156647
75%	6.36	21.67	926	157405
50%	6.65	18.10	1009	159206
25%	7.49	7.76	1141	159467
12.5%	7.76	4.43	1203	160473

Table 7.3. Summary of the simulation results of SCAN for different strategic scenarios for the storm of 30 May 2016 with implementation of green roofs across Antwerp.

	Maximum flood extent [ha]	Reduction of flooded area [%]	Net flood volume [m³]	Overflow (CSO) volume [m³]
Current state	6.00	0	966	187583
Green roofs				
100%	4.23	29.50	627	182979
75%	4.63	22.83	693	184147
50%	5.09	15.17	771	186054
25%	5.50	8.33	857	186430
12.5%	5.83	2.83	933	187190

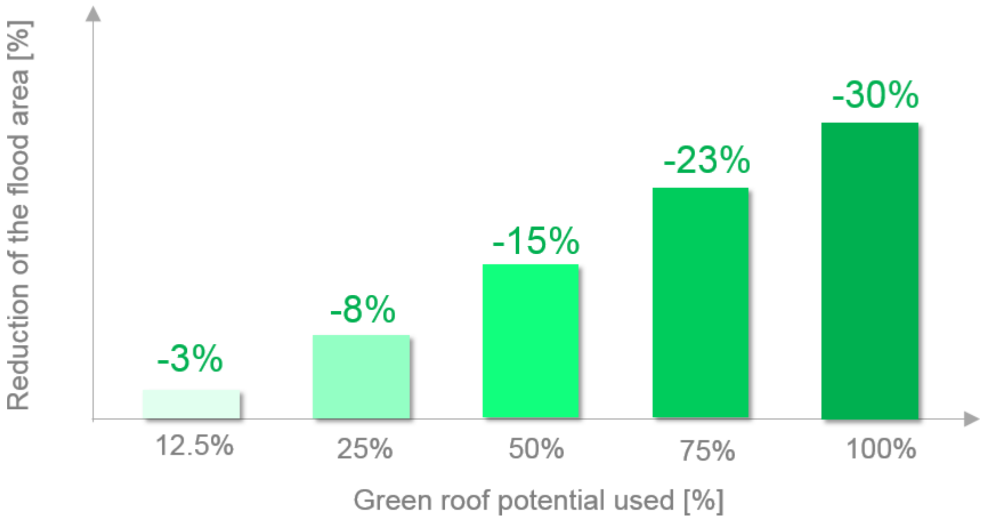


Figure 7.28. Impact of green roofs on urban floods for various implementation scenarios for the storm of 30 May 2016.

Table 7.4. Summary of the simulation results of SCAN for different strategic scenarios for the storm of 27/28 July 2013 after implementation in the Brederode district.

	Maximum flood extent [ha]	**Reduction of flooded area [%]**	**Net flood volume [m³]**	**Overflow (CSO) volume [m³]**
Current state	8.12	0	1281	160723
Green roofs				
Brederode 100%	7.48	7.88	1121	160300
Brederode 75%	7.57	6.77	1149	160468
Brederode 50%	7.78	4.19	1199	160539
Brederode	7.93	2.34	1225	160548
Brederode 12.5%	8.02	1.23	1253	160709
Permeable pav.				
Brederode 100%	7.81	3.82	1192	160190
Brederode 75%	7.92	2.46	1211	160342
Brederode 50%	7.95	2.09	1234	160478
Brederode 25%	8.04	0.99	1256	160591
Brederode 12.5%	8.09	0.37	1270	160689

Table 7.5. Summary of the simulation results of SCAN for different strategic scenarios for the storm of 30 May 2016 after implementation in the Brederode district.

	Maximum flood extent [ha]	Reduction of flooded area [%]	Net flood volume [m³]	Overflow (CSO) volume [m³]
Current state	6.00	0	966	187583
Green roofs				
Brederode 100%	5.34	11.00	826	187349
Brederode 75%	5.52	8.00	859	187552
Brederode 50%	5.68	5.33	892	187301
Brederode 25%	5.85	2.50	932	187216
Brederode 12.5%	5.92	1.33	949	187340
Permeable pav.				
Brederode 100%	5.71	4.83	901	187063
Brederode 75%	5.77	3.83	912	187249
Brederode 50%	5.87	2.17	936	186597
Brederode 25%	5.98	0.33	954	187584
Brederode 12.5%	5.98	0.50	957	187484

Figure 7.29 shows the simulated flood volumes in one sector in Antwerp (SC4) when each of the green roof types (DUO1, DUO2 or DUO3) is applied to a different extent (0% or “basis”, 12.5%, 25%, 50%, 75% or 100% of the potential locations covered by green roofs). The results of each type of green roof are summarized in 1 plot. From this figure, one can conclude that DUO1 is only able to reduce the floods marginally. One can also see that the impact of the green roof varies for different storms: for some storms, the impact is larger than for others. This is caused be antecedent conditions: if a storm hits just after a series of (smaller) storms, the roof is already saturated, and thus the impact on runoff mitigation is reduced. For DUO2, which is equipped with a buffer layer that empties gradually through a droplet-device, the impact is noticeably larger. More flood volumes are reduced significantly. This indicates that adding a buffer layer has a positive and noticeable impact on the reduction of the runoff flow from green roofs, and this also has an impact on urban floods. Naturally, the biggest impact is achieved by applying more green roofs (e.g. “g100” vs. “g25”). Also note that the effect of antecedent conditions is smaller for this type of roof compared to DUO1 or DUO3. Finally, the reduction if flood volumes by applying DUO3 are smaller compared to DUO2. DUO3 is characterized by a thicker substrate layer (20 cm in DUO3 vs. 8 cm in DUO2), but its buffer is not emptied gradually. Instead, the buffer of DUO3 can only be drained through evaporation. Hereto, antecedent conditions have a much bigger impact on the retention capabilities of DUO3 compared to DUO2. Thus, in terms of flood mitigation, a controllable buffer is more desirable. This example illustrates the importance of correctly accounting for antecedent conditions, and demonstrates the applicability of SCAN to assess different climate adaptation measures (i.c. innovations).

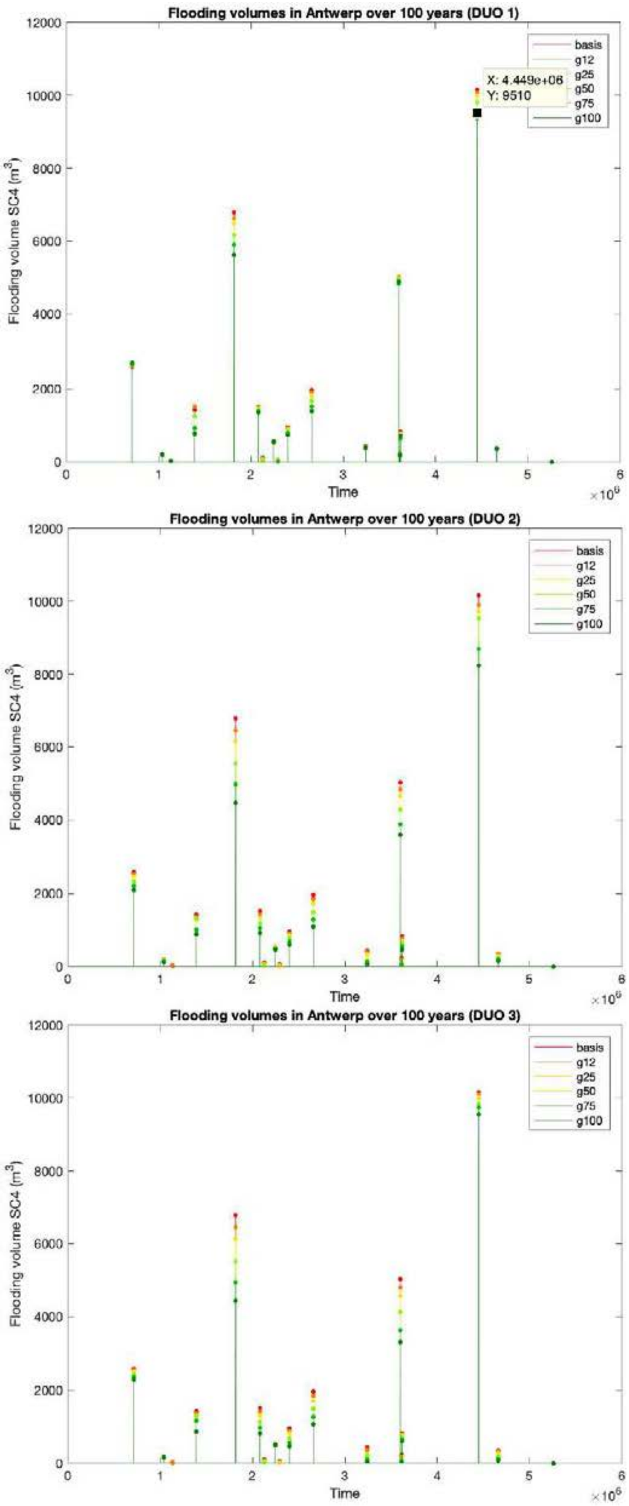


Figure 7.29. Simulated flood volumes over a 100-year period with different degrees of applied green roofs in 1 sector in Antwerp. From top to bottom: DUO1, DUO2 and DUO3.

7.7. Application to other test sites - summary

The proposed method of applying SCAN to perform the SPRC-approach and climate adaptation in general was also tested outside the city of Antwerp. Hereto, the SCAN platform, a BRIGAID innovation itself, has been further improved and extended by the Sumaqua team. More specifically, the SCAN platform was used for climate adaptation of the city of Bruges and the national airport (Brussels Airport). The different measures are not discussed in detail, but a brief overview of some results is presented to demonstrate its applicability.

Figure 7.30 shows the implementation of SCAN on the historical city center of Bruges. In total, 9 different scenarios were implemented. For each scenario, its impact is quantified on urban floods. These scenarios include the decoupling of pavement (roads, parkings, roofs, …) to canals, parks and source control measures. The scenarios are also spatially distributed, and can be simulated separately. As for Antwerp, the current and the future climate were simulated.

Figure 7.31 shows the simulation results of SCAN. In the current state and current climate, approximately

30.000 m² would inundate by 5 cm or more (selected threshold) during a heavy rainfall storm (with a return period of 20 years). In the future climate (high summer climate scenarios 2050 and 2100; see a separate BRIGAID report for the development of these scenarios), this flooded area can increase to approximately 65.000 and 105.000 m² for the same return period. Therefore, 9 clusters of adaptation measures were included in SCAN and simulated. These 9 clusters consists of different combinations and levels of the following solutions that were feasible/applicable to the different coloured spatial subcity zones as indicated in Figure 7.30: Blue-green solutions: Disconnection of public and private paved surfaces to rivers and canals, Wadi's (stormwater storage and infiltration), Smart greenroofs; Increasing the CSO levels to increase the storage capacity in the system and reduce the CSO outflows The results show that the flooded area in 2050 can be decreased by these measures, even when accounting for the high impact climate scenario. The flooded area in 2100 remains slightly higher, and thus it is recommended to develop and implement additional adaptation measures by then.

Further impacts, such as flood damage, the number of affected people and the number of critical buildings (e.g. kindergardens, elderly homes, …) were also quantified, but not included in this report. For more information, the reader is referred to the climate adaptation plan of the city of Bruges.

It is clear that the use of SCAN and the SPRC-approach allows to quantify the impact of such clusters of innovations easily, and can at the same time account for climate change scenarios.

Similarly, a SCAN model was set up for the national airport (**Brussels Airport**). Figure 7.32 shows this model. Currently, different clusters of adaptation measures are being implemented.

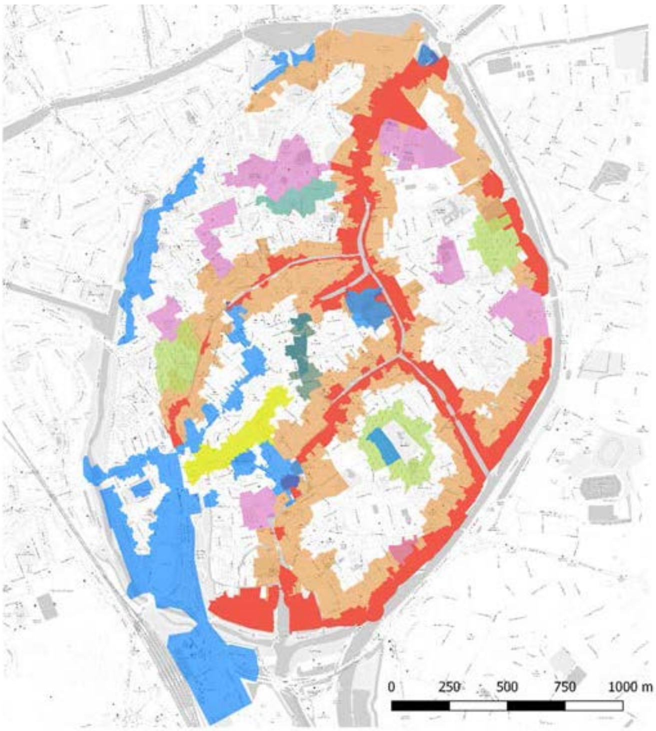


Figure 7.30. Implementation of SCAN for the historical city centre of Bruges. In total, 9 clusters of innovations were implemented and quantified.

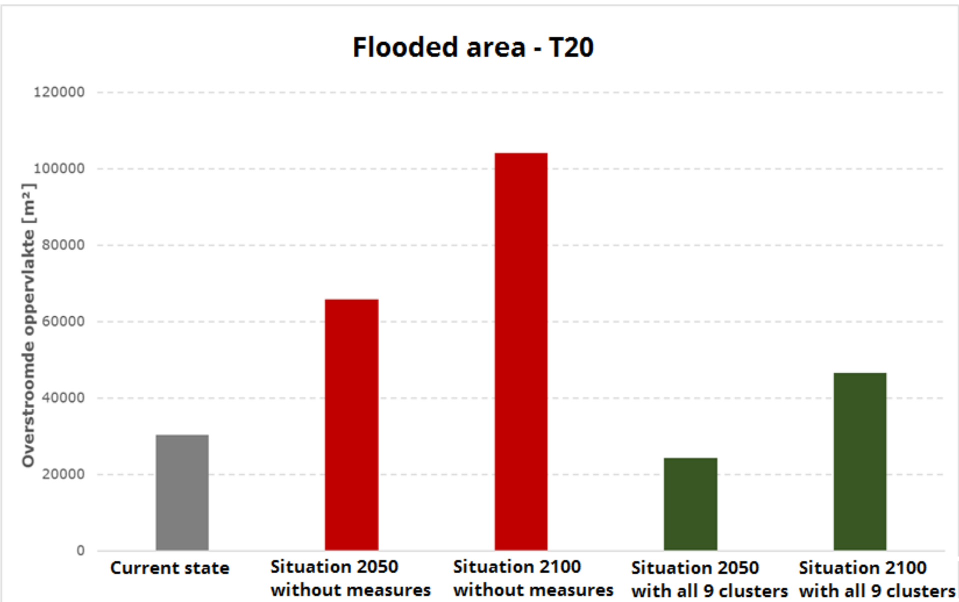


Figure 7.31. Simulation results of SCAN: urban floods in Bruges for the current and future climate, with and

without the implementation of 9 clusters of innovations.

Figure 7.32. SCAN model of Brussels Airport.

7.8. Communication and dissemination of the results

The results of these experiments were communicated broadly. Two dedicated workshops were set up on 11th of June 2018 in Antwerp to report on the outcomes of the experiments. One workshop focused on experts, while the other was aimed at interested citizens. In total, both workshops counted about 100 participants.

The results were also picked up and disseminated by the national news (article, video), radio2, and various journals.

Figure 7.33. One of the many tours organized on the BRIGAID green roof setup in Antwerp.

Figure 7.34. Extract of the invitation for the expert-workshop organized on June 11, 2018.

7.9. Conclusions

This section showcased the application of SCAN to assess (clusters of) innovations. SCAN is a tool that is currently under development at Sumaqua, and is a BRIGAID innovation itself. In this study, the impact and applicablity of the HydroVentiv green roof was tested within the context of climate adaptation planning, and compared to an alternative (existing) solution of permeable pavement and green zones. The

HydroVentiv green roof is also a BRIGAID innovation of the French company Vegetal I.D., and is currently monitored in the city of Antwerp.

The SCAN tool was used by the BRIGAID team to quantify the effects of the green roof on urban floods throughout the historical center of the city of Antwerp. Due to the flexibility of the SCAN tool in terms of model adaptability, the required model equations can easily be included within SCAN. Thus, SCAN can be modified to include any innovation, as long as equations are available that adequately describe the dynamics of the innovation. Likewise, equations to quantify consequences (such as, for instance, the number of affected inhabitants, or damage calculations) can also be incorporated within SCAN. In addition, SCAN can simulate years of input time series in just a few seconds. Given this very limited calculation time, one can assess different model structures and parameterisations, and thus perform sensitivity analyses easily. Finally, SCAN was extended with additional modules to visualize simulation results. More specifically, a 2D volume depth spreading algorithm was created to generate spatial flood maps (and quantify flood extents), and a procedure was established to create heat maps of flood volumes and locations (obviating the need of costly 2D simulations).

Simulations showed that the HydroVentiv innovation can have a significant impact on urban floods. This was evidenced by quantifying the impact of this innovation on urban floods for two historical storms and for different green roof configurations. When all roofs that can host a green roof are effectively equipped with such installation, the flood extents throughout the city can be reduced by approximately 30%. Next, a comparison was made with permeable pavement for the Brederodewijk, which is a flood prone district. The simulation results showed that both performed similarly. However, it is expected that green roofs have a lower installation and maintenance cost, and can be included easily in a legislative framework to force project developers to take appropriate measures to compensate for additional pavement. Such considerations were not explicitly quantified or investigated in this study, as this is not the goal of the analysis.

It was also shown how the HydroVentiv innovation and the SCAN tool itself can contribute to climate adaptation planning. Hereto, climate scenarios (composite storms perturbed to climate change scenarios) were simulated within SCAN, and the obtained flood extents were compared. Different maps were created to highlight the (potential) impact of climate change. As communication and visualisation is of the greatest essence in climate adaptation planning, it is important that SCAN can also provide such clear maps and summary of the results. In a next stage, the simulations can be repeated after implementation of the HydroVentiv (and alternative) innovations. Thus, this is an iterative procedure: climate impacts and consequences are quantified, followed by the formulation (and implementation) of adaptation measures. Then again, the climate impacts and consequences can be calculated, thus also including the inherent impacts of the investigated adaptation measures. In this study, the cylce was only completed once, but it is shown that this procedure can be repeated multiple times.

Currently, SCAN only focuses on urban (and riverine) floods. Thus, only the impacts of innovations on these hazards can be quantified. However, due to the openness of the SCAN platform, additional model equations can be included. Hence, in the future, it will also be possible to quantify the impact on city heat stress. In addition, by simulating continuous long term series, water availability and drought impact assessments can also be performed. Likewise, SCAN can be extended with additional model structures to quantify specific consequences.

Finally, the SCAN tool and performed analysis are confined by certain limitations. Firstly, the SCAN model is a simplification of reality which aggregates (lumps) processes on relatively large scales. Note that innovations, however, can be simulated on a fine scale (on the level of the innovation itself). Therefore, SCAN is mainly a Decision Support System (DSS) or tool to be used in a first assessment phase. It is not meant to substitute the detailed design process. Instead, SCAN is ideally suited to test various strategic scenarios (such as the overall impact of green roofs, ...), or to be used in various applications that require minimal simulation times (such as real time applications, optimization problems, ...). In fact, SCAN and the DSS is designed to be part of a multi-layer approach for risk management as demonstrated. This study and application of SCAN was also limited as it did not calculate consequences (such as flood damages) explicitly. However, it can easily be seen that such quantifications are also possible. The requisite data to perform these analyses was not available though. Therefore, the flood extent was considered as a proxy for the consequences.

SCAN is currently being used for climate adaptation planning for other regions, including the historical city centre of Bruges and Brussels Airport. Also, additional features, such as intelligent control of assets (such as green roofs and buffers) are being analysed. These features will be added shortly to SCAN.

8. Adaptation to coastal floods in a low-lying area: the case of Cesenatico, Italy

8.1. Overview of the site

8.1.1. Location

The Emilia Romagna littoral is located in the North East of Italy (Fig.7.1) and comprises 130 km of low and sandy coast, most of which are strongly urbanized. The impact of this site for the Italian economy can be summarised with a few figures (valid for year 2006) relative to tourism activities: 41 M person/day in the period May-September, 3'384 hotels, 154'000 employees, and a gross income per year of 9.8 billion €. A decennial coastal plan was recently published addressing the problem of integrated coastal zone management.

The Emilia Romagna beaches face the Northern Adriatic Sea, a relatively shallow epi-continental shelf with low tidal amplitude. A general erosive tendency is mainly caused by the reduced sediment transport rates of the rivers and by the increased anthropogenic subsidence. Subsidence, sea level rise and erosion of dunes pose a serious threat for coastal flooding.

Cesenatico municipality is included in the province of Forlì-Cesena. The site is famous for its marina and is a well known touristic resort with a sandy beach rich in bathing facilities.

8.1.2 Existing management of coastal flooding

The extension of the Port of Rimini strongly interfered with the littoral dynamics, inducing an erosive pattern in the northern beaches, aggravated by the reduced sediment discharge of the Marecchia river (Fig. 8.1). The erosion gradually moved toward Cesenatico, 20 km Northward, as a consequence of the reduction of long-shore sediment transport due to the continuous series of groins built between Rimini and Cesenatico in the period 1947-1997. In addition, the extraction of water, initially associated to land reclamation and, later, for agriculture and industrial reasons, induced severe subsidence, with peaks of 50 mm/y in the Eighties. A special law in 1980 regulating water extraction, and the building of the Ridracoli dike (Fig. 8.1) and water supply network, proved to be effective in reducing the subsidence rate.

Cesenatico coastline is approximately 7 km long and is divided by the harbour jetties into a Northern and a Southern area, and by a groyne to the North of the jetties into a Northern and a Central area. To face the beach erosive tendency and the flooding events, the following management is present (Fig. 8.2):

- Northern area: unprotected;
- Central area: protected by a sand-bag submerged barrier 0.8 km long, 12 m wide, 250 m distant from

the shoreline; it includes the canal harbour, that for water levels exceeding 0.9 m a.s.l. is closed by sea gates, the so called “Porte Vinciane”, 2.0 m high a.s.l.; the sea gates are combined with a pumping system to ensure the seaward urban drainage;

- Southern Area: emerged barriers, crest level 1.5 m a.s.l.; soil dike, integrated into the urban use of the back beach, 20 m wide, 1 m high, 1.4 km long, starting from the Southern jetty (extending Southward).
- The capacity of the drainage system has been recently increased and a by-pass system and a series of expansion basins were also built.

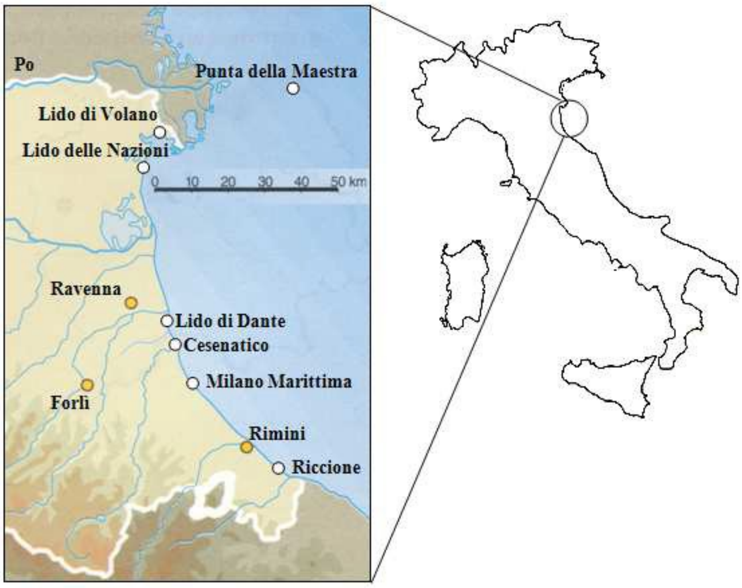


Figure 8.1. Location of Cesenatico along the Emilia Romagna coast, Italy.

A decennial coastal plan was recently published addressing the problem of integrated coastal zone management in the Emilia Romagna Region (Preti, 2009). However, this plan does not account in a systematic way for climate variability (i.e. extremes) and climate change effects. The approach is essentially driven by the consequences of major events: based on the damages to beaches and bathing facilities, on historical trends, surveys and climate studies, the Regional Government is recently proposing, in agreement with Municipalities, medium-term plans for beach nourishment along the whole coastline (Penning-Rowsell et al., 2014). The Regional Government needs of course to receive funding from the Ministry of the Environment in order to cover the expenses of the intervention.

Nourishment has been selected by the coastal authorities and local managers as the preferred technique to face both erosion and flooding mainly for the following reasons: maintenance of wide beaches for tourism and recreation; low environmental impact; low aesthetic impact. Although the impact of emerged barriers and groynes has been recognised, all management plans keep in place the existing structures due to high costs for their removal and the kilometres of barriers that were constructed in the past.

The impact of the creation of “winter dunes” by moving the sand in front of the bathing facilities and therefore reshaping the beaches is usually not tackled. These operations lead to undesired impact on the benthic communities that are very important indicators of water quality and therefore also bathing allowance.

Finally, so far other kind of measures such as insurance, evacuation plans (implemented so far in Cesenatico only), landscape planning, proactive citizen defence (for instance by means of temporary flood defences) have not been included yet in a systematic management protocol but have been used as exceptional measures in local rehabilitation designs.

8.1.3. Climate conditions

Most intense storm events come from Bora (NE) and Scirocco (SE) with similar intensity; waves may reach 3.5 m every year and rise to 6 m every 100 years. Wind is stronger and colder from the shorter fetch sector of Bora where it reaches frequently 35 knots intensity, whereas from the long fetch sector of Scirocco it seldom exceeds 30 knots and is typically warm. The tidal excursion is low; the average spring tide range is ± 0.4 m and extreme year values are around ± 0.85 m (IDROSER, 1996; CENAS, 1997).

Meteorological data produced by the Deutscher Wetterdienst and distributed by the Helmholtz-Zentrum Geesthacht, for the control century (1960-1990) were elaborated to produce forcings for a set of simulations for the Adriatic Sea basin, from the Venice Lagoon to the Emilia Romagna Littoral (Umgiesser et al., 2011). The meteorological data were computed as a regional downscaling with the SGA-CLM (COSMO-CLM) . SGA-CLM set of simulations, provided by the DWD, were initialized and forced 6 hourly by global coupled model ECHAM5-MPIOM (Max Planck Institute Ocean Model) and provided results with a spatial resolution of 18 km (Keuler et al., 2009) . The 30 years long time series was then statistically elaborated deriving the yearly maximum surge for period 1960-1990, and the correspondent significant wave height, peak off-shore wave steepness and wave direction

The synthesis of the results of these analyses are reported in terms of scenarios in Tab. 8.1. The typical storm duration was found to be of order 12 hours. The typical rise and fall time of the storms were also analysed, leading to the results that in at least 1 case out of 30, the rise time from H_s =0.5 m to H_s=3.5 m and the fall time from H_s =3.5 m to H_s =0.5 m have similar duration of order 1 h.

Figure 8.2. Aerial view of Cesenatico, subdivided into the areas recalled in the text, and pictures of the existing management a) semi-submerged barrier; b) sea gates at the Canal Harbour entrance; c) the “Gardens”; d) emerged barriers.

Table 8.1. Climate scenarios considering surge *Z* as the first variable in the statistics. Conditioned values of significant wave height ($H_s|_Z$) and peak wave period (T_p); wave steepness s_p is assumed to be equal to 3.96%.

h=14.7 m; s_{op} =4 %	Z (m)	$H_s|_Z$ (m)	T_{op} (s)
Tr=2 years	1.14	2.12	5.85
Tr=5 years	1.23	2.35	6.17
Tr=10 years	1.28	2.47	6.33
Tr=20 years	1.32	2.57	6.45
Tr=25 years	1.33	2.60	6.49
Tr=30 years	1.34	2.63	6.52
Tr=50 years	1.36	2.69	6.59
Tr=100 years	1.39	2.76	6.69

8.1.4. Coastal habitats

Only few natural habitats are present in Cesenatico, the most important being represented by sandy beaches. Other habitats are some scattered vegetated patches of limited naturalistic value. The building of tourism facilities substituted the dunes and altered the beach equilibrium.

The effects of breakwaters and the additional impact due to bulldozing and scraping during the winter season in the intertidal zone were investigated (Hanley et al., 2014) and the main ecological consequences can be summarized as follows.

- All physical and abiotic characteristics (organic matter, grain size, beach length) vary depending on the degree of beach protection, and specifically they increase in case of emerged structures with respect to submerged structures.
- The total number of individuals and number of taxa differs between the Central and the Southern areas. In particular very low abundance and number of species were recorded at high and medium tidal level in the area protected by emerged structures.
- Changes in the composition of benthic assemblages can be considered also as consequence of grooming and bulldozing.

Overall, it is worthy to highlight that the response of the benthic community depends on many physical and chemical factors and that the relationships among all the components are indeed very complex and not completely understood.

8.1.5. Society and economy

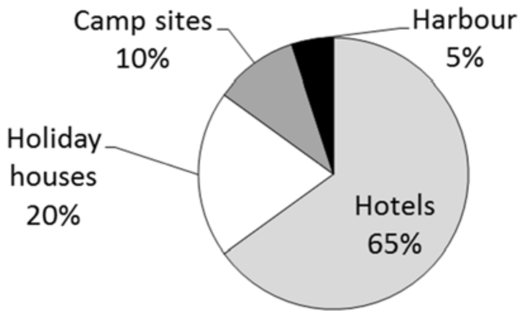
Cesenatico is a popular tourist resort. It is home to the Marine Museum (Museo della Marineria), where historic fishing boats are displayed in the canal. The town also features a 118 m high skyscraper, which for a few years was among the thirty highest buildings in Europe. The total inhabitants in Cesenatico were 25’375 in 2009. The average components of families (Household) are about 2.31 people. The population of Cesenatico has been growing in the last 150 years, from 5593 in 1861 to 15’878 in 1961 and 25’412 in 2011.

The impact of this coastal stretch for the Italian economy can be summarised with a few figures (valid for year 2006) relative to tourism activities: 41 Mperson/day in the period May-September, 3’384 hotels, 154’000 employees, and a gross income per year of 9.8 billion € (Preti, 2009).

Tab. 8.2 synthesizes the most relevant economic activities and related income and Tab. 8.3 Classification of land use types and related land use values in the three areas of Cesenatico (see Fig. 8.2).

Based on survey data (Zanuttigh et al., 2014c), the citizens of Cesenatico feel to be moderately exposed to coastal erosion and flooding risk (Fig. 8.3). In other words, they feel that this risk is significant but they do not feel to be adequately informed and prepared to cope with such risks. About the 30% of the citizens is not aware of the evacuation routes in case of a flood and only a minority of citizens (18%) is aware of the alert warning system by mobile phone (through SMS), despite it is generally rated to be a useful application. According to the surveys, the main risks associated to coastal erosion and flood are the damages to tourism and beach recreation (29%), the damage to the ecosystem (28%), the flooding of the city centre (23%) and salt-water ingression (15%).

Tab. 8.2 Economic activities and related income in Cesenatico.

Activity	**M€/ year**	**% of GDP**
Tourism	123	25% of Municipality GDP
		
Fishing harbour and infrastructures	52	2% of Municipality GDP
Private services	355	47% of Municipality GDP
There are no industrial firms in the area examined	87	18% of Municipality GDP

Tab. 8.3 Classification of land use types and related land use values in the three areas of Cesenatico (see Fig. 8.2).

Land use type	**Land use value €/m²**		
	Northern area	Central area	Eastern area
Residential homes	130	165	140
Holiday homes	191	217	199
Historical buildings	180	180	180
Hotels	152	152	152
Camp sites	61	0	0
Tourism harbour and infrastructures	-	97	-
Fishing harbour and infrastructures	-	179	-
Private services	3554		

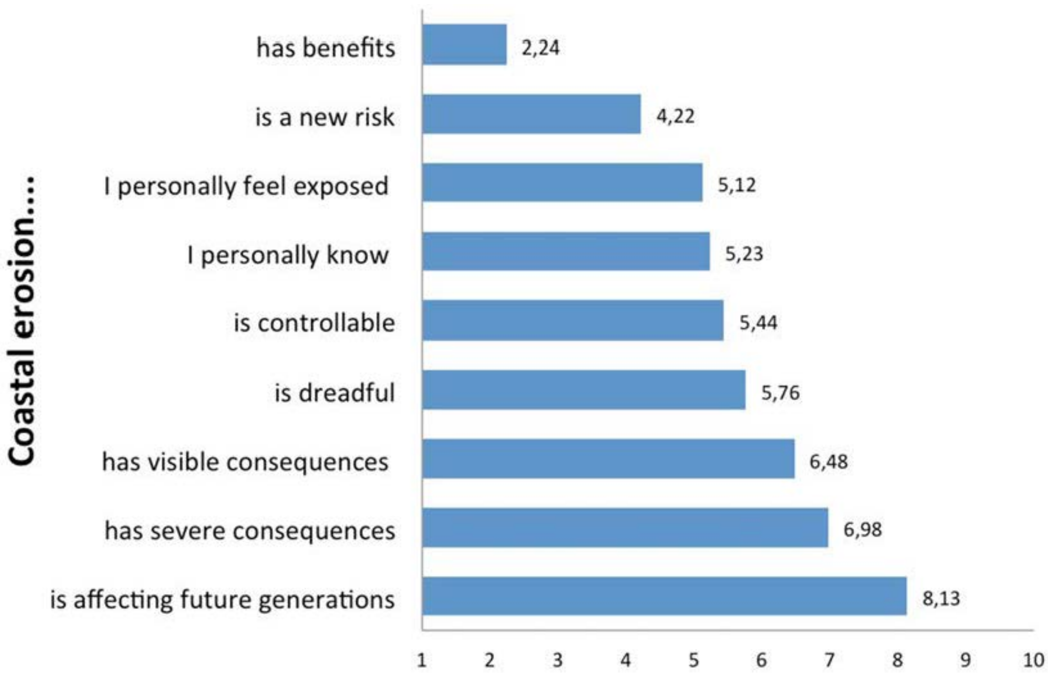


Figure 8.3: Perception of coastal erosion risk in Cesenatico residents (mean value from 1=”no risk” to 10= “extremely high”).

8.2. Application of the SPRC model

Since defence planning measures are usually taken at municipality level, the site extension is defined specifically by the Municipality border. The landward boundary follows the railway track. Therefore in this case the area under analysis with the Source-Pathway-Receptor-Consequence (SPRC) model does not correspond to a physiographic unit. This implies that the typical sediment long-shore transport budget in the area is assumed as a pathway and it is considered to be constant in the analysis, i.e. defence strategies at the site boundaries or low levels of sediment transport from rivers are not expected to change with time.

Sources, pathways, drivers and receptors are schematised in Figures 8.4.

Key receptors include the beach for tourism activities and ecological value (i.e. benthic communities), the urban area for social and economic activities, the marina that is crucial for the economy in the area, the railway that is the essential transportation route, and finally pinewoods and agricultural areas.

The identified pathways consist of the existing engineered management (non-protected beach to the North of the Northern groyne, submerged barrier to the North of the jetty, emerged barriers to the South of the jetty, sea gate to close the canal, soil dike starting from the southern jetty, nourishments), and of the geomorphological response (the sedimentary budget from/to adjacent areas and the subsidence).

Sources in order of importance are storm surge, runoff discharge and extreme wave events. Drivers are climate change, natural and anthropogenic subsidence that may significantly change over the time.

The methodology selected for assessing the relative impact of climate change on the Sources of the flood system is the development of risk multipliers (Evans et al., 2004). The estimated change in inundation probability due to changes in the sources is taken to be equivalent to the change in flood risk, being constance the social and economic situations. As the major effects of higher water levels is increased inundation frequency of the existing flood plain with flood plain expansion being a secondary effect, the change in inundation probability translates into a change in risk, all other factors being equal.

The evaluation of the risk multiplier is based on the comparison among the extension of the flooded area associated with a given risk probability. In this case, the selected risk probability is 0.01%, i.e. storm surge event with return period of 100 years at the current status and in the short, medium and long term scenarios. Values are reported in Tab. 8.4, which includes also two combinations of the Sources in order to emphasise the highly non-linearity of the site response to risk multipliers. The area indeed is flat and the maximum beach elevation (i.e. the natural beach limit in front of the urban area) coincides with the elevation of the street and urban areas immediately behind the beach. This elevation is of about 1.5 m, therefore the contribution to the risk and to its change produced by waves (through wave run-up) is relevant only when the beach is fully submerged, i.e. when water level (given by a combination of sea level rise, subsidence, storm surge level) is higher than 1.5 m. Since subsidence rate is much greater (so far it is 1 cm/year) than sea level rise, subsidence and time play the most relevant roles in the change of exposure to the flood hazard.

Ranking of the drivers is reported in Table 8.5.

Figure 8.4 Top) Sources, drivers and pathways,and bottom) receptors in Cesenatico.

Table 8.4. Risk multipliers for the Po Delta site. The risk multipliers indicate the multiplication factor of the inundated area forecasted at present (2010), with Tr=100 years. Mean sea level considers both sea level rise and land subsidence. Climate scenarios as in Tab. 8.1.

Driver type	**Name**	**2020**	**2050**	**2080**
Source	Waves	1.0	0.9	1.0
Source	Surge	0.8	1.0	1.3
Source	Mean Sea Level	1.1	1.4	2.1
Source	River flow	Not quantified (expected low)		
Driver type	**Name**	**2020**	**2050**	**2080**
Combined sources	Waves + Surge	1.1	1.2	2.0
Combined sources	Waves+ Surge + Mean Sea Level	2.0	2.5	3.0

Table 8.5. Ranking table for the Secondary Sources for Po Delta site.

Importance of Secondary Sources in flood risk over time		
2020s	**2050s**	**2080s**
Mean sea level	Mean sea level	Mean sea level
Waves	Surge	Surge
Surge	Waves	Waves
River flow	River flow	River flow

8.3. Vulnerability assessment

8.3.1. Modelling hydraulic vulnerability

Flood simulations in case of the existing management were carried out with MIKE 21 (HD), Release 2009, Flexible Mesh (Zanuttigh et al., 2014c). The input bathymetry was built-up on the basis of the Lidar surveys in the area, covering around 5.5 km long-shore and 3 km cross-shore on an average.

The simulations considered :

- three climate scenarios (short 2020s, mid 2050s and long 2080s term) for sea level rise, storm and surge, see Tab. 8.1;
- two storm surges combined with wave conditions reproducing a frequent and a severe storm, characterized by 10 and 50 years return periods respectively;
- present estimates of average annual river and channel discharges based on historical data;
- the most probable failure of pathways, based on the analysis of the system and on stakeholders

opinion: the missing closure of the sea gates at the canal harbour in Cesenatico due to sedimentation at the channel inlet.

It is worthy to remark that simulated conditions were not cautious since neither beach reshaping under storms nor subsidence were accounted for.

An example of the flooding depth and extension for a medium term scenario is reported in Figure 8.5. The Southern beach is wider but is characterized by lower elevation and lower steepness than the Northern one so that it is completely flooded even in the less severe conditions (Tr=2 years). Flooding waves propagate with modest velocities (up to 0.6 m/s) on the beach and then reach the third line of the buildings along the Southern urban area and the second line of the houses along the Northern area, still saving the urban area closer to the marina. The effect of the submerged barrier Northwards the jetty is therefore positive: while the area inshore the Northern unprotected beach is flooded, the area inshore the submerged barrier is not, showing that the barrier contribution to wave reduction prevails on the induced increase of piling-up.7

In case the sea gates are closed and all the by-pass systems are properly working, the existing defence works from high water levels in Cesenatico show to be an efficient measure for preserving the safety of the urban areas. The central area close to the marina is flooded - to the North of the canal harbour - only in case of the most severe condition (Tr=100 years) due to water overflowing the West bank of the marina. A verification of the marina and canal harbour banks would be therefore recommended.

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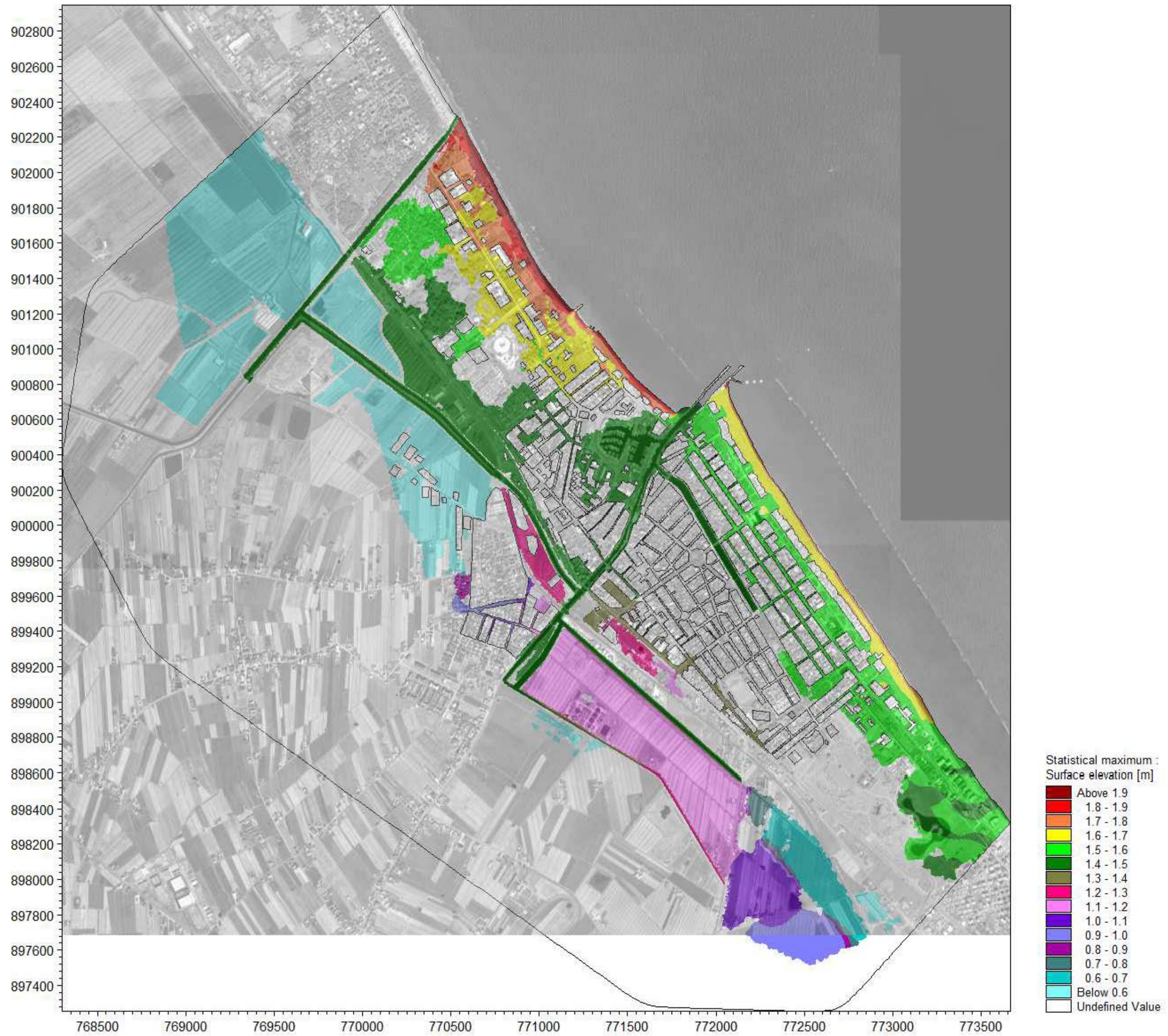


Fig. 8.5. Maximum surface elevations for a frequent storm with Tr=10 years. Medium term: 2050. Sea gates closed and operating pumping system.

8.3.2. Habitat vulnerability

As for sandy beaches the intertidal beach zone was considered to be the major ecological receptor of flooding events. Within this habitat, the benthic component was specifically analysed because it is generally considered as the most significant ecological indicator of the marine habitat status.

The response of the habitat to selected parameters, such as wave agitation, beach slope, sediment grain size, turbidity, etc. was assessed by means of a newly developed method Fuzzy Bayesian Method (FBM) which is a combination of fuzzy logic and a naïve Bayes (Bozzeda, 2013). The following measured data were used to train the FBM

- environmental variables (i.e., the input data): median particle diameter, sorting coefficient, organic matter percentage content (TOM %), intertidal zone length, tidal level, beach slope, wave height, riptide velocity, beach deposit index (McLachlan and Dorvlo, 2005);
- biotic/target variables of macro-fauna communities (i.e., the expected output): macrobenthic abundance.

All these data were considered as the set of "benchmark" values for establishing the EVI thresholds to evaluate the environmental impacts, see Section 3.2.

The impacts of flooding events on the macro-benthic abundance was then simulated for the whole set of climate scenarios reported in Table 8.6. Based on the application of the FBM and on surveys in the area the following empirical curves are obtained for beaches EVI_B and for pinewoods EVI_P respectively

$EVI\_B=B1y^2+B2y+B3$ $EVI\_P=P1h^3+P2h^2+P3h+P4$

where y=water depth (m) and h=duration of the flood (h). The specific coefficients are reported in Table 8.6 for both benthos and pinewood. These curves were implemented in the DSS.

As for the pinewoods, they resulted highly tolerant to salt water and marine spray whereas the roots are very sensitive to salt water intrusion and therefore even a short term exposure would produce a high impact, i.e. presumably non recoverable.

Table 8.5 Values of the parameters to evaluated the EVI Coefficients for Benthos (B) and Pinewoods (P), for each scenario and sea level rise (see climate conditions in Tab. 8.1).

Scenario	2010	2020	2050	2080
SLR	0	0.7	0.13	0.22
B1	0	0	0	1.333
B2	0.097	0.038	0.223	0.019
B3	-0.082	-0.014	-0.228	2.241
P1	-0.00006	-0.000006	-0.000100	-6E-07
P2	0.001	0.001	0.001	0.000
P3	0.06	0.06	0.08	0.096
P4	-0.4	-0.4	0.5	1.1

8.3.3. Analysis of social impacts

The analysis of social impact is mainly focused on two issues: (1) the damages to Critical Facilities (CFs); and (2) the expected number of fatalities. The approach to identify and evaluate CFs is already reported in Section 3.3.

The social impact on CFs has been estimated following these steps.

1. Ranking of Critical Facilities. A rank was derived based on the function of buildings in terms of use in emergency management, function in ordinary activities and community aggregation, and symbolic function. The corresponding Approximated Social Value (ASV) was evaluated, with values reported in Table 8.6 from 1 (low) to 5 (high). In Cesenatico it was possible to identify up to 80 Critical Facilities: 4 with ASV=5, 10 with ASV=4, 45 with ASV=3, 15 with ASV=2 and 6 with ASV=1. The ASV also provides a re-activation list in reverse order, as the highest values are supposed to receive priority in emergency interventions for reducing social damages. In the perspective of land use planning, the adoption of such an approach should lead to the relocation of high scoring buildings to safer areas or encourage measures to increase buildings resilience. Similarly, higher scores indicate where efforts for higher education and training of personnel should be concentrated and where emergency measures such as mobile barriers could be deployed with maximum effectiveness.
2. Estimation of physical damage for structures. The damage scale was estimated based on flood depth and duration. Following the method by Schwarz and Maiwald (2008), the damage grade is related to the flood depth (De) through a non-linear function. Intuitively, the effects on society and structures are inversely proportional to flood Duration (D), if one excludes flash flood phenomena. Long duration floods, even if relatively limited in space, produce greater impacts on social functions: a bridge blocked might be a nuisance for an hour, while it could compromise trade routes or tourism activity for a week. Therefore the following scenarios have been considered: i) Short D (Hours), ii) Medium D (Day/days), Long D (Week/weeks).
3. Definition of touristic impact. In Cesenatico, one of the most relevant variables affecting the ordinary social pattern is tourism. It can be presumed that not all the tourist had previous experiences of floods, and that if a flood happens with a large number of tourists in place CFs may suffer higher pressure and warning messages may face more dissemination problems. The tourist presence has been represented through a value reflecting seasonality S; this factor will act as a final scale multiplier, where low season (S=1) denotes ordinary conditions, and high season (S=2) implies that the effects will be exacerbated.
4. Estimation of Collateral Social Damages (CSD). A final estimation of the impact has been computed following this function that has been implemented in the DSS

$CSD = \Sigma_I ASV_i \cdot De \cdot D \cdot S$

The social impact on the expected number of fatalities has been estimated following these steps, see Section 3.3. The following function of life losses and injuries (NI) was derived from Penning-Rowsell et al. (2005)

$NI = (H*AV)/(Pa+ID)$

where H is the hazard rate, AV is the Area Vulnerability, Pa is the sensitive population (age<14years and age>65 years) and ID is the number of sick and disabled people. Table 8.7 reports the factors used to estimate life losses and injuries.

The function provides an overall number of people subject to death or injuries. These two aspects were not distinguished as too many external variables such as local lifestyle, wealth or public health services influence the final output of life losses, and the uncertainties are high.

Table 8.6. Ranking values of Critical Facilities (CFs).

Approximate Social Value (ASV)	Definition
5	Critical structures that if involved could compromise the emergency action, the coordination chain, public safety and public health in the long term. For example, hospital and emergency facilities.
4	Facilities that provide significant public services and should be activated within 24 hours. For example, nurseries, major water and sewer facilities, fire and police stations, schools and park facilities used to support critical purposes.
3	Facilities that provide important public services. Main centres of aggregation and education that are important to the community.
2	Facilities that provide public services but that are less critical for the community. For example, common storages, sport centres.
1	Places which value is mainly symbolical.

Table 8.7. Factors used to estimate life losses and injuries.

Value	Description
H	Hazard rate: H=NI·y·v·DF where N is the number of people involved in the flood, y is the flood depth, v is the flood velocity, DF is the debris factor equal to 1 for the Mediterranean and 2 for the Ocean.
AV	Area Vulnerability: AV = W+ Fo+ Na where W denotes the Warning, Fo is the speed of onset of flooding and Na is the Nature of the flooded Area.
Pa	Percentage of the sensitive population (age<14years and >65 years) Pa, derived from demographic data of Cesenatico (ISTAT, 2009)
ID	Percentage of Infirm/Disabled/ long-term sick population ID, based on data from the Municipality of Cesenatico.

8.3.4. Analysis of economic impacts

A consistent approach based on incomes for each economic land use was adopted (Zanuttigh et al., 2014c) for estimating the Economic Consequences (EC) e.g., hotels are evaluated in terms of annual GDP, houses are evaluated in terms of annual rents, beaches are evaluated in terms of annual willingness to pay to preserve them.

The EC in the Inland area ECI are supposed to be dependent on flood depth and duration following the formula, see Section 3.4:

ECI=vij•bj•Fd + vij•aj √Fy (7.6.5)

where vij are the values of land uses in euro/m^2/year from Census statistic data; Fd is flood duration and Fy is flood depth; aj are proportionality constants that are normalised for each land use j based on the maximum value of Fy in 2050 for a storm return period of Tr=100 years, assuming different reference percentage of damage depending on the use (for instance, 50% damage for buildings/homes/hotels, 25% damage for harbors); bj are proportionality constants that express the expected period to restore economic activities depending on Fd and on land use (for instance, a value of 30 is set for hotels and of 20 for private services) and are normalized to annual incomes with the days/year. Note that flood velocity is assumed to be irrelevant based on results of detailed mathematical modeling (Section 3.1).

The land use value losses are then combined with the EC along the Beach, ECB, due to erosion. By adapting the results of the survey Diaz et al. (2012) to the current population and to the GDP per capita prevailing in Cesenatico, the intangible value attached to beach is ECB=1.47 €/m^2/year.

8.4. Identification of adaptation solutions

The adaptation options most suited for Cesenatico were identified by considering jointly

- the existing management, and therefore the costs induced by any change of what is already in place;
- the historical management of the coastal area in the Emilia Romagna Region;
- the feedback from stakeholders during surveys and focus groups (see recommendations for risk assessment outlined in Chapter 2);
- the perceived effectiveness of risk management from public at large, see Fig. 8.2.

Table 8.8 includes the selected mitigation options, the rationale to propose them and the main challenges posed by these solutions.

Table 8.8 Lists of mitigation options together with the rationale and the main challenges.

Mitigation Option	**Rationale**	**Challenges**
Floating breakwaters	Low aesthetic impact Easy decommissioning Reduction of incident wave height Low sensitivity to water level variation Increase of near-shore biodiversity	Low effectiveness during storms Low structure reliability under large storms
Low-crested detached barrier	Reduction of incident wave height Low visual impact Increase of near-shore biodiversity	Increase of wave setup Sensitivity to sea level rise
Nourishment on the submerged beach	Availability of resource at low cost (off- shore dredged sands) Low environmental impact compared to hard defences Low aesthetic impact Low impact on benthos compared to emerged nourishment Reduction of incident wave height	Limited benefit to shoreline advancement
Nourishment on the emerged beach	Temporary increase or maintenance of beach width Recreational value Low environmental impact compared to hard defences Low aesthetic impact Reduction of wave run-up	Limited availability of compatible resource High sensitivity to negative impacts in case of unsuited nourishment material
Dune reconstruction	Significant reduction of wave overtopping Compatible with landscape	Feasible only where sufficient space is available Not easy to reinforce or maintain
Heightening of Vinciane sea gates	Significant reduction of the expected flooding of historical city center	Combined by-pass systems required Combined periodic dredging plans of the canal harbor entrance required Temporary reduction of harbor accessibility Negative social perception of the existing gates
Evacuation plan	Reduction of casualties Promotion of risk awareness	Non-effective communication Unclear responsibilities during crisis management
Insurance scheme	Promotion of rapid business recovery Market incentive mechanism (to reduce premium) Promotion of urbanisation of low risk (=low premium) areas Redistribution of damage	Unpopular introduction of adequate laws and regulations Careful estimate required of the additional cost paid by society to cover insurance profit

8.5. Preliminary design of adaptations

8.5.1. Engineering solutions

Past experience, environmental constraints and end users feedback suggest the traditional nourishment with blond sand (carried out on the emerged beach) as one of the most effective and suited mitigation option against erosion. All the engineering mitigation alternatives here proposed consider some sort of periodic sand nourishment, either on the emerged or on the submerged beach.

When performed on the emerged beach, the designed sand diameter is similar to the existing one, characterized by a d_{50}=0.2 mm, and the target beach advancement is 30 m based on historical data (Preti, 2009). Since the availability of inland sandy stocks of large diameter sand is rather limited, while there are large quantities (more than 50 Mm^3) of fine sand (d_{50}=0.1 mm) available from offshore pits, the option of nourishment on the submerged beach is also investigated. The fine sand may only be placed at a depth that where its stability is assured, and used to reduce the incident wave energy. Specifically, the option considers that the designed submerged nourishment is quite significant, i.e. 300 m^3/m, and the fine material is placed at isobaths -3 m b.s.l.

The vulnerability of the site from both flooding and erosion, the widespread use of detached breakwaters to defend the surrounding coastal stretches, the social perception of this kind of defence and the high costs for their removal suggest that the engineering management should consider to maintain and maybe modify the existing breakwaters.

Therefore, most of the selected solutions consider to maintain and reshape the existing breakwaters, to obtain a more homogeneous cross section and a better protection of the Northern area. The rationale of protecting the whole area with barriers is to minimize the losses of the nourished sand and to reduce the run-up on the beach, thus decreasing the flooding risk. The expected wave run-up is further reduced thanks to the combination of the breakwaters with nourishment interventions.

8.5.2. Dunes

Coastal dunes protection and restoration is made from ecological engineering techniques, using natural processes to help coastal ecosystem to regenerate and to improve its efficiency to fight against erosion.

The results of dune restoration depend on the following different factors:

- the sediment characteristics,
- the techniques used for sand trapping,
- the rate of sediment exchange between the beach and the dune after nourishment,
- the space available seaward of human structures.

The recommendations from other similar interventions carried out in the Northern Adriatic can provide useful inputs (Bezzi et al., 2009; Calabrese et al., 2010). A dune system with medium vulnerability is characterized by a foredune beach 40-70 m wide and a crest 1.5-2.5 m high.

The purposes of dune reconstruction in Cesenatico are mainly (i) to build a natural reinforcement of the beach to defend the inland area from waves overtopping the beach bank; (ii) to set-up a sand “reservoir” along the beach to mitigate the effects of erosion induced by severe storms; (iii) to recreate a valuable ecological habitat.

In Cesenatico, the Northern area appears the most suitable site due to beach width and absence of bathing facilities. The selected dune design parameter are reported in Tab. 8.8.

A common practice to restore dunes is to import sand by nourishment and bulldozing and then transferring the sand from low to high level. This method however may reduce the intertidal beach width and impact the benthic communities. This impact can be decreased if the bulldozing is carried out in winter when benthic populations are not in the reproductive phase and massive settlement by organisms does not occur.

Table 8.9 Design parameters of selected engineering and ecologically based adaptation solutions. The parameters in the table are the same implemented in the DSS.

Nourishment on the emerged beach		**Nourishment on the submerged beach**	
d_{50}	0.20 mm	d_{50}	0.10 mm
Nourishment volume	210 m^3/m	Cross-shore location	from -3.0 m to -4.0 m
Beach advancement	30 m	Nourishment per m	300 m^3/m
Length	5100 m	Nourishment extension Lb	5100 m
Estimated duration	5.0 y	Width of nourishment	75 m
Submerged barrier		**Emerged barrier**	
Crest freeboard	-0.5 m s.w.l.	Crest freeboard	1.0 m s.w.l.
Barrier length	2100 m	Barrier length	3000 m
Depth at the structure toe	3.0 m	Depth at the structure toe	3 m
Crest width of barrier	15.0 m	Crest width of barrier Bc	3.0 m
Gap width to barrier length ratio	30%	Gap width to barrier length ratio	0.3
Barrier offshore slope	1:2	Barrier offshore slope	1:2
Dune			
Inshore distance from the shoreline	40 m		
Crest width	2.5 m	Height	2.0 m

In the Emilia Romagna region the most suitable species for dune stabilization are the two perennial plants *Agropyron Junceum* and *Ammophila littoralis*. The plants have to be in good condition and with a well-developed root system and the has to be performed in late Autumn, when the temperatures still allow the vegetative activities and the water from precipitation or condensation is enough to guarantee the absence of great water stress.

Furthermore, the vegetation distribution on the dunes has to be established according to the natural zonation of each species. Historical information, photos or similar local beach environments may help to choose the best zonation. To ensure that the vegetation can grow and develop, the planted area has to be protected with a fence until the dune stabilization and the access to the beach has to follow established paths that minimise the interruption of the continuity of the dune system. A continuity of at least 300 m length of the dune system is one of the key parameters required to maintain a medium vulnerability level (Calabrese et. al, 2010).

8.5.3. Evacuation plans

In Cesenatico, the software "Serapia" has been used to calculate evacuation times (Hissel et al., 2014). This tool estimates the time needed for evacuating an area under different circumstances and can therefore assist in developing an effective evacuation strategy. The total evacuation time is divided into three time intervals: 1) the time it takes between the flood alert and the moment that inhabitants leave their homes;

2) the time it costs evacuees to travel from their home to a congested exit point; 3) the time it takes to drive through this congested point. For this estimation, the model needs as an input the following four sources of data.

1. The number of people to evacuate. In Cesenatico a significant percentage of their inhabitants will be able to leave the evacuation area with their own cars while others (elderly, residents of hospital and nursing homes) will have to be evacuated with buses or special vehicles. In our model (Hissel et al. 2014) a total of 9645 persons must be evacuated in case of a strong event to 18 evacuation sectors of the city. According to available data, in 2012 around 15'000 cars were registered in Cesenatico with average occupancy of 2.3 people per car.
2. The time between the flood alert and the departure from home. The duration of this time interval depends on how fast all inhabitants are informed, how well they are prepared, to which extent they are aware of the urgency of the evacuation and their willingness to leave home. A minor percentage of inhabitants will refuse to evacuate.
3. The travel time from the departure location and the location of the exits of the evacuation area. It depends on travel distance and average velocity. During evacuation, traffic behaviour is expected to differ from normal circumstances.
4. The chances of congestion. A congestion is likely to occur when many cars have to leave the area in presence of a small number of exits. Cesenatico is a relatively small town with many road exits. Five exit points have been identified to lead people towards shelters. Two safe routes with larger road capacity can be identified in the directions to the North and to the South, respectively Viale Saffi e SS Adriatica (Fig. 8.6).The capacities of evacuation lanes is going to be reduced by 50%.

According to Hissel et al. (2014), the following methods can be adopted to shorten the needed evacuation time:

- decrease the total number of vehicles leaving the area by raising the number of inhabitants per vehicle. This can be achieved through information campaigns;
- shorten the departure time by an effective warning system. In a previous survey, inhabitants in Cesenatico reported that they felt moderately informed about flooding risk in Cesenatico (the mean value being M = 4.25, in a range from1 to 10, where 1 means lowest and 10 highest). The municipality's alert system by mobile phone (SMS) was generally considered a useful instrument

(M=7.34, range from 1 to 10) but it was known only by 20.1% of citizens and a small minority was effectively registered to the service. A more effective warning system can be developed, by improving the existing measure (acoustic signal from the harbor area);

- shorten the travelling and waiting time by means of a better distribution of vehicles towards the different exits. In the Plan for Civil protection in Cesenatico, 18 safe areas have been identified and they are efficiently distributed in the area. However, according to the survey (Hissel et al., 2014), the majority of participants did not know evacuation routes (61.9%) and safe places. Information campaigns are therefore needed;
- increase the road capacity, for instance by using some roads in one direction only. Such measure requires effective organization and it does not seem advisable in this case.

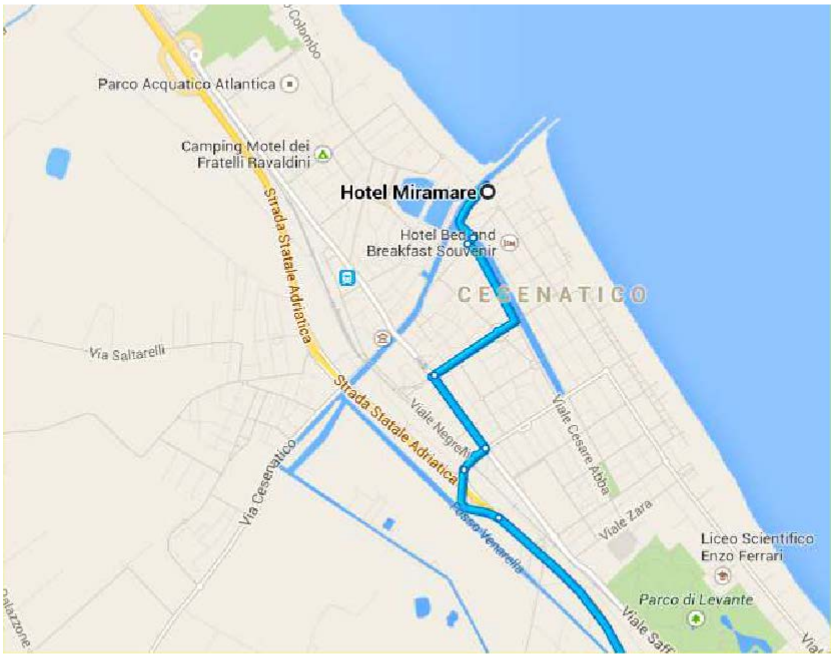


Fig. 8.6. Exit route from the historical urban area and the harbor area towards the South of Cesenatico.

8.5.4. Insurance

The estimated economic damages are spatially dispersed, since they are very high close to the rail-way, at the inland boundary, and high at the beach, at the water/land boundary. However they are also functionally concentrated, i.e. banks and markets. Therefore, the development of a dedicated insurance scheme is suggested.

Indeed, while the private sector is totally absent nowadays, in case of the 1996 flood the Emilia-Romagna Regional government covered 100% firms with an estimated damage larger than 2,5 k€ and 5% households, respectively with the 42% and 34% coverage rates.

It is here assumed a compulsory insurance scheme, without exemptions, where the premium represents a proportion of the average yearly exposure, either of property values (direct impacts) or of the business activities (indirect values) or of both. This scheme has been implemented in the DSS.

The Average Premium AP is evaluated as AP = c (AC + AI)

where AC are the Administrative Costs, AI is the Average Indemnity and c is the commercial viability that usually ranges from 0.5 to 1.0. Specifically, here c=1 to maximize insurance coverage; AC is given by the product of the average cost (10 €/per family), the family size and the total population (see the figures reported in Sub-section 8.1.5); AI=ECI/Tr, where ECI is given in Sub-section 8.1.5 and Tr is the return period associated to the selected storm scenario (Tab. 8.1).

Note that all the losses are estimated in terms of land use values (GDP).

In other words, a heterogeneous agent (as opposed to representative) perspective and a financial (as opposed to economic) approach are adopted. In particular, the standpoint of the individual household or organization involved, at local rather than at national level, allowed us to measure the financial direct and indirect losses to individuals and organizations which are affected rather than the national economic losses caused, and to consider, for example, the income loss in one particular retail shop, even if the trade this represents is likely to be deferred in time or transferred to another retail outlet.

8.6. Selection of the clusters of adaptations

Based on the rationale outlined in Section 8.4, Tab. 8.8, and on the site-specific preliminary design of the mitigation options carried out in Section 8.5, Tab. 8.9, a limited number of clusters was selected. Tab. 8.10 includes 4 clusters:

- cluster 1: is an engineering solution only, based on the traditional management of the area. It includes detached breakwaters and nourishment on the emerged beach. The breakwaters are re-shaped with respect to the existing ones, with prolongation in the Northern un-protected area;
- cluster 2 consists of social and economic measures only, i.e. the evacuation plan and the insurance scheme;
- cluster 3 is a purely ecologically friendly solution; the protection of the Northern area is performed by means of a dune system and the nourishment is carried out on the submerged beach, to limit the environmental impact and the costs;
- cluster 4 finally is somewhat a mix of the previous clusters, combining together all the types of solutions. From an engineering perspective, the existing structures are maintained and only re-shaped and extended without changing the submergence to avoid the costs of removal, lowering and at the same time the reduction of protection from coastal erosion. The nourishment is carried out on the emerged beach, to allow the immediate perception of the nourishment temporary effects and promote recreational activities. The ecologically based solution of creating dunes in the Northern area is incorporated to increase the resistance of the beach to wave run-up and flooding. Both social and

economically based options are also included, i.e. the evacuation plan and the insurance scheme respectively, as cost-effective and climate-proof solutions.

When the evacuation plan is included, its efficacy is limited to the 50% of the population at the selected time slice as a cautious assumption.

Table 8.10 Selected clusters of mitigation options.

Cluster #	Barriers		Wave Farm	Nourishment		Dunes	Insurace	Evacuation plan
	Emerged	Submerged		Emerged	Submerged			
1	South	North, Central		x				
2							x	x
3					x	x		
4	South	North, Central		x		x	x	x

8.7. Impacts of the clusters of adaptations

The hydraulic, social, economic and ecological impacts of the cluster of mitigation options in Tab. 8.10 were assessed by means of the Decision Support System (DSS) delivered by THESEUS project (see Section 6) and being fully upgraded within BRIGAID.

The new following indicators were selected to quantitatively synthesise the hydraulic, social, economic and ecological vulnerability maps derived from the DSS.

1. Hydraulic vulnerability:

- 1a: percentage of the flooded area with respect to the total area under investigation;
- 1b: percentage of the flooded area characterized by flood depth greater than 0.5 m with respect to the total area;
- 1c: percentage of the flooded area characterized by flood velocity greater than or equal to 0.5 m/s with respect to the total area;
- 1d: percentage of the flooded area characterized by flood duration greater than or equal to 6 h with respect to the total area;
- 1e: percentage of beach retreat.

2. Ecological vulnerability:

- 2a: percentage of the area where the EVI for benthos is greater than or equal to 2, with respect to the total area covered by benthos;
- 2b: percentage of the area where the EVI for benthos is greater than or equal to 2, with respect to

the total area covered by pinewood.

3. Social vulnerability:
   - 3a: percentage of CFs interested by a loss greater than or equal to 20%, with respect to the total number of CFs,
   - 3b: percentage of life losses greater than or equal to 1/1000, with respect to the total number of people.
4. Economic vulnerability:
   - 4a: percentage of the flooded area characterized by land value losses greater than or equal to 30% of the total value loss,
   - 4b: percentage of beach loss; actually this indicator is exactly the same as the indicator 1e by definition. However in this way it was disregarded the identification of a threshold minimum value of beach extension that implies a relevant beach loss. This is indeed in agreement with the fact that for simplicity the beach value is considered to be homogeneous over all the ebach width.
5. Risk indicator: percentage of the area characterized by the overall risk level greater than or equal to 2.

Of course the threshold values here selected for each indicator, for instance: the value of 2 for n.5, the risk indicator, or the value of the 30% for n.4a, the land value losses, are site dependent. These values were identified based on the results obtained for the non-defended cases and for the different climate scenarios (Tab. 8.1).

The results for the selected clusters of adaptations (Tab. 8.10) and a few climate scenarios are compared in Tab. 8.11. In order to consider a strategic planning, only the long term climate scenario (2080s) was simulated. This scenario was combined with two storms characterized by very different return periods (i.e. frequent, Tr=10 years, and exceptional, Tr=100 years) to verify both the effects of sea level rise and increase of storm intensity. The impacts of the clusters are compared with the case of the existing management.

- **Hydraulic efficiency.**

Cluster 1 is the more effective in reducing the extension of the flooded area and the flood depth (and therefore duration).

Cluster 2 does not mitigate flooding or erosion and therefore the results of the simulations essentially correspond to the benchmark cases without structures or other kind of protection schemes.

Cluster 3 offers a modest degree of protection that is more appreciable in case of the more intense storm.

Cluster 4 provides slightly better performance than cluster 1 thanks to the presence of the dunes in the Northern area.

- **Ecological sustainability.**

Benthos and pinewoods show different response dynamics that are coherent with the knowledge about these habitats (see Sub-section 8.3.2). The benthos sensitivity to changes of the wave height is appreciable (for storms with return periods of 100 years instead of 10 years), while it is modest in presence of sea level rise (by changing the time slice from 2010 to 2080).

The impact on benthos is reduced by a factor 2 in case of hard defence measures, i.e. cluster 1, if compared with the un-protected cases (cluster 2). The lowest impact on benthos is obtained with cluster 4.

The low values of the EVIs obtained for pinewoods prove that this habitat is resilient to the flooding and erosion conditions in Cesenatico. One determinant factor for the EVI is indicator 1d, the greater the flood duration the greater the EVI (of course the relation is non-linear).

Clusters 1 and 4 offer the best protection to the pinewood, giving a factor 2 less than in the un-protected case, cluster 2.

- **Social equity.**

Clusters 1 and 3 including hard defences reduce the impact on society (in terms of damage to CFs) of about 1/2 than in the un-protected corresponding case. Cluster 2 only reduces the impact on CFs and population of about 1/4 and – as expected - the impact decreases again for cluster 4, when hard engineering solutions are combined with the socio-economic ones.

- **Economic efficiency.**

Cluster 2 almost eliminates the economic impact in the area, and this effect is of course reinforced in presence of other adaptations, see cluster 4. Indeed, this 100% efficiency of the insurance scheme is due to the fact that each land use is assumed to be totally covered for its possible losses, by paying an insurance premium and by making people outside Cesenatico bearing the whole cost. Therefore an yearly insurance premium is much smaller than the related possible losses, although the former depends on the latter, together with the administrative costs.

Based on the overall risk assessment indicator, cluster n.4 offers the greatest reduction of risk in the examined area. This is quite obvious, since a solution based on an integrated multidisciplinary approach is the most suited to excel in a multi-criteria comparison.

From the detailed analysis of the impacts, it is evident that hard structures placed in front of Cesenatico are essential for the safety of this area. It is also imperative to boost the implementation of insurance plans and increase risk communication for efficient evacuation plans.

Table 8.11 Synthesis of the consequences of the clusters of mitigation options in terms of indicators, cluster of mitigation options (see Tab. 7.6.11) and climate scenarios (see Tab. 8.1). Where the number of the cluster is not indicated, the simulated condition corresponds to the absence of any kind of defence.

Scenario	2010	2080	2080	2080	2080	2080	2080	2080	2080	2080	2080	2080	2080
Tr	100	10	100	10	10	10	10	10	100	100	100	100	100
Cluster #				**1**	**2**	**3**	**4**	**5**	**1**	**2**	**3**	**4**	**5**
Indicators													
1a	13.56	13.65	13.58	3.88	3.6	13.65	13.51	3.44	6.06	3.51	13.58	12.42	2.42
1b	5.29	6.56	7.35	0.44	0.39	6.56	0.46	0.10	3.51	0.46	7.35	4.82	1.82
1c	2.47	2.61	2.48	0.29	0.27	2.61	0.31	0.00	0.49	0.31	2.48	1.58	0.49
1d	0.52	0.38	0.54	0.05	0.05	0.38	0.06	0.00	0.09	0.06	0.54	0.17	0.08
1e	30.81	39.00	42.76	34.09	20.39	39.00	27.48	21.95	36.84	38.47	42.76	39.42	32.94
2a	1.84	2.74	12.92	0.00	0.00	2.74	0.00	0.00	5.90	5.70	12.92	2.30	1.77
2b	1.61	0.23	1.99	0.00	0.00	0.23	0.00	0.00	1.35	0.86	1.99	1.70	1.35
3a	41.91	37.36	43.79	25.53	30.53	9.29	35.87	7.41	31.85	31.86	11.91	40.01	9.01
3b	24.29	21.02	31.04	12.51	14.03	9.49	15.33	6.33	13.92	15.92	10.41	20.32	8.21
4a	23.17	20.28	31.45	15.18	15.18	5.10	15.38	4.85	21.86	17.02	7.43	22.43	7.08
4b	30.81	39.00	42.76	34.09	20.39	39.00	27.48	21.95	36.84	38.47	42.76	39.42	32.94
5a	3.33	3.96	4.03	3.33	2.19	3.10	2.89	1.72	3.01	2.29	2.98	3.12	2.01

8.8. Conclusions on risk management in Cesenatico

In Cesenatico -as in most places along the Emilia Romagna region- the dominant flooding parameter is the storm surge level. Flooding is rapid but is characterized by relatively small flooding depth so that evacuation plans may be very efficient. The maintenance of the urban drainage system (sea gates opening/closure, by-pass and channel banks) and of the beach width is essential for the safety of the urban areas.

Tourism is the market force driving the Emilia Romagna coastal management and it should therefore be preserved if not enhanced. It is recognised that erosion is the most critical threat to the economy, jeopardising the site recreational value. In this perspective the management essentially consists of the optimisation of beach nourishment (i.e. the only measure that bathing owners, hotel owners, coastal managers and many citizens consider as the most useful measure) for maintenance or widening of the beach width, keeping high quality sand, for attracting tourists and improving recreational value. This poses social constraints to designs involving hard structures and innovative measures. In practice, the defences at the sea should be characterised by low aesthetic (submerged structures only) and environmental impact, so that for example new emerged barriers cannot be accepted. The use of other kind of mitigations (like insurance, evacuation, etc.), mainly focusing on reduction of coastal flooding risk, or the synergy of such mitigations with existing management has not been considered yet since the main target design objective is widening / maintaining the beach.

Market should drive the attention on the role of business recovery actions, insurance, land use planning, etc. and the combination of mitigation options that so far is poorly known and not practiced.

With respect to the distinction made by Renn (2008), governance is a combination 'adversarial' approach and 'fiduciary' approach under the following main aspects: 1. stakeholder involvement is considered as essential at least from a theoretical point of view and in the preliminary debate regarding the policy framework changes and/or new design plans; 2. different institutions/universities/public bodies try to emerge in the policy arena by disseminating their role and/or research outcomes; 3. decision-making at the operative level is confined to a group of few people who usually base the decision on historical data and on their expert judgement, while trying to account for the suggestions of the groups 1 and 2.

The following legal deficiencies for risk management can be identified

- lack of national resources/budget;
- lack of a national clear chain of responsibilities, and consequent need to stress the role of UN platforms tackling risk at national scale;
- lack of a national plan to prioritise the area of intervention considering impact-based indicators (following World Bank and similar approaches to identify hotspots);
- lack of coordination between projects, which make them more expensive than would be the case if parties would join forces (for instance, combined dredging and nourishment interventions);
- lack of harmonisation of monitoring plans, so that costs of surveys are too high and results are not suited to a large scale integrated planning;
- lack of prioritisation in testing innovative structures, not coordinated at regional scale.

Innovation in risk management is boosted by an increased sensitivity to potential environmental impact of traditional coastal engineering schemes designed to reduce risk from erosion or flooding (Penning-Rowsell et al., 2014). This, coupled with the increased possible threat from the impacts of climate change in increasing sea levels, requires rethinking of measures to reduce risk, and indeed a further emphasis on a philosophy of flood risk management rather than flood defence. Technical issues concerned with risk assessment and risk reduction choices are not central to the process of innovation with regard to risk management, but that institutional culture, traditions and capabilities are of greater significance. The real capacity for radical changes of institutional management approaches and the low level of public risk perception prevent innovation more than the lack of risk information or a poor understanding of the performance of innovative measures.

8.9. Proposing new clusters of innovations in Cesenatico

More solutions to climate adaptation in Cesenatico can be found in the BRIGAID climate innovation window (http://climateinnovationwindow.eu/), see Section 5.4. The following solutions have been found specifically relevant to the case of Cesenatico.

- Temporary flood defences to face floods in the urban historical area (the Central area in Fig. 8.2) where the channel banks are insufficient and when the sea gates do not close, such as: NOAQBoxwall and SLAMDAM, which can be suited only in the areas characterised by a low flood velocity and limited flood depth; NOAQTubewall and NoFloodsBarrier instead are suited also for more intense storms.
- Flip-flap cofferdam dike, to offer a variable protection to coastal flood in the Northern un-protected area. This would cause the loss of the beach, which is indeed undesirable due to high recreational value of the area, but it may be integrated in the new plan for urban development and retreat from the sea proposed by the Municipality in the Northern beach.
- Multi-functional dikes, such as the OBREC device, that can be integrated in the small marina jetties to offer protection from waves and contemporarily produce energy. In this site however the climate is relatively mild so that the energy production is expected to be rather limited and for local use in the marina only.
- Green roofs HYDROVENTIV, to promote a synergic approach to reduce risk from extreme rainfalls and heat waves and at the same time reduce risk from flooding in the urban area.
- Early warning systems, such as the Application framework with drone systems, which can be complementary with the existing very simple early warning system based on the closure of the sea gates. At present, a sms-system alerts the citizens about the sea water level. Maybe the use of the MyWaterLevel app could improve the warning effectiveness.

The following Section is proposing an application of the TIFF for a cluster of innovations composed by an Early warning system, a mobile flood defence and the Flip-flap cofferdam dike.

8.10. Example application of the TIF for clusters of innovations in Cesenatico

The three innovations that are proposed as relevant for Cesenatico (see Section 8.9) - Drone system, Tubebarrier and Flip-Flap cofferdam - have been analysed through the application of the TIF tool, in order to achieve a combinatorial profile capable of mitigating the risk of coastal floods in such a scenario. The main features measured by innovation experts are categorized into four indexes: technical performance (range from 0 to 1) related to specific indicators of effectiveness, durability, reliability, flexibility; environmental impact (range from -1 to + 1) consisting of the quantification of environmental design and impact, as well as ecological impact; sectoral impact (range from -1 to +1) concerning the effects on agriculture, energy, forestry, health, infrastructure and tourism; and societal performance (range from 0 to +1) in terms of psychological, inflexibility, usability and responsibility concerns. Table 8.12 displays the scores obtained for the aspects described above; while the four indexes are the result of the arithmetic mean of the sub-level indicators for each innovation (Figure 8.7). The comparative analysis that enables a combination of the innovations (CoIs) is based on the algebraic sum of the four main indexes for each innovation, as well as the relative sub-level indicators. The overall results illustrated in Figure 8.8, report quite high technical (2.18) and societal performance (1.87) in a range from 0 to 3, and a reasonable environmental (0.28) and sectoral impact (0.58) in a range from -3 to +3. The differences between the TIF profiles of each innovation depend on the design features of the innovation and the way it is executed. However, since they have the same functionality, their combination allows to reduce especially in urban areas, the coastal floods hazard to a greater extent, thus reaching high levels of TIF indexes.

Examining in detail the CoIs profile, it is noticeable that the three innovations physically prevent the hazard from occurring and provide significant technical advantages in term of risk reduction compared to the traditional measures or conventional technologies (effectiveness), while they may require additional testing or substantial upgrades under future climate conditions. Thanks to the design characteristics of the innovations, the level of required maintenance is shallow, frequent inspections are not necessary, thereby increasing their level of reliability. Moreover, such technologies are continuously operated over their lifetime, and in case of emergency repair incorporating materials or software can be easily obtained and integrated by the end-users (durability). Despite few vulnerabilities during the testing, only related to the Tubebarrier innovation, and the execution of tasks by humans to be successfully operated during their operation or for their activation, all the three innovations do not require repair or replacement of components during the hazard event, in fact, they are designed to fully withstand the flooding (reliability). Furthermore, they present considerable flexibility level, as they can be easily adapted to different implementation context without additional testing or substantial upgrades to be marketed. An additional reason for flexibility is identified in Flip-Flap cofferdam innovation that has a secondary benefit: during non-emergencies, it can be used as boardwalk for pedestrian and bicycle traffic.

According to societal performance, the CoIs achieves a high degree of acceptance. The motivations are surely connected to their design features, that are: they do not use any “unfamiliar” materials like nanomaterials or genetically modified materials, or they don’t release any materials such as sprays or coatings; their application doesn’t disrupt daily activities, for example road closures. Besides, as they do not need large amounts of capital investment or long lead time between users placing and their execution, they raise minimal levels of psychological and usability concerns. Of the three innovations, only Flip-Flap cofferdam requires significant changes to existing infrastructure and special training, however the organization provides help and support to users of their innovation. The implementation of the CoIs has proven to reinforce the existing ways of working, and primarily protect public infrastructure, private properties and assets. Therefore, the effects that it produces are directly publicly tangible: seeing flood defences working or hearing a warning alert system are important observable benefits for society, leading citizens to increase own level of perceived personal control and perceived safety, as well as of trust in technology, innovation and emergency local management. However, some reasons of public concerns can be traced in the responsibility issues concerning the payment of the innovation, the implementation and the compensation in case of failure, which may vary from government authorities to private companies or local communities.

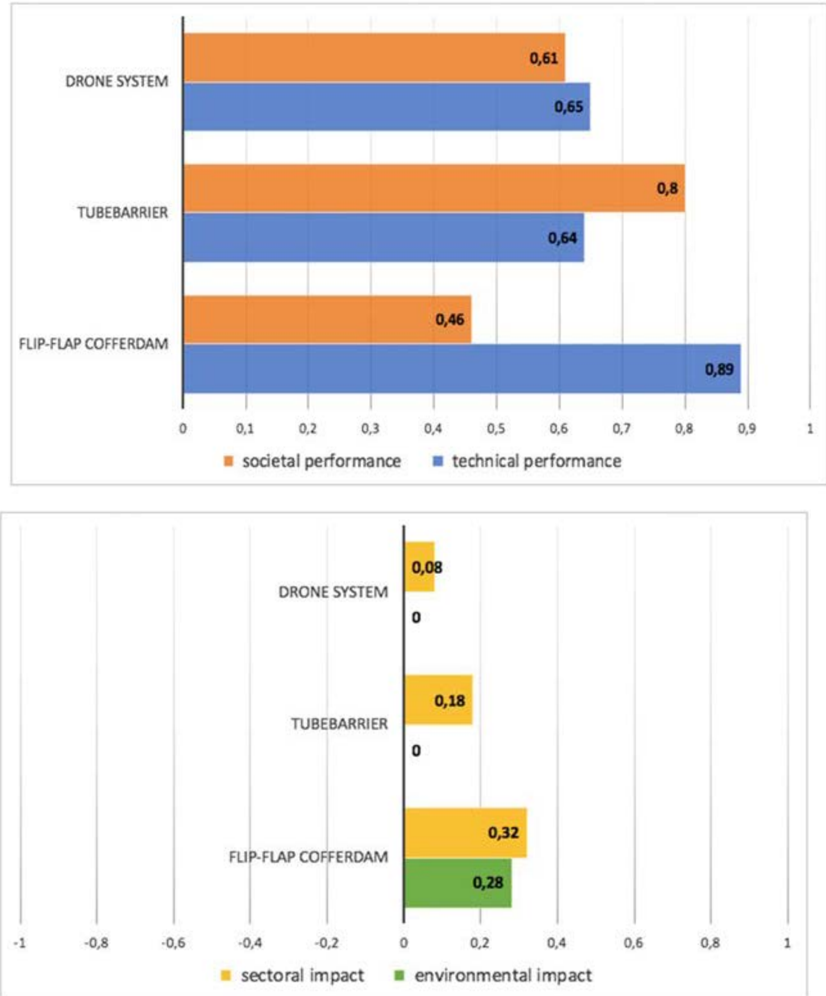


Fig. 8.7. TIF results of each innovation applied in Cesenatico.

The sectoral impact assessment denotes that the main benefits of CoIs can be identified in health, infrastructure and tourism sectors. Indeed, it decreases the number of fatalities as well as of people affected by the hazard in their physical, mental and psycho-social health. Furthermore, it improves the quality of built environment (residential, commercial and industrial), and the reliability of critical infrastructure networks. It also impacts the attractiveness of the area for recreational activities (Flip-Flap cofferdam). In other domains such as agriculture, energy, forestry, and tourism, it has not a specific impact and neither worsening effect. Analogously, the CoIs doesn't impact on the protected nature area, or on the quality of protected habitats and species, or specifically on the quality of water, soil and air, because of their operational purposes. For this reason, the CoIs presents a limited degree of environmental impact, although they do not interfere with the environment (it doesn't cause any pollution or environmental deterioration).

In particular, Flip-Flap cofferdam innovation is made of 93.5% recycled material and are 100% recyclable at the end of construction life span. Finally, the global evaluation reveals that three innovations fit harmoniously into the implementation context and their combination represents a successful adaptation strategy for coastal floods in Cesenatico and similar scenarios.

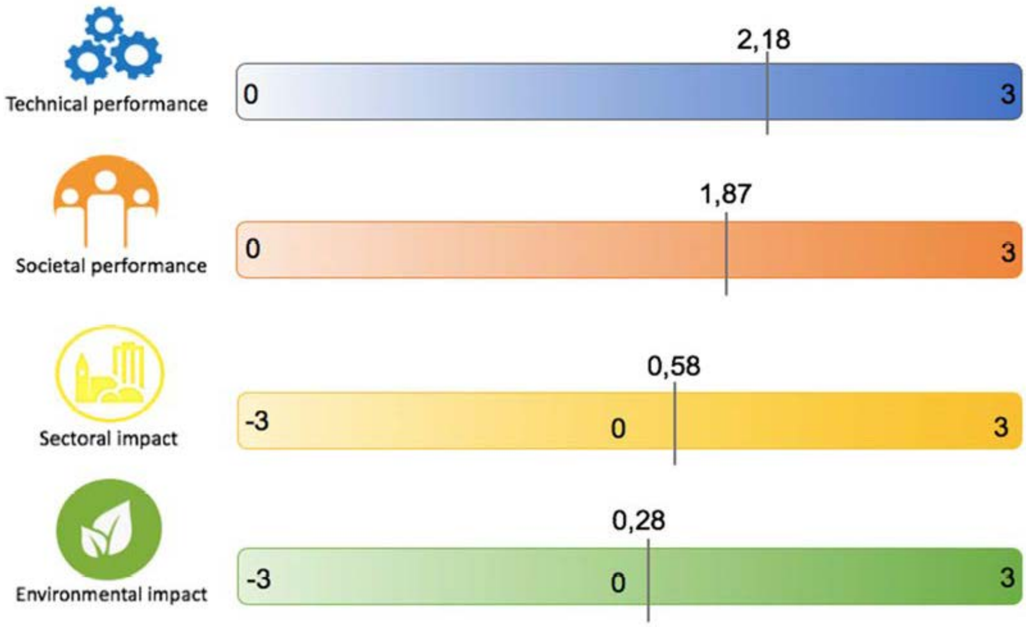


Fig. 8.8. TIF results of the CoIs applied in Cesenatico.

Table 8.12 Summary of the TIF results for each innovation and their combination.

	Application framework with Drone system	*Tubebarrier*	*Flip-Flap cofferdam*	**Combination of Innovations**
Technical Performance (min=0, max=1)	**0.65**	**0.64**	**0.89**	**2.18** (min=0, max=3)
effectiveness	0.50	0.75	0.75	2.00
durability	0.80	0.80	1.00	2.60
reliability	0.80	0.40	0.80	2.00
flexibility	0.50	0.60	1.00	2.10
Societal Performance (min=0, max=1)	**0.61**	**0.8**	**0.46**	**1.87** (min=0, max=3)
psychological concerns	0.75	0.75	0.75	2.25
inflexibility concerns	0.80	0.80	0.60	2.20
usability concerns	0.88	0.63	0.50	2.01
responsibility concerns	0	1.00	0	1.00
Environmental Impact (min=-1, max=1)	**0**	**0**	**0.28**	**0.28** (min=-3, max=3)
environmental design	0	0	0.67	0.67
environmental impact	0	0	0	0
ecological impact	0	0	0.17	0.17
Sectoral Impact (min=-1, max=1)	**0.08**	**0.18**	**0.32**	**0.58** (min=-3, max=3)
agriculture	0	0	0	0
energy	0	0	0	0
forestry	0	0	0	0
health	0.5	0.75	0.75	2.00
infrastructure	0	0.33	0.50	0.83
tourism	0	0	0.67	0.67

9. River flood losses in Dresden, Germany

This case study is developed on the basis of data and simulations provided – with the kind support of Fraunhofer Institute - by Dresden Municipality. These data have been particularly object of further analysis within the H2020 project EU-CIRCLE "A pan-European framework for strengthening Critical Infrastructure resilience to climate change" (Grant Agreement n° 653824) 1, which is closely related to BRIGAID. Indeed, the projects fall under the European call for proposal (EU-CIRCLE in 2014 and BRIGAID in 2015) about Disaster resilience & Climate Change, topic 1: Science and innovation for adaptation to climate change: from assessing costs, risks and opportunities to demonstration of options and practices.

9.1. Introduction

With a length of 1094 km and a total catchment area of about 150.000 km^2, the Elbe river and its tributaries belong to the major European river systems. Originating in the highlands of the Czech Republic at an altitude of 1386 m a.s.l., the Elbe drains large parts of the Czech Republic and of eastern Germany before flowing into the North Sea with a mean annual discharge of about 860 m^3/s at the river mouth. The discharge regime of the Elbe river is driven by the combined effects of rainfall and snowmelt and shows a peak discharge in March/April in the long-term mean. Still, extended precipitation events can cause major floods also during summer (Kotlarski S. et al., 2012). In Dresden - the largest city in the Eastern part of Germany, Saxony – the river Elbe is characterized by a width of around 110 m.

Major recent flooding events in the city of Dresden are registered in August 2002, March 2005, April 2006 and June 2013 and are due to intense and long rain. The flood in 2002 was an extreme event, only comparable to flooding in 1862 and 1890 in Dresden, characterized by a return period between 100 and 200 years (Gerl et al. 2014, Kreibich and Thieken, 2009). The flood discharge in 2006 was the second highest discharge since 1940 at the Dresden gauge although its return period was only about 15 years. In the 2002 flood of the Elbe and its tributaries, the severity of the event, along with low preparedness of authorities, public health institutions and households caused enourmous lossess in both the historical and residential areas of the city (Kreibich and Thieken, 2009, Meusel and Kirch, 2005). Losses to residential buildings only amounted from 240 million € to 304 million €, while companies have suffered damages amounting to 467 million € and damages to municipal infrastructures are estimated at 357 million € (Gerl et al. 2014). In the subsequent events, lessons learnt lead to an increase of precautionary measures and a new and improved flood management concept (Kreibich and Thieken, 2009).

Currently, along with an established awareness about river flood hazard, there is an increasing concern with respect to rapid growing of minor mountain streams in Dresden sourroundings area and consequent flash flooding phenomena.

Nevertheless – according to the research performed in the EU-CIRCLE project, which also included direct consultation with local actors and stakeholder, it results that damages associated to flash floods in Dresden area are moderate and Elbe river flooding represents the most relevant climate hazard.

[1] http://www.eu-circle.eu/

9.2. SPRC framework and use loss assessment as tool for risk analysis

In oder to evaluate the performance of different Clusters of Innovations (CoIs), a risk-based approach is floowed in this case study. The developed approach is based on the Source – Pathway – Receptor – Consequence (SPRC) framework already introduced in the previous chapters, implemented by a specifically tailored loss assessment methodology. For the aim of this work, the loss assessment is tailored to river flood risk and will be specifically referred to for the evaluation of the perfomance of the CoIs.

9.2.1. Risk estimation

Based on conventional approaches to flood risk estimation, the SPRC model visualises flood risk estimation as a linear process involving a 'Source' of flooding, flood 'Pathways' and affected 'Receptors' associated with different 'Consequences'.

Currently, risk-based approaches have been increasingly accepted and operationalized in flood risk management during recent decades. Within this work, it has been decided to refer to the loss assessment methodology for the implementation of the SPRC framework because, among the existing approaches, flood loss models are capable to describe the relationship between hazard intensity metrics such as flood depth, velocity, etc. and a damage ratio that can be translated into a monetary quantity. These relationships constitute a critical component of flood risk analyses and consequently play an important role in the implementation of risk-oriented management approaches as described by legal frameworks such as the EU-flood risk management directive[2] (Gerl et al., 2016).

The global increase of flood damage observed during recent decades is a prime mover to improve our understanding of flood impacts and consequences, for developing reliable loss models and efficiently reducing flood risk (Gerl et al., 2016). Available studies for economic losses from river floods and storms in Europe suggest that the observed increases in losses are primarily because of increases in populations, economic wealth and developments in hazard-prone areas, but the observed increase in heavy precipitation in parts of Europe may have also played a role (EEA, 2018). Just to give an idea of this fact in the European context, according to the Emergency Disasters Database (EM-DAT), between 2001 and 2011 the number of large-scale floods around Southern Europe increased with respect to the previous decade to over 120 major events causing some 345 fatalities and an estimated economic loss of at least €12 billion (Pistrika et al. 2014).

Despite the fact that great uncertainties affect the evaluation of the effects of climate change on flood hazard and risk estimation, it is recognized that changes in river flows due to climate change depend primarily on changes in the volume and timing of precipitation and, crucially, whether precipitation falls as snow or rain. A robust finding is that warming would lead to changes in the seasonality of river flows where much winter precipitation currently falls as snow, with spring flows decreasing because of the reduced or earlier snowmelt, and winter flows increasing, with likely consequences to flood risk. Overall, climate change is likely to cause an increase of the risk of riverine flooding across much of Europe. Flood risk and vulnerability tend to increase over many areas, due to a range of climatic and non-climatic impacts whose relative importance is site-specific. Deforestation, urbanization, and reduction of wetlands diminish the available water storage capacity and increase the runoff coefficient, and human encroachment into unsafe areas has increased the potential for damage, resulting in societies that become more exposed, developing flood-prone areas (maladaptation) (Kundzewicz et al. 2010). According to IPPC, a global warming of 1.5°C would also lead to an expansion of the global land area with significant increases in runoff (*medium*

[2] https://eur-lex.europa.eu/legal-content/en/TXT/?uri=CELEX:32007L0060

confidence) as well as an increase in flood hazard in some regions (*medium confidence*) when compared to present-day conditions. With medium confidence, this status would worsen in case of reaching a global warming of 2°C.

Losses represent a straightforward indicator of the resilience of e.g. a city. A resilient city is indeed capable of regaining its integrity after the extreme event, but it is also able to minimize the damage induced, thus reducing the need of subsequent repair. In this sense, resilience stands as a form of natural hazard mitigation and adaptation and should be pursued by planners and designers (Kotlarski at al., 2012). Flood loss estimation is also important for insurance and reinsurance companies to design insurance products and set appropriate premiums, as well as to estimate probable maximum losses to their portfolios, which in turn helps companies and regulators enforce the industry's solvency requirements (Gerl et al., 2016).

9.2.2. Main principles of Loss Assessment

The general aim of loss assessment is to estimate the total cost of damage of an asset or an area caused by external natural hazards, i.e. river flood along this document.

Cost, or loss, may be intended as economic, environmental or social (Menna et al., 2013). Economic costs are associated to the substitution or restoration of damaged buildings, assets or activities (in terms of labour and raw materials), but may also be calibrated to include indirect costs due to downtime and loss of functionality. Environmental costs are associated to the energy consumption and emissions required to repair/substitute the damaged objects and to the disposal or recycle of replaced components. Environmental impacts can be expressed in terms of non-renewable resource depletion,waste generation, energy consumption and GHGs emissions. Social costs and impacts measure the acceptable risk (safety) for a society. They are associated to human life losses and inconvenience perceived by the population as a consequence of the hazardous event. Flood damage can be also classified into the following four types: direct tangible (e.g. physical damage due to contact with water), indirect tangible (e.g. loss of production and income), direct intangible (e.g. loss of life) and indirect intangible (e.g. trauma). Most commonly, direct tangible damages are the only type assessed – and this trend is followed within this work (Jongman et al. 2012, Romali et al., 2018).

The estimation of direct flood damage is a complex process involving a large number of hydrologic and socioeconomic factors. The structure, inputs and outputs of a specific damage model are defined not only by the available data, but also by the purpose of the model (Jongman et al. 2012).

Although various different approaches for flood damage evaluation exist, basic necessary elements for the estimation can be summarized into (Romali et al., 2018):

- flood hazard (hydrological characteristics);
- exposure and value of elements at risk;
- susceptibility of the elements at risk to particular hydrologic conditions.

The combination of these elements allows the development of flood risk/damage assessment framework.

The amount of damages resulting from a flood depends on variable flood parameters, such as flood water depth, flood water velocity, year of flooding, duration of flooding, sediment and effluent contents, flooded area covered, and flood warning system (Romali et al., 2015).

Nevertheless, the internationally accepted and most common method for the estimation of direct flood damage is the application of depth–damage functions that are seen as the essential building blocks upon which flood damage assessments are based (Smith, 1994). For a given flood depth, the depth-damage function gives expected losses to a specific property or land use type. Differences in the methodological framework of flood damage models based on depth-damage functions are for example apparent in the spatial scale (object- versus area-based), damage-function type (absolute versus relative), damage classes, cost base (replacement cost versus depreciated cost) and the number of hydrological characteristics included. Also, while some damage models are constructed using empirical damage data, others are defined on expert judgement in combination with artificial inundation scenarios (Jongman et al., 2012).

In practice, the loss assessment methodology based on depth-damage functions consists in using such curves to associate to each level of intensity of the hazard a damage state that generates a certain amount of losses. It is highlighted that the level of damage at a given flood height is taken as deterministic according to the current practice of flood damage assessment (Gerl et al., 2016).

The input for depth-damage curves is derived thanks to a hazard analysis, which consists in the estimation of the water depth levels in the studied area under a selected scenario. The hazard analysis is thus the main step to carry out the loss evaluation. Afterwards, a suitable depth-damage function or a suitable set of depth-damage functions must be selected considering at least the type of assets/land use for which losses are calculated and the geographic location of the area where losses are calculated.

9.2.3. Implementation of loss assessment within SPRC framework

The operative steps of loss assessment analysis based on depth-damage functions well fit within the theoretical framework of the SPRC model for risk assessment. As a matter of fact, this is reasonable considering that on one side, the SPRC model is a conceptual framework for risk assessment, while, on the other side, loss assessment analysis is a methodology that allows to actually perform the risk assessment. A high degree of correspondence is thus to be found between the two topics and, specifically, it is identified a clear connection between the hazard analysis step of loss assessment and the source and pathway components of the SPRC model and between the losses estimation by depth-damage functions step and the receptor and consequence components (Figure 9.1).

Hazard analysis & Source and Pathway: the hazard analysis has as input information about the source of risk, which in this case is represented by fluvial discharge, likely generated by heavy rainfall. Depending on the type of hazard analysis performed, input data may be either the hyetograph of the rainfall event or directly the discharge/gauge values registered for the river. The hydraulic model used to determine inundation areas and related flood depths starting from input data is a representation of the pathways of the source to potential receptors in the flood-prone area. Indeed, it includes the main geomorphological characteristics of the flood plain area and river basin and may include existing flood protection installations and works. The scale and the resolution of the hydraulic model shall be set depending on the quality desired for final ouput of the hazard analysis.

Losses estimation by depth-damage functions & Receptor and consequence: the selection of depth-damage functions depends directly on the receptor of the flood hazard. Within loss assessment, a receptor is typically a building or an area. In case of buildings, depth-damage functions vary according according to either the class of the building (e.g. commercial, residential, etc.) or the structural typology (e.g. steel building, mansor building, etc.). The consequences of flood hazard are expressed by depth-damage functions most commonly in terms of direct tangible economic losses.

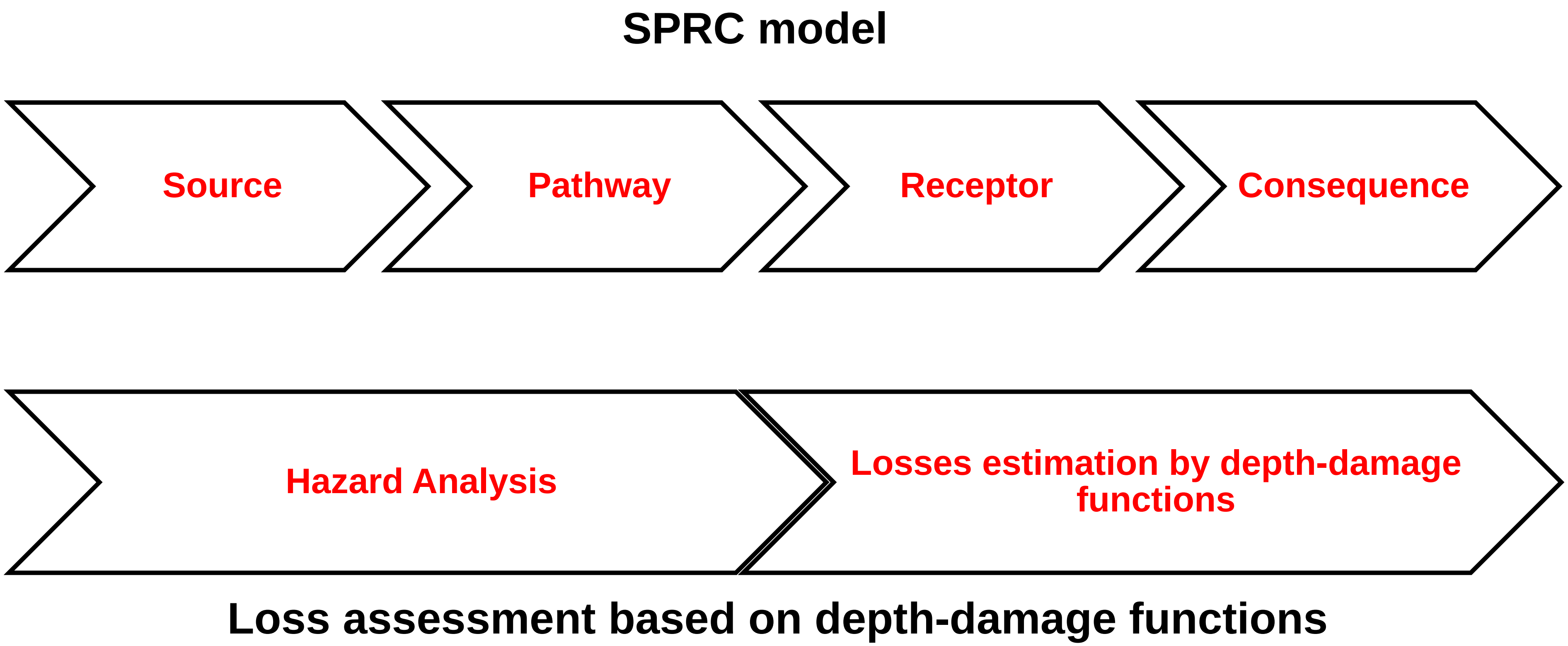


Figure 9.1: Implementation of loss assessment within SPRC framework

9.3. Methodology

Within this deliverable, the loss assessment analysis is applied with the aim of identifying the effects in reducing losses of clusters of innovations. The underlying idea is that effective clusters of innovations are able to reduce direct tangible losses and are thus effective in the view of climate change adaptation.

Initially, the study area is outlined on the basis of available hazard analyses and hydraulic models and assets for which losses are calculated are defined on the basis of main land uses encountered in the area.

For the severity scenarios outlined, the hazard (i.e. flood depth in inundated areas) is estimated. In detail, multiple hazard analyses performed with a 2D hydraulic simulation have been provided by Dresden Municipality to RINA Consulting for the purpose of this analysis.

The methodological approach that will be followed for the analysis reflects directly the methodology of loss assessment analysis based on depth-damage functions already introduced in a previous section.

For the purpose of this work, a suite of area-based damage functions representative of the european context is sought. Functions shall also vary according to land use class and shall provide the absolute value of tangible economic losses.

Subsequently, clusters of innovations are composed, considering the different perspectives from which river flood risks can be mitigated. Examples of general mitigation strategies include pre-, during, and post-disaster investments in preparedness activities and associated infrastructure, flood plain policy development, effective watershed land use planning, flood forecasting and warning systems, and response mechanisms (UNISDR, 2002). An effective cluster should be able to cover more than one mitigation strategy.

Having defined geographic boundaries for the assessment, severity levels, suitable depth-damage functions, and innovations of interest, a baseline loss assessment analysis is performed for the given scenarios, without considering the presence of any innovation.

Afterwards, the effects of each innovation are modelled by modifying the depth-damage functions according to the features of the innovation. From a theoretical perspective, this approach corresponds to assume that innovations directly act on the vulnerability of the urban area studied with respect to river flood hazard. A possible alternative approach would be to implement the innovations within the model for hazard analysis, imaging that the effects of an innovation could be represented by a hazard modification (ideally, reduction).

As last step, the effects of different single innovations are combined with the purpose of evaluating the performance of CoIs. Combination through overlapping is possible as the innovations within a cluster act on different aspects of risk (i.e.: on the vulnerability and on the hazard) and in some cases on different land use areas.

The methodology described provides as output an absolute value of economic losses for each scenario that varies depending on clusters of innovations implemented. This value can support the decision making process of municipalities, authorities, insurance companies willing to select effective strategies to minimize tangible costs caused by river flood hazard.

9.4. Case study development

9.4.1 Boundaries definition

On the basis of available hazard analyses and hydraulic models, the studied area stretches along the river Elbe, from the Loschwitzer Brücke (N) in Meissen area to the level of Birkwitz (S) in Pirna area (Figure 9.2).

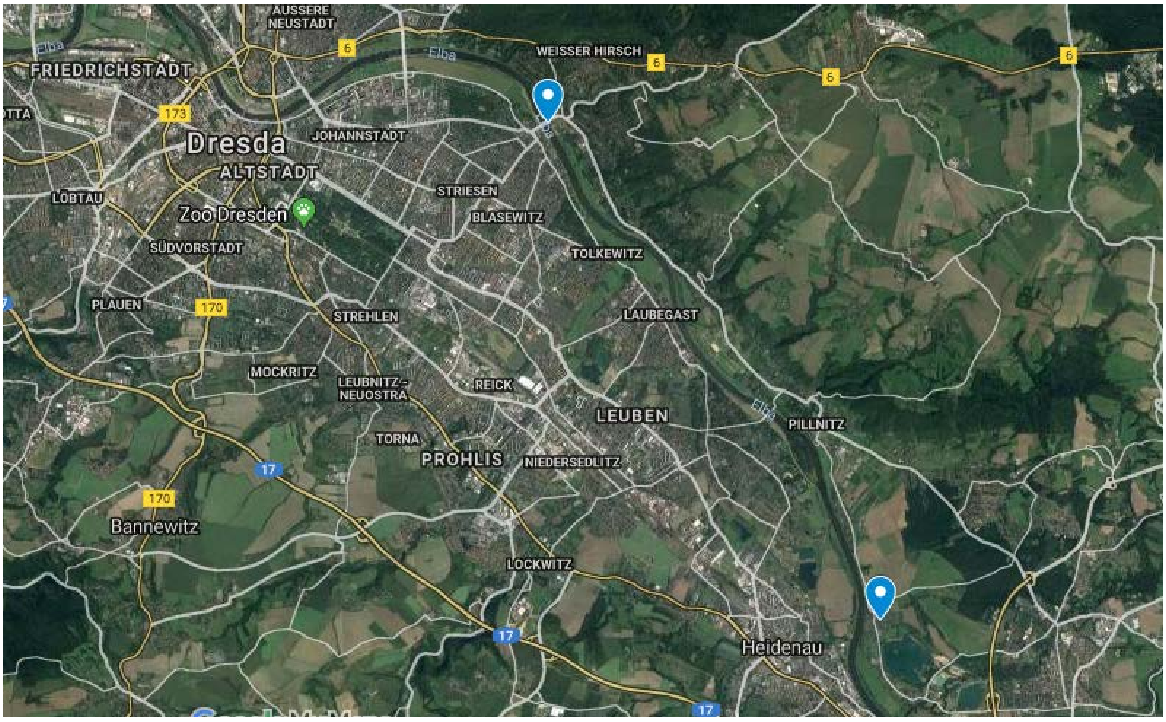


Figure 9.2: Location of the case study area

According to Corine Land Cover database (CLC 2012)[3], the area is occupied mainly by discontinuous urban fabrique, industrial or commercial units, pastures, green urban ares, sport and leisure facilities, broad-leaved forest, non irrigatd-arable land, complex cultivation pattern, coniferus forest and fruit trees and berries plantation (Figure 9.3). Considering land uses observed in the case study areas and on the basis of mos tipycally available depth-damage functions, losses are evaluated for residential buildings, commercial and industrial buildings and areas dedicated to agricultural activities. It is highlighted that, in theory, this approach does not assure to evaluate the most relevant losses as, for example, a particularly valuable asset (e.g. a monument, a museum, a strategic plant, ect.) are not specifically included within land use maps, which typically do not have such high resolution. Nevertheless, it is reasonable to assume that the calculation of losses for most typical activities of the area is able to provide a significant estimation of losses and it can be used as a strarting point for more refined and specific loss analyses.

[3] https://land.copernicus.eu/pan-european/corine-land-cover/clc-2012

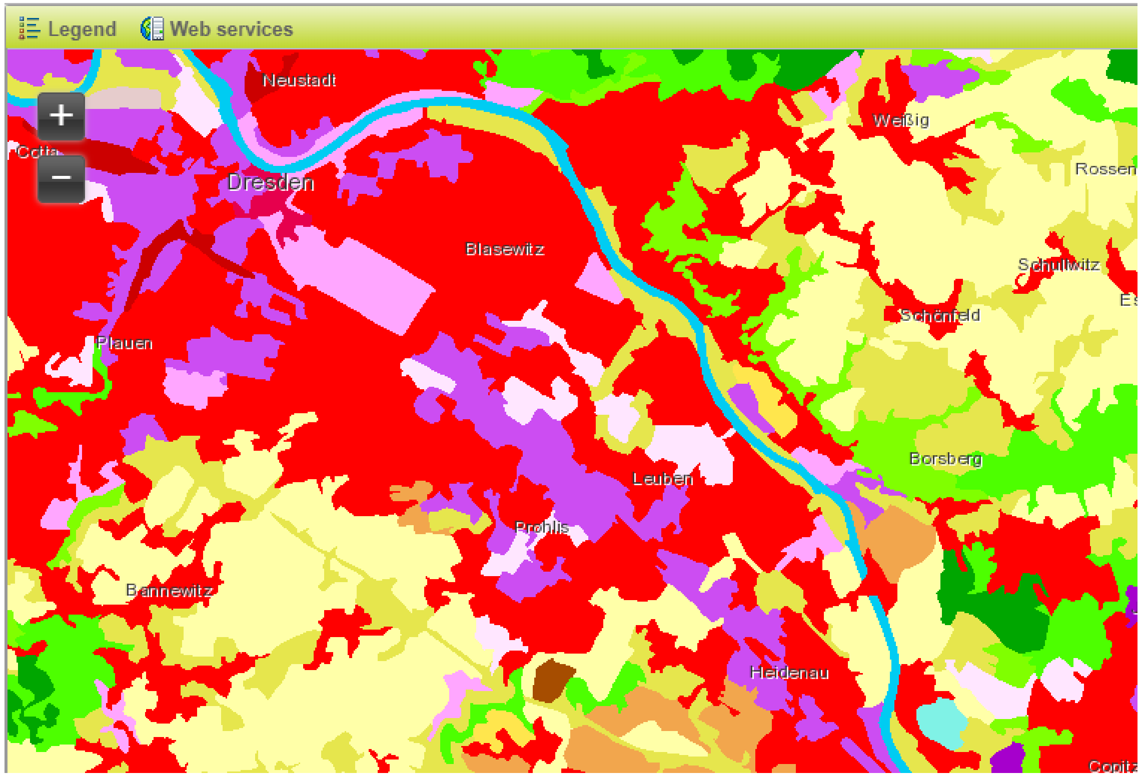


Figure 9.3: Land use of the case study area

9.4.2 Hazard estimation

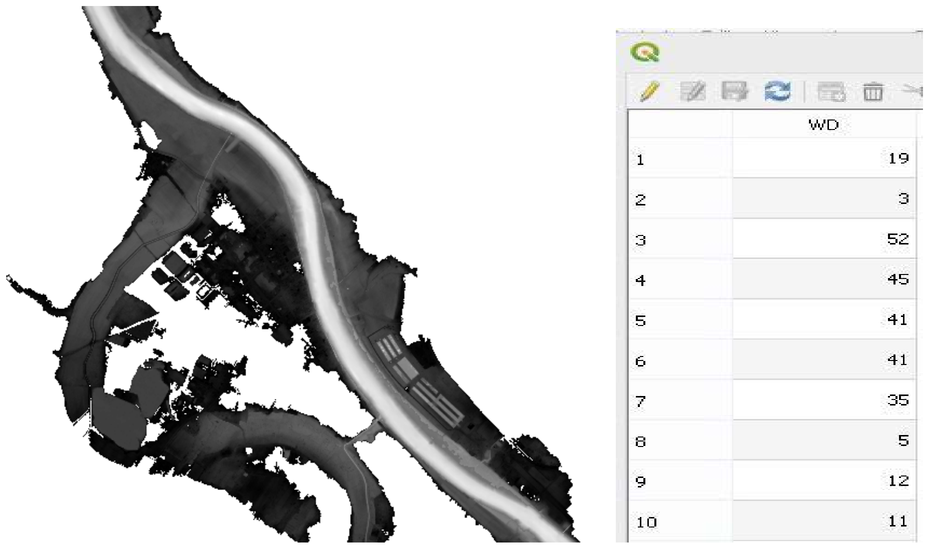
The severity scenarios (SS) considered to evaluate the effectiveness of the CoIs are the following:

- SS 1: 100 year-return period discharge, correponding to a Elbe water level of approximately 900 cm – the severity of this scenario is comparable with the severity of the flood in 2002;
- SS CC: discharge under climate change conditions, corresponding to a Elbe water level of approximately 1050 cm in 2050.

A 2D hydrodynamic numerical simulation model has been developed by the TU Dresden Institute for Hydraulic Engineering and Technical Hydromechanics. The model has been used to assess potential flooding areas corresponding to Elbe water levels ranging from 3.50 m to 10.50 m at the Dresden gauge. The 100-year return period flood scenario is included in the analyses as it corresponds to a water level of about 9 m at Dresden gauge, and the flood scenario under climate change is included in the analyses as it corresponds to the current 500-year return period flood scenario, corresponding to the highest water level simulated within the hydraulic model.

As shown in Figure 9.4, the main results of each simulation are:

- flooded areas;
- water depth levels in flooded areas.



	WD
1	19
2	3
3	52
4	45
5	41
6	41
7	35
8	5
9	12
10	11

Figure 9.4: Main results of hydraulic simulations

9.4.3 Focus on climate change scenario

It is well known that the effects of climate change will, in the short future, alter the exposure to natural hazard in complex ways (Thober et al., 2018). When performing risk analyses considering the impact of climate change, this fact should be coupled with foreseen socio-economic changes, which are directly connected to vulnerability and exposure factors.

As for the case of river Elbe in Dresden, studies show a clear increase in river flood hazard (Thober et al., 2018, BRIGAID, 2017, Dankers and Feyen, 2007, Hattermann et al., 2014, EEA, 2016, JRC, 2009), even though indicators used for hazard representation vary and quantitative results produced show significant variability.

An incease in river flood hazard can be visualized from two different perspectives:

1. a flood of given severity will have a shorter return period in the future compared to its actual return period, i.e. it will be more frequent. For example, according to (Dankers and Feyen, 2007), a 100-year return period Elbe river flood will have a return period of approximately 20-50 years in 2071-2100 under the climate change scenario family A2 of IPCC (IPCC, 2000);
2. a flood with a given return period will be more severe in the future. For example, according to (EEA, 2016), it is expected that in 2080, the magnitude of a 100-year flood for river Elbe will increase of approximately 30% compared to 1990 levels.

For the purpose of this analysis, the hazard scenario considering the impacts of climate change (SS – CC) is set as an increase of 30% of current 100-year return period discharge at Dresden gauge in 2050, corresponding roughly to a water depth at Dresden water gauge of 10,50 m (Bartl et al., 2009). The correspondent climatic scenario according to (EEA, 2016), is derived from a large ensemble of climate projections at pan-European scale derived from 12 climate experiments, in order to take into consideration climate model uncertainty when assessing the impact of climate change on future flood hazard (Rojas et al., 2012). The experiments have a lateral resolution of approximately 25 km, covering the period 1961–2100 and are forced by the SRES-A1B scenario, as defined in the IPCC special report on emissions scenario (IPCC, 2000).

It is pointed out that the effects of climate change are accounted for only for hazard definition, but do not include changes and transformations of land use and damage value.

9.4.4 Depth-damage functions

The selection of suitable depth-damage functions is a crucial point for the loss estimation phase. In this context, it is based on a globally consistent database of depth-damage functions recently published by the European Joint Research Center (Huizinga et al., 2017).

Specifically, a set of area-based functions that allow estimation of relative damage at European level is extrapolated from the database. In order to shift from relative damage to absolute damage values taking into account the specific features of the country where the analysis is performed (i.e. Germany), the database provides country-specific maximum damage values These maximum damage values are based on construction cost surveys from multinational construction companies, which provide a coherent set of detailed building cost data across dozens of countries and are transformed to area-based values by introducing a building density value. If not further elaborated, they are to be intended as replacement costs.

On the basis of the most common land use classes encountered in the case study area (*boundaries definition* section), depth-damage functions are selected for residential, commercial, industrial and agricultural areas (Figure 9.5).

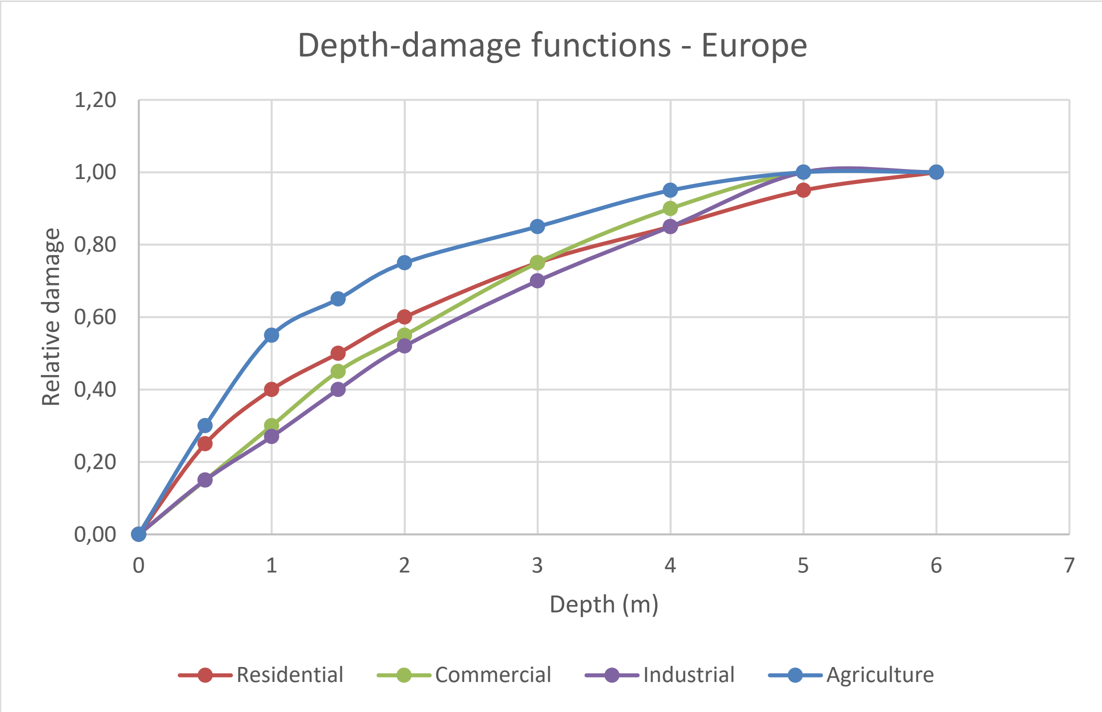


Figure 9.5: Depth-damage functions

For Germany, the following land-use based maximum damage values are provided:

Table 9.1: Maximum damage values for land uses in Germany

LAND USE	MAXIMUM DAMAGE VALUE
Residential	157 €/m^2
Commercial	326 €/m^2
Industrial	264 €/m^2

In addition, for areas dedicated to agricultural activities, the maximum damage value is interpreted as value added, as indeed, damages in the case of agriculture are rather related to a loss in output due to the yields being destroyed by floods. The value added is estimated considering average value calculated on a five years basis in order to minimize single-year deviations. For Germany, an added value of 1208 €/ha can be assumed.

Considering the specific features of land cover classes described and shown in (Kosztra et al, 2017), the following matches between land cover class and depth-damage function to be used for that class are assumed:

For the scope of this work, Corine land cover classes are thus aggregated into three main classes of land use: residential, commercial and agricultural. It is noticed that the depth-damage function for industrial land use has not been used for the following analyses.

Land cover classes relaed to forests are not associated to any economic damage. Anyway, in this case study the assumption does not affect final results as areas dedicated to forests are not floodable under the scenario considered.

Table 9.2: Corine land cover classes and correspondent depth damage functions

CORINE LAND COVER CLASS	DEPTH-DAMAGE FUNCTION
Continuous urban fabrique	Residential
Discontinuous urban fabrique	Residential
Industrial or commercial unit	Commercial
Non irrigated arable land	Agricultural
Fruit trees and berry plantations	Agricultural
Pastures	Agricultural
Complex cultivation patterns	Agricultural

9.4.5 Losses estimation

The estimation of losses is carried out following an analysis performed with the open source software QGIS[4]. Precisely, the QGIS analysis for each hazard scenario consists in the steps reported below:

- aggregation of hazard analysis results: identification of areas associated by flood depths within a given range, its average value, i.e. water depth reference value. This operation allows to limit the computational burden of the following steps;
- areas associated to each reference water depth value are intersected with areas associated to each land use type, in order to calculate the extension of areas, for each land use type, associated to a certain average value of water depth.

For each water depth reference value, and for each land use type, the damage ratio is estimated from the depth-damage functions and is then multiplied for the area corresponding to that reference water depth value and that land use type in order to calculate the amount of total losses for the scenario. Partial results such as the estimation of losses for a certain land use type or for a certain water depth range may also be retrieved.

9.4.6 Innovations and CoIs

Clusters of Innovations are defined considering different categories of innovations, namely warning systems, barriers for existing building and assets and innovations to reduce river flood hazard in urban areas. Each category includes a selection of innovations from the BRIGAID Climate Innovation Window[5].

These categories of innovations correspond to complementary strategies to reduce flood risks. Indeed, as confirmed also in (UNISDR, 2002), there is a growing realization that various flood mitigation measures must be combined in ways that are appropriate to effectively address local situations. Strategies to reduce flood

[4] https://www.qgis.org/en/site/
[5] https://climateinnovationwindow.eu/

losses should include both structural and non-structural measures, such as improving land use regulation, insurance schemes and increased participation of communities and their ability to work togheter on preventive measures as, indeed, combined structural and non-structural flood mitigation plans seem most promising and are expected to result in significant economic benefit (Kreibich et al., 2005).

Categories of Innovations

- Warning Systems

Flood warnings are an important mean of adapting to growing flood risk and learning to live with it by avoiding damage, loss of life, and injury (Parker, 2017). A flood warning system that is properly planned, constructed, and operated gives property owners and floodplain occupants and those responsible for their safety more time to respond to a flood threat before the threshold is exceeded. With this increased mitigation time, lives and property are protected (Carsell, 2004). It should be pointed out that a clear difference between information, education, and communication exists (UNISDR, 2002). For example, a forecast of water level by the technocrat may not be meaningful to the target groups. The forecaster and the people must be educated so that the message is understood by the various users and suitable means of communication should be selected.

Innovations of this type are theoretically able to reduce damages for all land use types. Nevertheless, in such case it is assumed that flood warning systems are associated to a reduction of economic losses for residential areas.

Among the innovations of BRIGAID, there is a variety of warning systems, such as for example:

- Flood local tool;
- Application framework with drone system;
- My water level;
- SAEx;
- Operational flood forecasting system including levee performance.

These warning systems are characterized by different warning lead times and correspondent reliability level of the forecast. In addition, they are based on ICT technologies and they can provide also warning messages directly to the citizens, via smartphones, along with offering support to municipalities.

- Barriers for existing building and assets

Flood proofing of existing structures is difficult and expensive. In general, it can include raising of structures to prevent damage, relocation of utilities, changed building use, installation of protective walls and waterproof closures, and use of materials that are not damaged by water and can be easily cleaned after the flood event (UNISDR, 2002). Permanent or mobile water barriers can be used to keep flood water out of individual buildings or whole urban areas. In case of a flood warning some time is needed to set them up, depending on the system. If there is enough time, barriers made of sandbags can be constructed. Their efficiency depends on the number of rows and the duration of the flooding (Kreibich et al., 2005).

Innovations of this type are able to reduce damages for residential and commercial and industrial areas. Within this work, it is assumed that barriers are rasied only for protection of commercial and industrial areas.

Among the innovations of BRIGAID, there is a variety of innovative barriers for building assets, such as for example:

- NOAQ boxwall and Tubewall;
- Self - erecting flood protection system;
- NoFloods mobile barrier;
- Tubebarrier.

In general, their main potential is that they are very flexible in terms of location for the installaion and semplicity of installation and can thus be used as temporary, only when needed.

- Innovations to reduce river flood hazard in urban area

Serveral ways to protect urban areas from inundation due to river flood exist. Among the most common, there are structural measures, that include the construction or improvement of flood protection infrastructure, through the construction of dams, diversions, storm channels and levees.

Innovations of this type are able to reduce damages for all land use types, as they reduce the directly the hazard.

Clusters of Innovations

Clusters of Innovations (CoIs) are defined taking into account the different types of innovations that can be implemented simultaneously and the land cover classes the innovations can be influencial for.

The following clusters are thus introduced (Table 9.3):

Table 9.3: COIs definition

CoI 1	Warning system	Residential areas
	Barriers	Commercial and industrial areas
CoI 2	Warning system	Residential areas
	Barriers	Commercial and industrial areas
	Reducing hazard (levees' improvement)	Residential, commercial and industrial, agricultural areas

9.4.7 How to account for innovations and CoIs in loss assessment

Warning Systems

The effects on direct tangible losses of the implementation of one (ore more) warning system(s) can be captured by using the so called Day's curve (Carsell et al., 2004, Scawthorn, 2006). This curve predicts direct tangible damage reduction in percentage terms out of the maximum potential flood total damage as a function of the warning time guaranteed by the warning system.

The curve has been developed for residential areas and its trend approaches a maximum value of approximately 35% for structural, content, and business inventory losses regardless of how much warning is available, considering that some properties, including mostly structures, cannot be removed. In addition, within HAZUS[6] – the well-known and established American methodology for estimating potential losses from disasters – some modifications to take into account warning dissemination and public response to warning are given (Scawthorn et al., 2006).

On the basis of the general features of the innovations and of the data gathered from the innovators, for this case study a warning lead time of 2 hours – corresponding to approximately a damage reduction of 5% is considered in the analysis. As the warning systems can also send warning messages via smartphone, it is assumed that all the citizens are reached by the alarm and no reduction to take into account the level of dissemination is considered. Furthermore, due to the low value of warning time conservatively assumed, and thus high reliability, reductions for limited response to warning are not introduced.

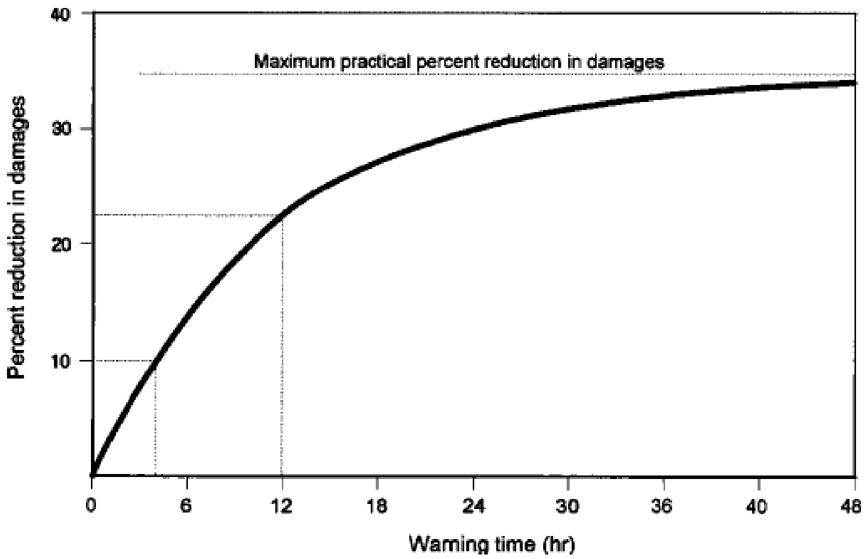


Figure 9.6: Day's Curve (source: Carsel et al. 2004)

Barriers for buildings and assets

Barriers are effective in reducing potential damage, if not overtopped. Nevertheless, barriers cannot avoid damages related to groundwater. According to the indications provided in (International Commission for the Protection of Rhin, 2002), it is conservatively assumed that an effective barriers (i.e. not overtopped) may reduce damage up to 80%. Indeed, if it possible to state that cellars are properly sealed and rising of

[6] https://www.fema.gov/hazus

groundwater is avoided, damage reduction may reach 100%.

Depth-damage functions will thus be scaled by 80% for those water depths that do not overtop the barrier.

On the basis of the general features of the innovations as outlined in D2.2 (BRIGAID, 2016) and of the data gathered from the innovators, for this case study it is assumed that a 1 m high barrier is put in place to protect commericial assets of the case study areas. The possibility of taking into account the fact that only some of the potentially flooded asset are protected by barriers is not considered within this study, also in the light of the fact that barriers are suitable to be installed in mostly all kinds of urban areas, including grass or pavements.

Innovations that directly limit river flood hazard in urban areas

The effects of structural inteventions, which are aimed at reducing river flood hazard in urban areas, can be taken into account by performing a new hydraulic simulation and hazard analysis (*hazard estimation* section), where these structures are modelled. Nevertheless, such kind of analysis is very demanding in terms of efforts, software availability and knowledge and will thus not be performed within this case study.

In order to take into account the reduction of flood losses related to the installation of innovations that behave as structural measures, being able to limit flood hazard in the case study area, a peformance criterion is set. The criterion establishes that the innovation shall be designed in order to guarantee an average (in space) reduction of flood hazard (i.e. maximum water depth) of 10% for the selected scenario.

Clusters of Innovations

In order to consider the reduction of economic losses related to CoIs, the rules introduced to account for the single innvoations are integrated as follows:

- CoI 1: the depth-damage function for residential areas is modified to take into account for the warning system implementation and the depth damage function for commercial and industrial areas is modified to account for the presence of barriers. The depth-damage function for agricultural land is not modified.
- CoI 2: the depth-damage functions for residential and commercial and industrial areas are modified in the same way as for CoI 1.

9.5. Results and discussion

For this analysis, the loss assessment methodology has been used to evaluate the effectiveness of CoIs in reducing river flood risk in Dresden area, along river Elbe (Germany).

Results obtained can be useful to support the decision making process of the Municipality, showing overall avoided losses and the impact of each CoI on different sectors and for each scenario. The analysis can be made more robust when exploring also the effectiveness of the same CoIs under additional river flood scenarios and it may be expanded to take into account the costs for the design, purchase and installation of the innovations, in order to carry out also a cost-benefit assessment.

Overall synthetic results (Table 9.4) consist in the values of economic losses associated to the different scenarios outlined. In addition, percentage reduction of losses with respect to the correspondent baseline scenario (i.e. no innovations, with or without climate change effects) is shown.

Table 9.4: Results

Scenario	Total losses [€]	Reduction from baseline [%]
SS 1 - Baseline	267,255,764	-
SS 1 - CoI 1	253,612,721	5.1
SS 1 - CoI 2	241,505,615	9.6
SS CC – Baseline	780,271,098	-
SS CC - CoI 1	720,633,624	7.6
SS CC - CoI 2	678,995,291	12.3

Results show that when considering the impacts of climate change, expected losses increase significantly, almost tripling losses of the correspondent scenarios without including climate change effects. Nevertheless, it is pointed out that when more severe scenario is considered, innovations become more effective in reducing losses.

For both SS 1 and SS CC, as expected, the smallest value of losses is associated to CoI 2, which includes early warning, barriers and hazard reduction systems.

For SS 1, losses are reduced of almost 10% compared to the baseline scenario, while a 5% reduction is associated to CoI 1, including early warning and barriers only. For SS CC, reductions from the baseline case, are higher than in SS 1, both in relative and absolute terms and represent the 7.6 % of baseline losses for CoI 1 and 12.3% of baseline losses for CoI 2.

Overall losses, in euros per unit of floodable area, are shown in Table 9.5 below, considering an overall floodable area of 9,104,512 m^2 for the SS 1 scenario and of 27,260,890 m^2 for the SS CC.

Highest values of losses per floodable area are recorded for the SS 1 because, in the case of SS CC a significant portion of floodable consists in forests, which are not associated with any loss.

Furthermore, it is interesting to extrapolate from the results the values of avoided losses, according on land use class. They are shown in Table 9.6 for SS 1 and in Table 9.7 below for SS CC.

In light of the results obtained, with or without climate change effects, it is pointed out that both in the case of CoI 1 and CoI 2, major benefits are associated with the residential land use class. In relative terms, reduction of losses is maximum for commercial and industrial areas for both the CoIs. The low value of avoided losses for agricultural areas when CoI 2 is implemented is explained considering the low value of losses per m^2 of agricultural areas on one side and considering that only the innovation aimed at hazard reduction is effective in reducing losses in agricultural areas.

Table 9.5: Losses per unit of floodable area

	SS 1	SS CC

Baseline	29.3	28.6
Col 1	27.9	26.4
Col 2	26.5	24.9

Table 9.6: Avoided losses compared to baseline per land use class – SS 1

	Col 1		Col 2	
Land use class	Avoided losses [€]	Reduction from baseline [%]	Avoided losses [€]	Reduction from baseline [%]
Residential	10,528,857	5	19,755,019	9.4
Commercial & industrial	3,114,186	5.9	5,879,881	11.1
Agricultural	0	0	115,249	3.0

Table 9.7: Avoided losses compared to baseline per land use class – SS CC

	Col 1		Col 2	
Land use class	Avoided losses [€]	Reduction from baseline [%]	Avoided losses [€]	Reduction from baseline [%]
Residential	30,745,006	5.0	59,787,366	9.7
Commercial & industrial	28,892,467	18.0	41,384,057	25.8
Agricultural	0	0	104,383	2.0

10. Conclusions

D5.7 presented a comprehensive quali-quantitative methodology for risk assessment and management by the appropriate selection of clusters of innovations.

The application of the SPRC methodology allows to obtain a qualitative risk assessment in a given site, including a full description of the system exposed at the hazard/s and promoting a participatory approach within the local communities and the experts. The detailed modelling of the hydraulic vulnerability is then the first step to derive a quantitative risk assessment, which can be performed by means of decision support systems, leading to the quantitative assessment of social, economic and environmental impacts. This assessment can be run for different clusters of innovations, leading to the selection of the optimal cluster for a given site in terms of risk management effectiveness. This information can be complemented by qualitatively assessing the sectoral impact assessment of the clusters through the linear combination of the tables describing the sectoral impact assessment of each innovation within the cluster.

Managers and policy makers can benefit from the support of decision support systems, which have been developed also in the BRIGAID project (for instance, the COASTS tool) and are available through the Climate Innovation Window. These systems allow for a simplified run of many climate scenarios, representing different sources of hazards, such as coastal floods, riverine floods and rainfalls, and allow to include clusters of adaptation solutions. The results of the risk assessment maps can be used to support the selection of different clusters.

D5.7 presented also three examples, showing how to select and implement clusters of innovations in different sites: in Cesenatico, IT, in Antwerp, BE, and in Dresden, DE. In these sites, risk assessment was first carried out by applying the SPRC method, in cooperation with the local communities. The quantitative information about the hydraulic vulnerability of the areas were then derived from detailed hydraulic modelling. In both Cesenatico and Antwerp, the assessment was performed thanks to decision support systems. In Cesenatico, an application of the sectoral impact of Clusters of Innovations starting from the available TIF was also presented.

In Antwerp the selection of the innovations to be combined at the site started from addressing two complementary hazards, extreme rainfalls and floods. A new prototype experiment to be monitored in BRIGAID was set-up, by designing green roofs and temporary flood barriers to protect part of the city.

In Cesenatico, the social, environmental and economic effects due to the combination of breakwaters, evacuation plans, insurance plans and environmentally friendly solutions like dune restoration were examined. Based on the experience gained in BRIGAID, a new set of solutions was proposed, including mobile flood defence barriers, early warning system with drones and Flip-Flap cofferdam dikes. For this cluster, the analysis of the combined sectoral impact was carried out, in strict cooperation with the developers of these innovations.

In Dresden, the combination of flood mobile barriers, early warning systems and maintenance/consolidation of existing levees was analysed, showing the significant potential of damage reduction in climate change scenarios.

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